Fertigungstechnik - Erlangen

Herausgeber:
Prof. Dr.-Ing. Jörg Franke
Prof. Dr.-Ing. habil. Marion Merklein
Prof. Dr.-Ing. Michael Schmidt

Jan Tremel

293

Flexible Systems for Permanent Magnet Assembly and Magnetic Rotor Measurement / Flexible Systeme zur Montage von Permanentmagneten und zur Messung magnetischer Rotoren

Meisenbach GmbH Verlag

293
Permanent magnet assembly
Tremel

ISSN 1431-6226
ISBN 978-3-87525-419-8

Jan Tremel

Flexible Systems for Permanent Magnet Assembly and Magnetic Rotor Measurement / Flexible Systeme zur Montage von Permanentmagneten und zur Messung magnetischer Rotoren

Jan Tremel

Flexible Systems for Permanent Magnet Assembly and Magnetic Rotor Measurement / Flexible Systeme zur Montage von Permanentmagneten und zur Messung magnetischer Rotoren

Bericht aus dem Lehrstuhl für Fertigungsautomatisierung und Produktionssystematik
Prof. Dr.-Ing. Jörg Franke

FAPS

Meisenbach
GmbH Verlag

Als Dissertation genehmigt von der Technischen Fakultät
der Friedrich-Alexander-Universität Erlangen-Nürnberg

Tag der mündlichen Prüfung:	18. November 2016
Vorsitzender des Promotionsorgans:	Prof. Dr.-Ing. Reinhard Lerch
Gutachter:	Prof. Dr.-Ing. Jörg Franke
	Prof. Dr. Thorsten Schüppstuhl, Technische Universität Hamburg-Harburg

Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.ddb.de abrufbar.

ISSN 1431-6226
ISBN 978-3-87525-419-8

Herstellung: inprint GmbH, Erlangen
Printed in Germany

Flexible Systems for Permanent Magnet Assembly and Magnetic Rotor Measurement

Flexible Systeme zur Montage von Permanentmagneten und zur Messung magnetischer Rotoren

Der Technischen Fakultät der
Friedrich-Alexander-Universität Erlangen-Nürnberg
zur

Erlangung des Doktorgrades Dr.-Ing.

vorgelegt von

Jan Tremel

aus Lichtenfels

Als Dissertation genehmigt von
der Technischen Fakultät
der Friedrich-Alexander-Universität Erlangen-Nürnberg

Tag der mündlichen Prüfung:	18.11.2016
Vorsitzende des Promotionsorgans:	Prof. Dr.-Ing. Reinhard Lerch
Gutachter/in:	Prof. Dr.-Ing. J. Franke
	Prof. Dr.-Ing. T. Schüppstuhl

Vorwort

Die vorliegende Arbeit entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Lehrstuhl für Fertigungsautomatisierung und Produktionssystematik (FAPS) an der Friedrich-Alexander-Universität Erlangen-Nürnberg.

Mein Dank gilt dem Leiter dieses Lehrstuhls, Herrn Prof. Dr.-Ing. Jörg Franke und dem Gründer des Lehrstuhls, Herrn Prof. Dr.-Ing. Klaus Feldmann, die mir die Möglichkeit zur Promotion gegeben haben. Das entgegengebrachte Vertrauen, die wissenschaftlichen Freiräume und die vielen konstruktiven Anregungen förderten stets meine Forschungsarbeit. Darüber hinaus bedanke ich mich bei Prof. Dr.-Ing. T. Schüppstuhl und Prof. Dr.-Ing Waigel für die Übernahme des Koreferats bzw. der Mitgliedschaft im Prüfungskollegium.

Ein sehr großer Dank gilt auch allen Mitarbeiterinnen und Mitarbeitern des Lehrstuhls FAPS, die im Laufe meiner Promotionszeit nicht nur Kollegen in spannenden Projekten waren und zu zuverlässigen Freunden geworden sind. Die administrative, kaufmännische, technische und fachspezifische Unterstützung sowie die angenehme Arbeitsatmosphäre hat ganz entscheidend zum Gelingen dieser Dissertation beigetragen. Insbesondere möchte ich allen von mir betreuten Studenten und wissenschaftlichen Hilfskräften für ihr großes Engagement danken, mit dem sie mir bei der Forschungsarbeit und der Realisierung meiner Ideen und Konzepte geholfen haben.

Besonderer Dank gilt meiner Familie, die mich während aller Phasen meines Lebens und meiner Ausbildung gefördert haben, fördern und Rückhalt bieten.

Erlangen, im Dezember 2016 Jan Tremel

Flexible Systems for Permanent Magnet Assembly and Magnetic Rotor Measurement

Table of Contents

1 Permanent Magnet Motors Enable New Drive Technologies.

Production methods for electric motors have been pushed due to an increased demand for electric drives with optimized efficiency and flexible variant production in small, medium and large batch sizes tailored to suit industrial needs. Additional new markets arise from the technological shift from combustion based motors to electric drive systems.

For the production of permanent magnet drives, investment for semi- or automated handling and workplace equipment is necessary. For traditional manufacturers of PM-servo motors, this means a long-term investment including an assembly solution for a series of standard drives. Therefore new motor variants are built up by either alternating the winding scheme of the stator side or by adapting the permanent magnet design of the rotor. Customers expect expanded product service lives and have high requirements towards product quality also within small to medium scale batch sizes. The introduction of additional variants on the magnet side is cost intensive, because high invests for tooling (e.g. interlocking tools for production of lamination, or magnetizing tools) are needed. Permanent magnet handling is therefore sensitive for new products and production equipment. Proprietary solutions are maintained for a long time because risk and investment are estimated too high for innovative workplace engineering and the introduction of new workflows.

Besides economical concerns the handling of permanent magnets also enables technical advantages and can lead to improvements in production. Therefore process chains for electric motor production are challenged by:

- Higher batch sizes: with the right strategy for the complete rotor assembly process and workplace layout optimization, batch sizes can vary and be enlarged with one toolset for all magnet shapes.
- More flexibility: the workplace must be expanded for new types by implementing a distinct workplace workflow.
- Better quality: strong improvements have to be achieved with an adapted strategy for handling the magnet, starting in material reception in factory until workplace supply including a hand contact free operation during the assembly process even for manual assembly processes.
- Shorter cycles: Handling devices need to shorten assembly cycle times even with manually driven workplaces.
- Process control: The inline implementation of magnetization checks for single magnets or magnet assemblies has to provide additional information for failure detection.
- A description of grippers including solutions for SPM and IPM motor designs must be established ideas for fast prototyping of rotor variants

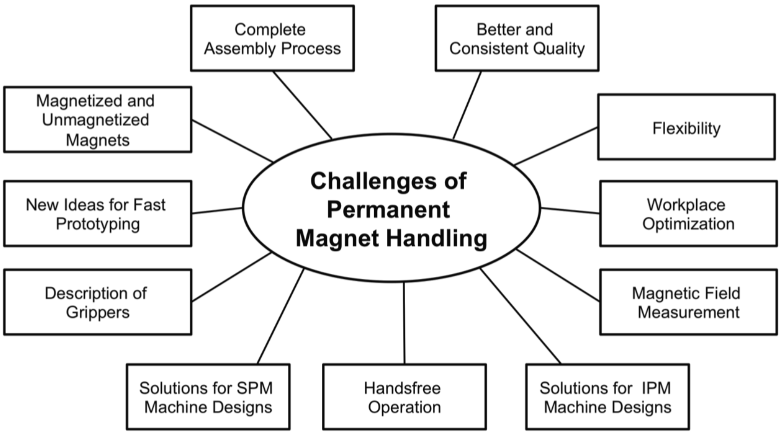


Fig. 1. The challenges of the handling process of permanent magnets have an increasing influence for future electric motors.

Fig. 1 shows existing problems and challenges. The design of permanent magnet handling systems for production is difficult for a couple of reasons. At the time no standard gripper system is available. The worker needs to take the magnet with his hands, taking the risk that the magnet can be contaminated with dirt. For product specific assembly, companies develop fixture systems for distinct products [1]. The manual assembly of magnets leads to a number of failures that severely influence the function of the finished motor over its operational lifetime. Magnetized magnets are delivered with strong attraction forces within a stack, making it hard to separate them without damaging. The material is very cost intensive and broken workpiece magnets need to be recycled or repaired. Grippers are needed for the control of the magnetic field of permanent magnets during the assembly process.

1.1 Process innovations for magnet handling and testing

Permanent magnets are widely used for the excitation of magnetic fields for rotating and linear motors with highest power to size ratios. Neodymium Iron Boron, Samarium Cobalt and Molded Compound Magnets have led to more specific drive designs in the last years enabling e.g. new drive concepts for electric vehicles with the same or even better power characteristics as combustion cars and effective generation of electricity with wind turbines. Additionally, cultural, societal and political sensitivity changes towards more sophisticated use of energy for mobility and industrial purposes, leading to an increased customer demand for high efficient electric motors.

Planners need to enlarge the production capacity of their assembly lines. For flexible workplaces with changing motor products, the question of production capacity comes up. One chapter describes therefore a model for rotor production that takes three example lot sizes and variant options into account and gives advice for workplace evolutions.

The production of surface mounted permanent magnets is at present the common standard for synchronous motors. For flexible magnet assembly with customized rotor and lot sizes, a method for placing magnetized permanent magnets in production is wanted to avoid cost-intensive magnetizing fixtures. To support manual assembly of permanent magnets, a new electromagnetic gripper (ELMAG) approach and its calculation scheme are presented.

Another motor design concept implements the magnetic material into the sheet lamination stack (IPM). As cavities hold the magnets, methods for flexible insertion are examined, resulting in a gripping system for flexible placing and fitting of magnets into the cavity.

The concept of gripper systems for IPM and SPM assembly need to be implemented in a workplace concept, that is competitive towards raising lot size and quality requirements (see also Fig. 2). With MTM-based determinations, a semi- automated workplace is therefore presented, that takes all the previously shown details into account.

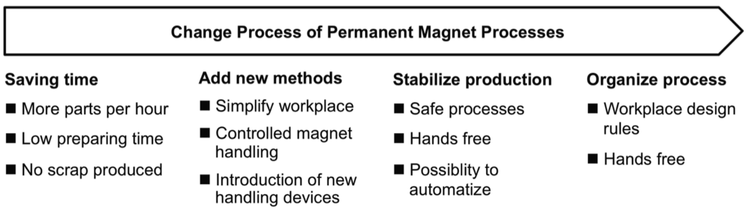


Fig. 2. Assembly planning requirements related to permanent magnet processes

The test of the permanent magnet field itself, during the manufacturing process and in the assembled state is going to be very important for medium to large series production. Although magnetic field sensors are already used in non-destructive material testing, concepts for magnetic field testing in production use are presented. A new developed hall line sensor is presented.

Besides new applications (electric mobility, energy generation, robotics), the traditional industry sector is using PM-excited motor types to save electric energy compared to standard induction motors. In combination with intelligent power distribution, efficient use of motors as well as energy generation during braking and deceleration is also possible.

For electric vehicles, the major application of electric motors will be for hybrid systems in the first instance. Further integration steps include the development of electric car drives for full replacement of combustion machines.

1.2 Contributions to magnet handling and magnet testing

The work splits up in eight chapters and presents the research work following the magnet supply chain from magnet supply to full assembly. In chapter 2, the permanent magnet processing, the rotor designs and the transport handling is explained, including the logistics paths for magnets inside the factory to the assembly workplace.

Chapter 3 explains process chains for three batch sizes and their effect on the design of workplaces for magnet assembly using SPM and IPM magnet technology.

Derived from these process chains, gripper concepts for SPM-assembly have been evaluated. Chapter 4 explains the development of the gripper systems and the resulting electromagnetic gripper system.

These grippers have been implemented in workplaces for inner and outer runner rotors. Chapter 5 shows these concepts and the realized workplaces.

Chapter 6 shows the results of flexible handling devices for IPM rotor assembly with the development of a vision tool for detecting the placing position in the lamination stack and its implementation in magnet insertion tools.

The second part of the work presents new concepts for measuring the magnetic field of permanent magnets. Chapter 7 points out available measurement equipment. Chapter 8 presents measurement solutions for inline testing, which have been developed and realized in this work. This contains measurements with available devices and the development of an inline Hall sensor for scanning complete rotors.

2 Permanent Magnet Processing, Rotor Designs and Transport Handling

The characteristics of modern sintered rare earth or bonded permanent magnets strongly differ from well-known standard Ferrite, Ceramic or Aluminum Nickel Cobalt (AlNiCo) magnet materials [2]. Diverse geometrical forms and magnet strengths are found, depending on cost and desired functionality of the product. For rotors of synchronous motors, Samarium Cobalt (SmCo) and Neodymium Iron Boron (NdFeB) compositions are gaining importance for e-mobility and energy generating applications. Large amounts of the needed raw materials are produced in China, which makes the country an important supplier [3], [4].

Material science groups focus on magnet material processing and improvement of magnetic properties, while production development must develop processes with given available materials for production. Deeper integration of magnetic circuits and functions in electric motors will inevitable lead to closer collaboration between material science of discrete magnet processing and production technology for the whole drive system. Taken this into account a short overlook over permanent magnets and the basic production technologies for the used rare earth permanent magnet material are presented in the following.

2.1 Permanent magnet development

For electric motors distinctive magnet geometries, field strengths and magnetizations are used ranging from small motors for micro system pumps to main aggregates for power stations [5]. Typical permanent magnet materials are the material groups of Ferrite, AlNiCo, SmCo and NdFeB (see Fig. 3) [6]. A comprehensive overview of the standard magnet types is presented in the IEC Standard 0100-00 [7], in the handbook for magnetic materials [8] and given in [9].

Besides the four main groups, research is also done for Platinum Cobalt (PtCo, for medical implants), Manganese Aluminum Carbon (MnAlC, Rare Earth free), Iron Chromium Cobalt (FeCrCo, good for forming and stamping). Even more combinations are possible with binders for bonded magnets. This magnet group offers the advantage of additional geometric design possibilities in the molding process. Disadvantages need to be considered towards magnetic and thermal properties from dilutions of the inset polymer matrix. [10].

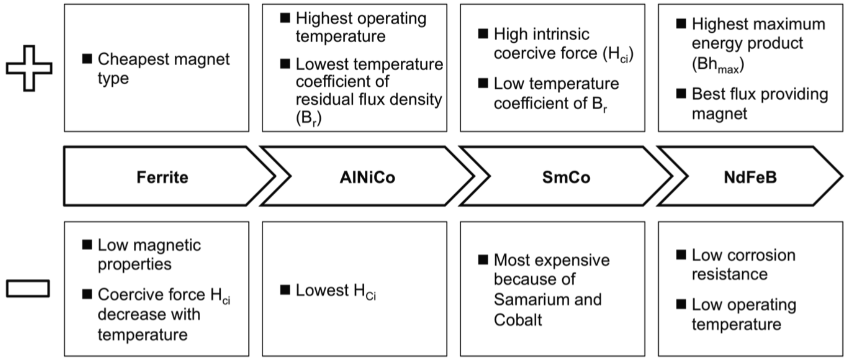


Fig. 3. Permanent magnet types for typical technical applications are divided into four main groups [6], [11], [12]

2.2 Production methods and the influence on magnetic field performance

Research focuses on further improvements of magnets, not only concerning the maximum energy density, but also corrosion resistance, temperature and mechanical stability or innovative shaping for individual product developments [13]. For improvements of the known materials based on the developments of [14], [15], [16], [17] the crystalline structure of the basic ingot material is shifted from micro- towards nanocrystalline structures. This enables new possibilities for leaving out components or integrating additional less cost intensive elements instead of the cost-intensive rare earth element Dysprosium [18], [19], [20].

The product quality of permanent magnets is based on the process technologies. For modern rare-earth-type magnets, the production sequences have severe influence on the magnet properties. A good overview of fabrication routes for NdFeB- based magnet compounds are described in [21] and based on processes for nano- and microcrystalline structures. For the production of permanent magnets the following processes are important:

- the hydrogenation, disproportionation, desorption, recombination (HDDR) method [22]
- the Melt-Spinning [23] and
- the classic microcrystalline jet milling route

Starting material is mainly an induction-melted or strip-casted alloy (e.g. composition of NdFeB). The HDDR method was initially investigated by Mitsubishi and the Department of Materials Science and Technology of the Kyushu University [24], with results deriving from coercivity relation models of Livingstone [25]. In the standard

HDDR treatment the cast alloy ingot is driven by decrepitation under a hydrogen pressure up to a reaction temperature between 750 and 850 °C [26]. Hydrogen diffuses into the material, expands it and cracks the ingot. Further steps include crushing and sieving to get a single crystalline powder. This method produces a very small-grained powder with structural sizes of several nanometers, as shown very well by the summary of Sugimoto and Book [27].

The melt-spinning or planar flow casting process is used to produce powders with nanostructured grain sizes mainly for bonded magnets. The alloy ingot melt is cast through a spray valve and is led onto a fast turning, water-cooled wheel, reaching chill rates of about 10^6 K/s. Important properties are the 3D-positioning of the spray valve, the application of inert atmospheres or vacuum and high speed of the cooling wheel.

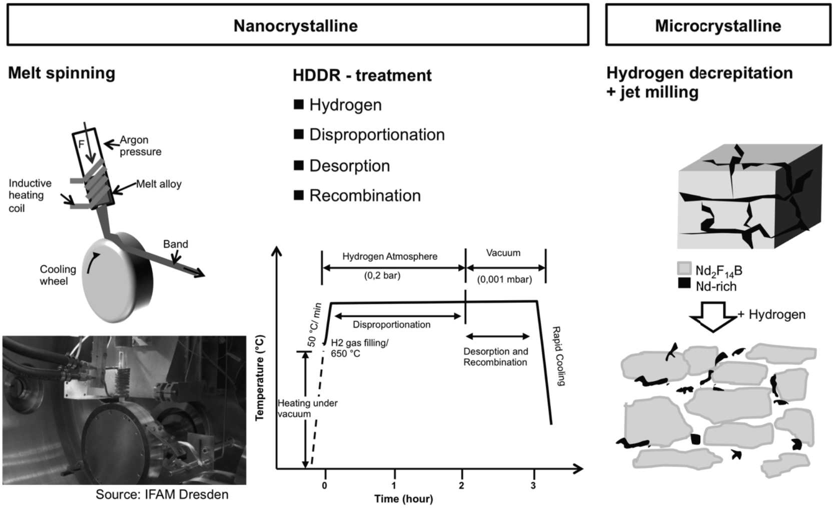


Fig. 4. The genesis of the compound structure depends on the manufacturing process for the powder [28], [29].

The classic strategy found in most mass magnet production sites is the jet milling of pre-cast alloy stripes. To support this milling process and to reach a fine and even grain structure, the stripes are decrepitated by high-pressure treatment with hydrogen, cracking the alloy stripes. Although the grain structure is in a scale ten times larger [24], available remanences are amongst the highest for NdFeB magnets.

The powder structure of the basic alloy compound must be further manufactured to a distinct magnet shape. For this reason, the permanent magnet is pressed and sintered. Possible process variants are therefore:

- Pressing of parts in axial field – Axial Pressing (AP)
- Pressing of parts in transverse field – Transversal Pressing (TP)
- Isostatic pressing of blocks – High Remanent (HR)
- Pressless process (PlP) without external field [30]

The forms of permanent magnet geometric shapes are biased with a strong permanent magnet field to prealign the compound particles for end magnetization as shown in Fig. 5.

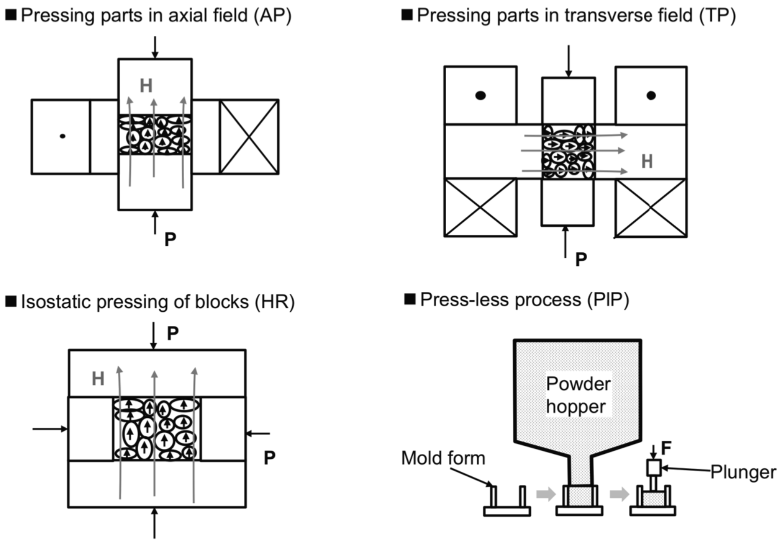


Fig. 5. The workflow for production of sinter-ready magnet bodies requires pressing of compound powder [31–33].

The processing methods differ in the resulting quality and performance of the sintered magnet accompanying with various grades of magnet orientation. During or before sintering, the particles in the green compact are pre-aligned to an external enforced electromagnetic field. Transversal field (TP) pressing differs from axial pressing (AP) in the way the exterior magnetic field is applied, AP grades match magnetic field and pressure force introduction directions, whilst in TP grades the magnetic field is fed vertically to the pressure direction. Loading with powder compound and unloading of green compacts can be arranged automatically and reaches nearly end shape geometries, if shrinkage is considered for calculation of the toolsets. The AP-process is suited for simple 3-dimensional geometric shapes and for mass productio and therefore used for most magnets with simple block, disk or arc shape. In contrary to the simple AP and TP processes, isostatic presses (HR – “high remanent”) work with rubber molds in sealed chamber requiring a high degree of manual loading and handling processes. Therefore, this method is used to form whole blocks, from which several magnet bodies can be cut out. Sagawa is developing a new pressless method [30] with additional stamping simplifying the process chain substantially. HR (2% better than TP) and TP (6-8% better than AP) grades magnets reach slightly higher remanences, whereas AP grade production is still used due to simpler processing equipment [34]. The press-less process (PlP) is in recent development and will show its advantages with measured values for remanence. A good and comprehensive introduction for powder production processes can be found in [33].

Performance characteristics for magnet production are stated by manufacturers [35], [36] as following:

- Magnetic homogeneity,
- highest remanence,
- good dimensional magnet accuracy and
- precise tool dimensioning

After pressing, the compacts have to be transported to the sintering process. Fig. 6 shows the sinter process for permanent magnet production includes several steps to reach the wanted grain sizes. Due to the high interstitial hydrogen affinity of modern rare earth magnets, inert or vacuum environments are inevitably necessary during and between each process step.

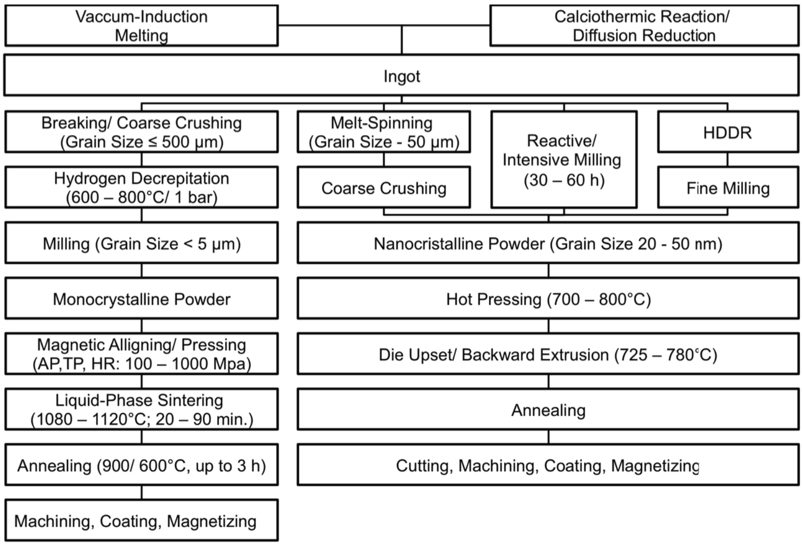


Fig. 6. Process routes for sintered-magnets manufacturing. [33], [37]

Modern material research of magnets focuses strongly on a shift of production technology towards nano-technology and the production of smallest grain sizes for the sintering powders [38]. This also enables the possibility to optimize the use of rare earth metals (Dysprosium for improved temperature performance and demagnetization resistance) [39]. For this aim, new production technologies for mass production need to be developed. Besides the composition of the magnet body itself, the protective coating should be presented.

2.3 Protective surface coatings

Permanent magnets consist mainly of ferrous ingredients, which are prone to oxidation processes. To avoid the unwanted corrosion and therefore an early failure of the permanent magnet, a coating is provided after all production steps [40]. The common coating types shown in Fig. 7 protect permanent magnets in industrial production.

The epoxy-style permanent magnet is widespread found in modern electric drives, as it can be easily handled in industrial environments, interacts very well in combination with chemical fixation systems and has very good withstanding against salt spray and humidity tests.

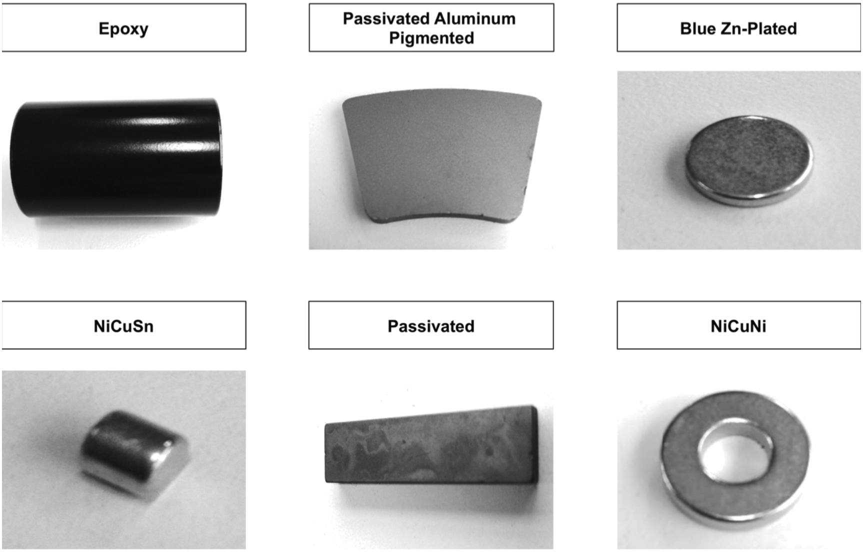


Fig. 7. Magnet coatings have distinctive surface appearances.

There are sub-types available differing in price and resistance against working environments for the magnet against aggressive media in pump systems, water applications, dust and dirt contamination or differing climate conditions [41].

Corrosion resistance of permanent magnets is tested with salt spray and humidity tests. Two types of coatings are distinguished: metallic and inorganic coatings. The first methods developed have been metallic coatings. In [42] basic evaluations have been made for Nickel plating and determined a good performance against humidity. At the time, Nickel plating has been a significant part of the production costs, so alternative coatings have been examined. Zinc [43], polymer and lacquer coatings under acid and humidity test conditions have been tested as shown by [44], where epoxy-based coatings showed the best results. Tab. 1 gives an exemplary listing of the available coatings. For applications in electric motors the producers nowadays use epoxy coatings, for consumer products with lower requirements towards mechanical stress, Nickel coatings and variations thereof are found. If the coating of the magnet is not tight enough and cracks open up, oxidation processes lead to continuous destruction of the part structure accompanying with detoriation of the magnetic field.

Tab. 1. Permanent magnet coatings are evaluated against humidity and salt spray [45].

Surface	Type	Coating Thickness	Deposition Process	Surface Color	Characteristics
Passivation		≤ 1 µm	Phosphating	Silver - Grey	Temporary conservation
Nickel	Ni + Ni	10 - 20 µm	Barrel or rack electroplating	Silver - Silk	Excellent against humidity
	Ni + Cu + Ni				
Zinc	Zn	8 - 20 µm	Barrel or rack electroplating	Former Yellow, Blue („White“)	Good against salt spray
	C-Zn				
	Zn/3CrZn				
Tin	Ni + Cu + Sn	15 - 20 µm	Cathodic arc physical vapor deposition	Silver - Silk	Superior against humidity
Gold	Ni + Cu + Au	10 - 20 µm	Barrel or rack electroplating	Gold	Superior against humidity
Copper	Ni + Cu	10 - 20 µm	Barrel or rack electroplating	Gold shiny	Temporary treatment
Epoxy	Ni + Cu + Epoxy	15 - 25 µm	E-Coating or wet painting	Black, Red, Grey	Excellent against humidity & salt spray
	NiCuNi + Epoxy				
	Zn + Epoxy				
	Epoxy cathodic electropho-retic coating		electrophoretic cathode metal coating		Good against humidity, in contact with weak acids as alcalic and salinite solutions
Parylene	Parylene	5 - 20 µm	Chemical vapour Deposition	Grey	Excellent against humidity, salt spray, superior against solvents, gases, fungi and bacteria, FDA approved

The grain sizes for nano-crystalline permanent magnet structures and substituting materials for the iron part of the compound are examined in [46]. Partial substitution of Iron (Fe) parts with Cobalt (Co) and Gallium (Ga) improves corrosion resistance reducing the affinity and binding energy for hydrogen. Coarsening microstructure results in better corrosion performance of these materials. The finer the magnetic compound is produced, the more the coating has to prevent corrosion or influence from the environment.

The influence of magnetic fields introduced to the magnet material is evaluated and determined by [47]. In combination and contact with acids, the material loss is accelerated. This can influence the methods for storing and handling the magnet unmagnetized or magnetized.

Coating films are tested with the following methods:

- Scratch test
- Salt spray test (SST)
- Temperature and moisture tests (HAST, THB, UAT)

The scratch test (also: scotch tape test or cross cut test) describes the mechanical intrusion of the coating surface with a probe to determine the coating resistance against mechanical abrasive forces.

Another important test propagated for testing permanent magnet coatings is a salt spray test [48]. The test is described in e.g. ASTM B117 and DIN ISO 9227 [49]: Here, the specimen is sprayed by a NaC- solution of 50 g/l within a temperature of 35 °C. Although PM-excited synchronous motors are shielded against the working environment, dangerous moisture levels can intrude the motor during operation in extreme environments (sea application, hard industrial applications).

Tests include accelerated stress tests incorporating a combination of temperature, humidity and pressure, as known in electronic productions. Therefore the methods are taken over, or are slightly adapted. The Highly Accelerated Stress Test (HAST; also known as Pressure Cooker Test (PCT), or the Unsaturated Pressure Cooker Test (USPCT)) derived originally from a test method described in [50]. A sample of the permanent magnet is placed into a sealed pressure cooker style chamber. Major distinctions of the test methods are temperature rise and humidity change, as described in [51]. The first chambers were rebuilt vertical loaded medical autoclave chambers. Today, horizontal loaded modern chambers enable additional bias tests with saturated and unsaturated moisture atmospheres. The HAST protocol used on uncoated NdFeB magnets qualitatively reflects the service life of the magnet. During this test method the permanent magnet is exposed to 130 °C, 95 % relative humidity (RH), at 2,6 bar for 20 days. The mass of the magnet is weighted before and after the test. The weight loss should be less than 3 mg/cm^3.

Other methods are described by EIA- JESD standards in [52] for the Unbiased Autoclave Test (UAT) (121 °C, 2,05 bar and 100 % relative humidity (RH)) and in [53] for the Temperature Humidity Bias life test (THB) (85 °C and 85 %RH). The condensation moisture test covered by the ISO norm 6270-2 [54] incorporates even an Alternating Humidity and Air Temperature (AHT), ranging from 18 – 28 °C and <100 %RH.

Understanding the common characteristic values is important for the assembly process on the rotor itself. The standard values can be derived from magnet suppliers. An overview is given e.g. in [55] and [32].

The material behavior of permanent magnets depends on the production methods. Required characteristics for future applications can be reached with improved magnet production methods:

- The manufacturing of permanent magnets is provided with coarse material treatment processes.
- For improved permanent magnet characteristics, methods will be developed towards nanostructured production methods for being able to substitute rare earth metals.
- The magnet features will be optimized to improve temperature and operational characteristics.
- Test methods for magnet properties and coatings are set by standards.

2.4 Permanent magnets for SPM applications

A clear distinction for handling permanent magnets is the difference of the assembly application. Therefore handling of permanent magnets can be separated into surface and interior mounted permanent magnets. Surface mounted design is the most popular permanent motor design, because of the simple assembly of the magnets onto the surface of the rotor shaft. For larger drives without high speed applications (e.g. torque drives) the magnets are immediately glued onto the rotor and e.g. used without bandaging layer and small air-gap in direct interaction with the stator poles. This leads to:

- less magnet material needed compared to IPM with same power density
- more simple shape design of the lamination stack
- easy application of the magnets on the cylindrical surface of the rotor
- changing pole designs with magnet change

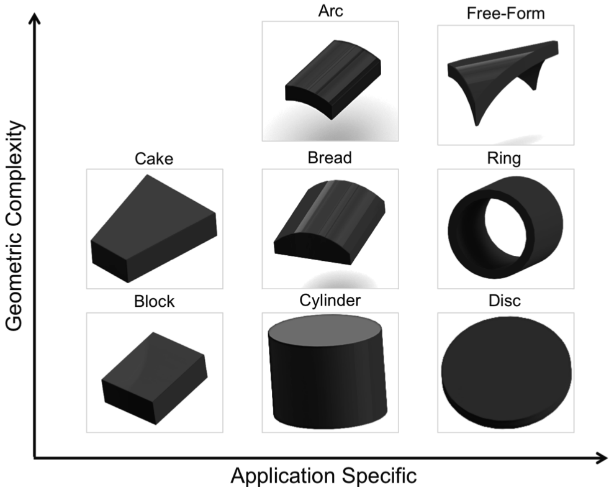


Fig. 8. SPM applications spread into a broadband of geometrical shapes [56].

An optimized electric motor with permanent magnets requires adapted shapes for the flux design [57]. Fig. 8 classifies the complexity of the geometric shapes against specific applications. Experiences in manufacturing research [58] and industry have proven that block and segment magnets are used at the beginning of the design process for new motor designs. Further developments and manufacturing improvements lead to cylinders or arc segment shaped magnets.

Finally, within scenarios of mass production, the magnet shape design leads to integrated designs towards 3D-structures for product optimization [59]. Designs for new motor configurations and optimized material usage arise, so the material composition needs to be included during development of the motor. Developers become aware of new shapes and forms needed for their calculated permanent magnet field [60].

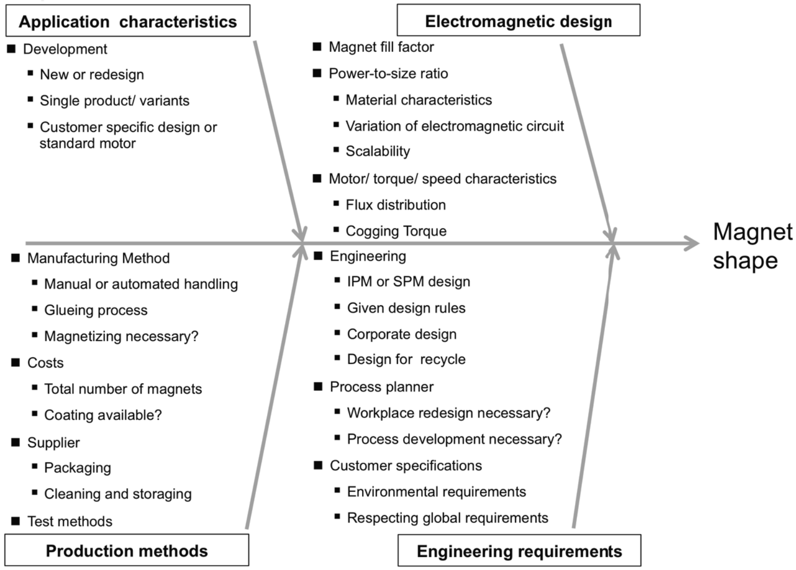


Fig. 9. The magnet shape is influenced by requirements ranging from application to design [61], [62], [63].

Reasons for the use of distinct magnet shapes are varied by influences of development and production partners (see Fig. 9). Customer specific developments with complex flux geometries require complex magnet body shapes. This is accompanied by requirements towards the motor characteristics, e.g. if the air gap should be minimized to increase flux density [64].

The assembly method is also important for the necessary shape. Magnets for large drives are found fixed by screws, so the geometry must be equipped with the necessary holes for fixation. The number of magnets to assemble is critical for the cycle time and therefore influences the workplace capacity. As prices for magnets increase by market demand and the cost for the magnet material nearly overturns the overall costs for the rest of material, simpler shapes are preferred, as costs increase with additional requirements towards geometry. Procedural challenges are necessary for using more complex magnet shapes, especially if the brittle magnet material does not exactly fit the tolerances for inner and outer rotor lamination stack diameter.

A problem for electric motor manufacturers is the magnetic test of the shapes. This is geometrically difficult for varying three-dimensional structures in small batch sizes, because of necessity for fixtures and keeping the specified tolerances. Designers of new motor variants have to consider which kind of magnet should be used and mention calculation factors and to ensure save operation. Process planners need to be invoked, because they have to set-up initial workplaces or machine equipment for complicated manufacturing scenarios, if magnets are already ordered magnetized. In this case, two batches of magnet geometry have to be ordered and supplied to assembly. (Magnetized batches with alternating polarities)

Field distribution or an optimized material use can be introduced by shaping the permanent magnet body. For the simplest form, the block size, cavities or a polygonal shape of the rotor shaft surface is necessary. This leads to a polygonal rotor surface and to inhomogeneities of the flux linkage between rotor magnet surface and stator pole surface. This can be compensated by changing the geometry to bread or arc style shapes. If the rotor pole is assembled with separate magnet rows, the bread style magnet is quite complex in production. Therefore the arc shaped permanent magnets are widely used for small industrial drives, as they are glued directly onto the rotor surface. If the cogging torque has to be reduced a common way is to twist the permanent magnet pole of the rotor or the lamination stack with the stator winding. For synchronous motors the winding process for twisted poles is much more complex than to use adapted magnet forms. If it is too complicated to produce a certain shape, a ring of permanent magnet material can be installed. Problems can occur with this shape, if the inner diameter of the magnet ring does not fit exactly to the outer diameter of the rotor. The magnet can burst if the mechanical stress is too high or in contrary a high compensation for balancing is necessary, if the mechanical partners have too high tolerances. On the other hand, the mechanical manufacturing complexity can be reduced, as only one part has to be assembled instead of several separate pole magnets.

2.5 SPM rotor concepts

The technology of placing permanent magnets on the inner (for external rotors) or outer (for inner rotors) surface of the rotor part is the most common design type. Innovations can be implemented without changes to the lamination stack, e.g. if larger magnets should be divided into several magnet parts or if the magnetic flux path should be skewed.

Fig. 10 shows how rotors with permanent magnets on the surface can be designed and built with the following methods:

- One segment/ one row per pole: One magnet body or several in one row create the magnetic pole
- Several rows per pole: One magnetic pole is created by adding two or more magnet rows together
- Skewed magnet application with one or several skewing steps: Magnets in one ore more accompanying rows are set with an angular offset to create a distinct magnetic skewing

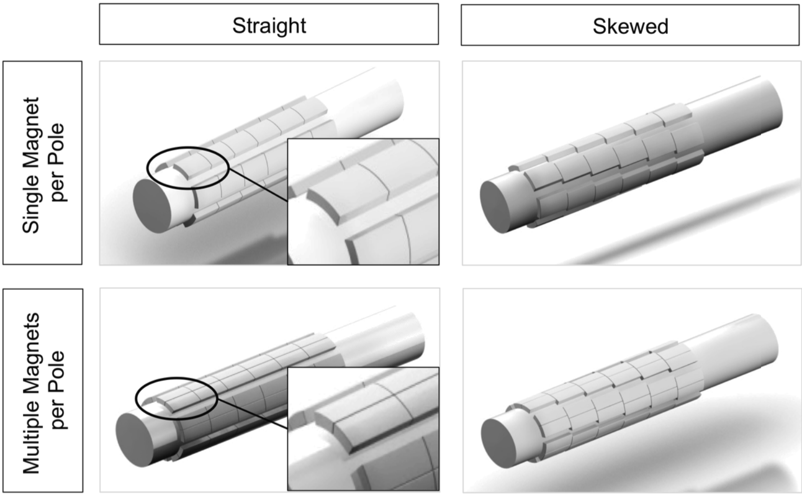


Fig. 10. SPM-technology spreads up into four main placing designs.

Skewing is necessary, when cogging needs to be avoided. Simple realizations for larger rotors just insert one skewing step (by skewing in the middle of the lamination stack), more elaborated designs use an angular shift between each magnet length of the lamination stack. If the magnet is assembled directly on the shaft (e.g. small servo motors), arc magnets are used and therefore assembled with angular displacement.

For surface mounted magnets, flexible-handling strategies can fulfill design approaches:

- Skewing of magnet positions help to optimize torque ripple
- Handling equipment must be flexible to provide a solution for customer specific rotor design
- Block shaped magnets will be substituted by adapted permanent magnet geometries, to create a round rotor surface

2.6 Rotor concepts for IPM applications

There are three fundamental design variants for IPM assembly based on straight or skewed inset permanent magnets. The assembly process is getting more complex towards a multiple-skewed segmented rotor, as possible insert directions of permanent magnets differ and the classic assembly process of mounting the lamination stack onto the shaft must be rearranged.

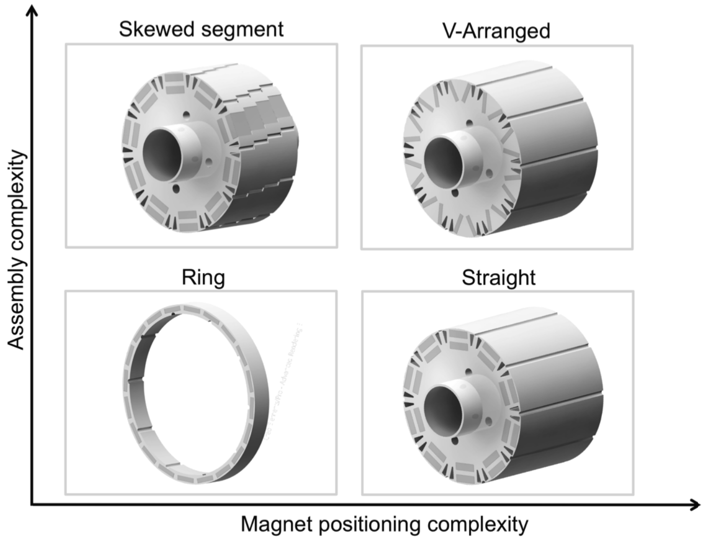


Fig. 11. IPM-rotor technology spreads up into four magnet-positioning designs

As shown for SPM- technology, there are design variants for creating the necessary magnetic field. In Fig. 11 a classification of example rotor geometries is depicted. Subdivisions are categorized in:

- Ring type or one segment: the magnets are arranged concentric. This includes segment types, which are assembled to a ring structure.
- Straight inset magnet: multiple magnets are pushed into one slot cavity
- Skewed segmented: multiple rotor segments are arranged with slight skewing to reduce cogging torque
- V-type arranged rotors: one magnet pole is created by the sum-field of at least two or more permanent magnets.

Ring type

A simple type regarding magnet positioning and assembling is the ring type. The lamination stack is build up to the height of one magnet. The magnet bodies are inserted from both sides. The segment length is therefore equal to the length of the magnet body. The tolerance of at least one lamination sheet thickness should be given ensuring the magnet does not outstand the lamination stack:

$$Height_{Lamination\ segment} = Height_{Magnet} + Height_{max.tolerance\ magnet}$$

Straight inset magnet

The straight sheet metal lamination stack is subdivided into staples with same length to smooth out tolerances in the lamination stack thickness. Each sheet of the lamination stack is cut the same way so straight continuous cavities for the permanent magnets are created. The lamination stack is created as a complete rotor with shaft. For applications demanding less rotary speed and more torque the diameter is increased and the rotor itself is integrated e.g. into the transmission gear housing of a car. The lamination stack for this type is not cut in one piece but assembled of several lamination sheet parts.

New motor designs for bigger rotor sizes (e.g. generators) with long active lengths, create a skewed rotor by turning the lamination stack 180 degrees, so the rotor has to be filled from two sides. Therefore the length of each lamination stack has to be an even number of permanent magnets, otherwise, there would be a huge unused gap. This design is divided into two segments, so that the magnets for each lamination side are accessible from one side. This requires a turning of the work piece. In this case, the lamination stack can be filled with magnets after the lamination stack and the shaft are combined.

Skewed segmented rotor

The segmented rotor IPM- type uses special lamination sheet cuts. Several cutting variants with changing mounting holes or referencing geometries are necessary to be able to stack the lamination stacks. The lamination stack must include a possibility to arrange the segments for constant angle shift to reach the desired skewing. In the field, this is done by a gradually shifting bore pattern serving as guide for full lamination stack length retention screws, ensuring a small shift between each segment. This minimizes torque ripple and cogging of each pole. For this type, the permanent magnets must be set into each lamination stack before complete assembly. This inverts the manufacturing order, as the shaft can only be mounted after the lamination stack is fully assembled. Otherwise it is not possible to insert the permanent magnets.

V-type arranged

The insert-direction, the exact positioning, and the magnet geometry are complicating the assembly process. If the magnets are arranged in a V-shape, the magnet positioner must position the magnets for each position with precise insertion positions.

The variants of rotor designs for IPM and SPM technology show several important key points for further developments:

- The necessary process equipment (fixtures and grippers) needs to adapt to magnet sizes and forms.

- Magnetized and unmagnetized magnets need to be handled for IPM.
- Although there are lamination stack variations, block style magnets are used for IPM motors.

2.7 Transport of permanent magnets

Magnets can be handled safe, when carried in an unmagnetized state. In this case the packaging needs to ensure a moisture and vibration save environment. The magnets are assembled and magnetized directly in production. As most of the manufacturers start to develop new PM-excited motor variants and serve customers with small batch sizes for specific applications, not all designs can be magnetized with one magnetizing shot (e.g. magnetic pole area too big/small, magnets in the lamination stack cannot be saturated, magnetic circuit without enough pole separation) [65]. The transport of already magnetized magnets is still necessary for current production sets.

Transport of magnetic goods causes the following problems:

- No standard transport container for magnetized magnets available
- Packaging waste materials must be separated into fractions (carton, metal plates and plastics)
- Magnetic shielding of the transported permanent magnets against other goods
- Storage environment of permanent magnets to prevent corrosion
- The magnetic field of permanent magnets can disturb sensitive instruments when transported in airplanes.
- Introduction into production line: Extra workplaces necessary to unpack the magnets and prepare them for assembly
- Unpacking complexity: Magnets for larger motors need to be separated in the stack with spacers.

The transport of permanent magnet materials is not yet a standard process and not optimized for manufacturing requirements. Unmagnetized magnets are delivered in blister magazines (see Fig. 12). For all magnet shapes an automatic solution for picking unsorted (delivered in plastic bags) unmagnetized magnet bodies is possible (e.g. with SCARA robot and vision system). Another found method (for smaller magnets) is delivering the magnets unsorted in a bag and a vibration feeder system for sorting the magnet bodies.

Standard transport packages for magnetized magnets consist of a variety of materials, shielding the environment against magnetic, preventing the magnets from being contaminated by dirt or moisture during storage and supporting unpacking and separation. Sheets of metal are placed on each side of the carton, followed by separator pieces between magnet packs with stacks of coherent magnets. The separators are made of plastic, wood, carton or polystyrene. The permanent magnet stack itself is divided into a certain number of magnet bodies covered with paper and plastic or wooden spacers to ensure safe separation of each magnet without scratching the surfaces. Fractions of materials from the packaging need to be separated for disposal.

If magnets need to be stored, several boundaries for magnets should be taken into account:

- The magnet material is prone to corrosion. The transport carton can draw water. For larger sets of magnets this can be critical, when magnets are stored for longer time until they are assembled.
- The right safety set for storing not assembled magnets during manufacturing breaks within the assembly work place has to be ensured; the magnets have to be sealed from the environment with covers or packaging. Otherwise unwanted snapping and contamination with ferromagnetic particles is possible.
- Workers can be affected and harmed, if the package place is leaking magnetic fields and is not appropriate secured. Unwanted snapping of permanent magnets towards magnetic parts can occur.

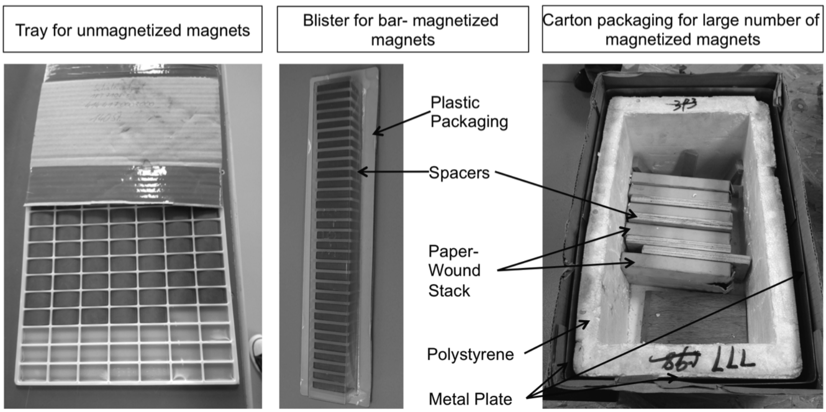


Fig. 12. Permanent magnets are packed with a mix of plastics, metal, wood and paper/ cardboard for safe transport.

Magnetized permanent magnets are not save to transport from the supplier to the manufacturer as well as inside the assembly factory, as unwanted magnetic interaction with the permanent magnet field can occur at any time. Following the IATA 953 (former IATA 902) permanent magnets belong to the group of “Dangerous Goods” and are regulated for the transport per airmail [66], majorly concerning the disturbance of the earth´s magnetic field. Therefore the package good has to be measured for horizontal magnetic stray fields for shipping magnetized goods within the range of sub-µ-Teslas [67]:

Tab. 2. Declaration of magnetic goods depending on measured flux densities [67]

Distance from permanent magnetic object	Measured flux density	May be declared and shipped as
2,1 m	< 0,525 µT	Uncritical/ not magnetic
4,6 m	< 0,525 µT	Magnetic good
4,6 m	> 0,525 µT	Approval necessary

The package is influencing the handling in the factory and in the assembly line. Magnets have to be unpacked manually and packaging must be separated in sorted fractions separately. This causes extra expense for the assembly of the rotor. If the magnet arrives without order (e.g. in a bag), it must be sorted into the manufacturers carrier system– for small productions manually- and checked in an extra step. With presorted magnets, damages to the magnet body can be prevented. In this case the transport package can be recycled and the machine feeding and check mechanism be simplified. Furthermore, an optimization of packaging saves storage of cost-intensive and corrosive permanent magnet material. Compared to production of printed electronic circuit boards, this is an important factor if certain motor designs are produced customer specifically, with longer terms of still stand.

In-house transport with fork- and handlifts

- Goods received and plausibility check
- Central storaging
- Packing from skeleton container onto europallet
- Stretch foil fixation of cartons
- Preparing for assembly line

Magnet handling

- Lifting cartons with magnets onto table
- Open transport cartonage
- Remove shielding and polystyrene packaging
- Take out magnet stacks
- Separation of magnet-blocks and place on table
- Unpacking magnet blocks
- Throw away waste and remove spacer
- Polarity check
- Preparation of magnet stacks for assembly position

Fig. 13. The in-house magnet transport process incorporates the supply from receiving to assembly.

Packaging also always needs an extra expense for unpacking. If the magnet is big, additional attention needs to be paid for the material flow path safety to protect the worker. Extra space for the waste as well as a separate workplace with holding and preparation fixtures is necessary. The extra time expense for unpacking the permanent magnet can also exceed the assembly time for the magnet, if e.g. additional magnet separation steps (from a stack) and preprocessing steps (cleaning for glueing process) are necessary.

For assembly environments a magnet transport strategy shows clear advantages by identifying the process steps shown in the following Fig. 14. Each step leads to defined material positions and information in the process. Furthermore, control steps for geometric and magnetic properties can be planned and integrated. Starting with unsorted magnet stacks (this can be magnetized or unmagnetized), the magnets need to be sorted with first checks for geometric and mechanical integrity. A check for the right magnet product can be introduced to avoid confusion with similar magnet sizes.

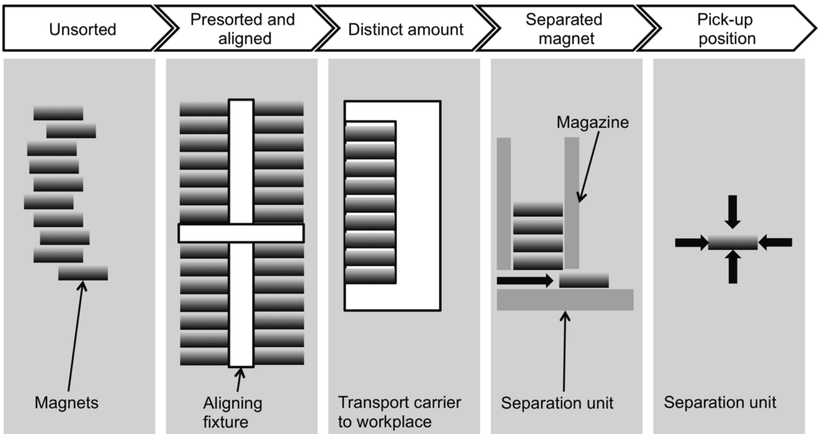


Fig. 14. The transport handling in the assembly line follows 5 steps.

The magnet stacks are later on sorted and divided into certain amounts of magnet quantities. This can be important for buffering a magnet refill and sorting process in an automatic machine environment. From this number magnets are separated and positioned in the process (e.g. for magnetization, for magnetic checks, for in process treatments). Fig. 15 shows excerpts of an optimization process in a magnet assembly station that has been optimized with an industrial partner using the developed process concept. The concept has been improved with transport containers for less unpacking and matching exterior and interior transport paths.

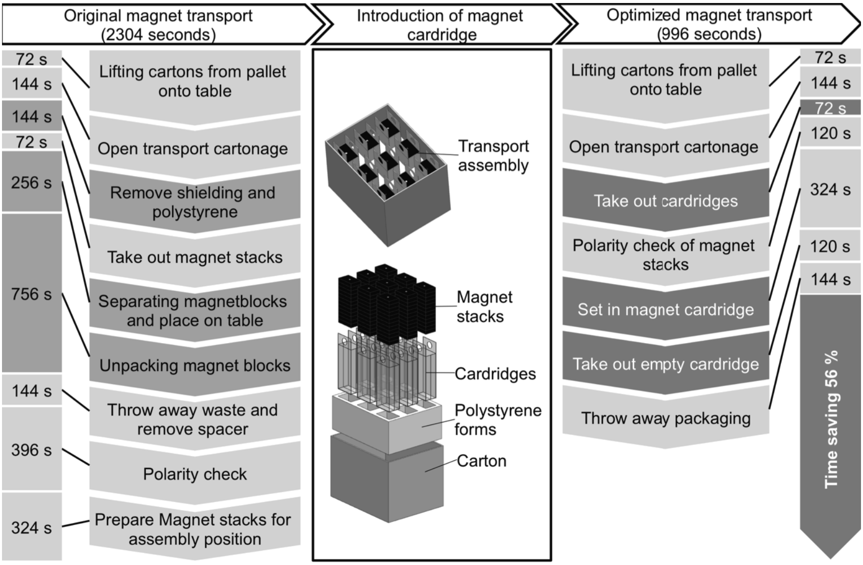


Fig. 15. Savings of time of more than 50 % are achieved by introducing an innovative magnet transport packaging.

The new packaging concept offers improvements in the last steps, the separation and positioning for assembly, because a lot of extra checks need to be implemented to ensure that magnets are not damaged by manual influence of the worker. Sometimes, due to the workplace environment, extra cleaning steps have been integrated revealing simple and huge optimizing options.

For the transport of permanent magnet improvements have been detected for the assembly process:

- Carrier design avoids additional cleaning, sorting or separating and influence on inner and outer logistics.
- A direct integration of magnet transport packaging into machine process is possible.
- An improved magnet transport package saves time and improves the work piece quality by less manual operations.
- Packaging is usable for magnetized and unmagnetized magnets.

Looking at the supply steps in production (see Fig. 16), four main steps can be localized. After arriving in the factory from external suppliers, the magnets are stored and delivered to the station. As most of the permanent magnet material is shipped over sea, the materials are still packed in carton and magnetically shielded, to avoid magnetic flux leaks threatening the environment during transport. The magnets are therefore packed in cardboard boxes, sealed as stacks in oilpaper avoiding moisture.

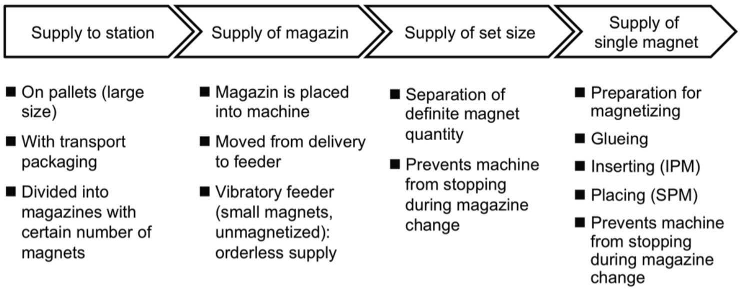


Fig. 16. The necessary production steps for in-house supply chains of magnets

When the magnets are magnetized, plastic or wooden spacers are used to separate the single magnets. If required, a customer-defined pole of a magnetized stack is marked with a dot, or the magnet itself gives information about the polarization due to geometric design (e.g. a notch in the middle of the magnet surface). Instead of oil paper, magnet suppliers pack stacks with spacers in blister style packaging. For unpacking of magnetized permanent magnet therefore a vast amount of work time has to be spend as well as for depositing the waste. A magnetic test seems inadequate for all magnets, but visual tests for broken magnets or polarity tests are necessary. In unmagnetized state, the unpacking procedure is reduced significantly, due to the absent coercive force. The next step in production is the separation and supply of large magazines for assembly. In semi- or fully-automated workstations, the machine is fed with a sufficient number of magnets to ensure several work piece cycles without refilling using separators for unstacking of single magnets. Small unmagnetized magnets can be sorted by a vibratory feeder and allocate a continuous set of magnets. A distinct amount of permanent magnets is necessary as buffer, when the workstation needs to ensure functionality during magazine exchange.

2.8 Summary

In this chapter the assembly concepts of permanent magnet rotors has been described. Magnets are distinguished by its material composition. Magnet compositions with rare earth metals are used for electric motors. The production steps for NdFeB based magnets have been presented. The production processes themselves influence the homogeneity of the magnetic field and enable higher energy densities. Magnets are very corrosive due to the high iron fraction and need to be coated. These coatings are tested with standard procedures and ensure safe lifetime operation against environmental impacts.

With evolving motor concepts, requirements for the shape of the magnet rise from the well-known standard block shape towards more complex 3D shapes. This opens the possibility for optimization of material consumption.

The standard technologies are the assembly on the surface (SPM) and buried in the lamination stack (IPM). These two technologies also have sub-variants and affect the assembly strategy. A common, but disregarded field has been shown with the transport of the magnet material, divided into transport of magnetized or unmagnetized material. As shown at an example transport situation, the determination of the single transport steps has led to essential evaluation of time-savings. An innovative magnet packaging system offers to tap the potentials and simplifies the magnet transport inside the workplace.

3 Scenarios for PM-Rotor Production

Assembly of permanent magnets for rotors is added to production of standard asynchronous motors to implement new variants. These motors with permanent magnets are designed and produced in smaller batch sizes. If customers accept the new products and batch sizes begin to excel the workplace capacity, the manufacturer faces two challenges:

- Enlarge the production capacity
- Ensuring quality also in higher batch sizes

Therefore workplaces for production have to be improved. Flexible tools for permanent magnet assembly support requirements towards higher capacity of a workplace. The necessary process chains for the design variants of SPM and IPM are presented in the following chapters.

3.1 Work sequences for PM-rotor production

The assembly processes for or magnetized and unmagnetized magnets differ for SPM and IPM technology. For SPM types, the assembly process steps are equal for small as well as for larger motors. The process chains for IPM-assembly include procedural changes between small and large motor types, as they need a certain amount of lamination stack diameter for inserting the magnets. In the following the process scenarios for the assembly of SPM and IPM rotor designs are presented:

SPM assembly

Rotors are built up sequentially starting with the shaft processing and the assembly of the lamination stack. For smaller drives the outer diameter of the shaft carries no lamination stack and the magnets are directly assembled on the rotor surface. A hollow shaft is used, if the rotor is part of a larger motor and integrated e.g. into transmission gearboxes.

The lamination stack and the shaft are connected mechanically. This is supported by introducing a temperature offset between the shaft and the lamination stack leading to an expansion of the outer part or temporarily shrinking of the inner part.

In Fig. 17 a flowchart for the manufacturing methods is depicted. The magnetizing process can be set on multiple positions in the workflow depending on the inset technology. If permanent magnets are supplied magnetized, then the lamination stack/shaft can be assembled directly with magnets. For unmagnetized magnets a distinct magnetizing step needs to be added and cannot be applied after full assembly of the rotor. This is the case for large drives with a lot of magnetic material or for multipolar rotors requiring exact magnetic field positioning. In the first case, the necessary magnetizing tool is too big, very cost intensive and a large energy supply for magnetizing complicates the assembly process. For multipolar magnetization the magnetizing step is divided into North- and South- sub-magnetizing steps. Depending on the design and geometric size the surface is not accessible with an appropriate magnetizing tool for accurate magnetization power. For skewed magnet assembly an unwanted crosstalk between a North- and a South magnetizing step cannot be prevented.

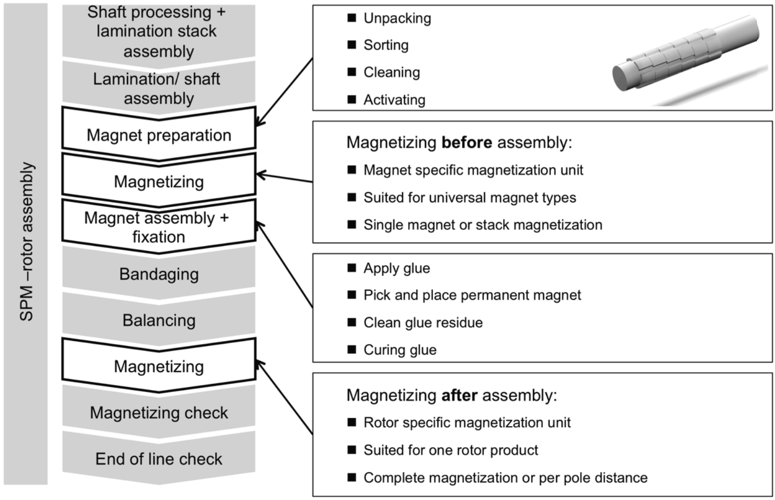


Fig. 17. The process chain for SPM-style motors

The magnet is glued onto the rotor surface. Magnetized magnets need additional attention for this step, as the magnetic fields of assembled and handled work piece magnets interact and lead to unwanted failures. Unmagnetized magnets are mounted quite simple by positioning into glue and curing, including a batch oven for accelerating the curing time. The assembled magnets on the rotor are then secured by an additional bandage, which is wound over the assembled magnets. The bandage should prevent the magnet from lifting off.

Balancing is done with a chemical add-on step (balancing kit), a mechanical take-away (milling) or an adjustment part (balancing disk with mounted weights). If the rotor is already magnetized, a mechanical take-away from the rotor must be done with non-magnetic material (e.g. brass), as milled material would snap onto the magnetic parts of the rotor.

For larger batch sizes of motors, a magnetizing device saves a lot of time, which is necessary for holding a magnetized magnet on its final position until it is cured enough to hold the magnet. In larger series production thus a magnetizing station is set after the magnet assembly. After magnetizing, the field of the rotor is checked for unmagnetized or false polarized magnets (due to wrong positioning of the magnetizing head or wrong magnetizing direction). Further checks also include the magnet field strength. The end of line check includes a control of all processing steps with predefined quality characteristics (correct bandaging or magnet placing, damaged parts).

IPM assembly

The IPM assembly splits up into two common assembly scenarios: one for smaller motors and one for larger (generator- type) motors: Motors with complex requirements towards power-density, weight and size (e.g. traction drives for cars) need to provide a torque optimized magnetic field propagation. This includes skewing of the magnetic pole layers. For full skewed rotors, the magnets need to be magnetized before assembly, if full saturation is not possible after inserting the magnet into the cavity (e.g. V-geometry). The lamination stack is prepared for a distinct height of one magnet. As each layer is skewed to each other, reference holes or geometric details have to be inserted to be able to reference the angular displaced disks for assembly.

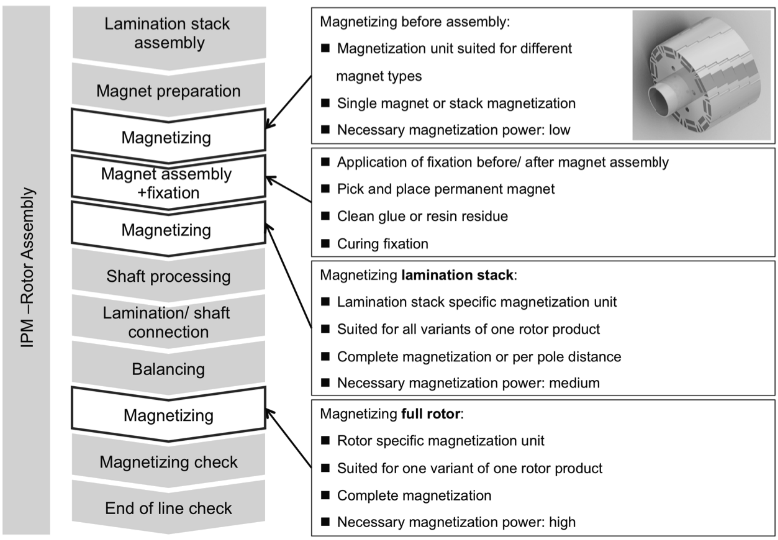


Fig. 18. The production process for smaller IPM motors.

When the lamination stack is created and the magnets are prepared for the fixation process (separated, cleaned and depending on fixation: activated), the assembly process begins (see Fig. 18). As for SPM technology, major caution is needed for magnetized magnets, as they are pulled into the lamination stack by the remanence forces if not fixed properly. The magnet will then in consequence snap onto the part of the cavity with the most surrounding lamination stack material. The outer lamination stack diameter over the magnet is designed very weak, so the magnet snaps towards the shaft against the centrifugal force during operation. Unmagnetized magnets are just set into lamination stack, but need to be held until they are fixed.

Magnet fixation for IPM motors is done by four methods:

- Chemically (adhesive) by filling the cavity tolerance gap between magnet and lamination stack. This is done with two- component resin recipes, consisting of resin and reacting hardener. The mixing proportion sets the processing time to cure the resin.
- Mechanical methods with deformation of the lamination sheets.
- Inserting additional mechanic screw or clamp elements for fixation
- Direct pressing and fit-in process without additional fixation

The shaft is added after the magnet assembly, because the magnets in the inner lamination stacks cannot be added after assembly of lamination stack and shaft due to the twisted offset between the lamination stacks. For shaft assembly the lamination discs with the magnets are exactly positioned while the shaft itself is prepared. For connection, a mechanical nut/notch system or a blank shaft (for mechanical couplings) can be chosen. If the magnet is already magnetized and fixed, then heating of the lamination stack can harm the magnetization, so the shaft must be cooled and shrunken to enable mounting of the two parts. Otherwise the shaft can also be pressed in directly. After the mechanical assembly and the balancing step checks for magnetization can be inserted including additional part mounting steps (encoder discs, shields, bearings) until the motor is transferred to the end- of- line test and further to end assembly.

The same effort cannot be taken for larger IPM motors (see Fig. 19). Lamination sheets have larger diameters and overall masses require additional lifting aids (transport cranes, forklifts). If lamination sheets are too large for automatic stamping or process stacking, they are stacked and fixed manually. For slightly skewing, the whole lamination stack can be split into two pole rows with angular offset. Each pole is then accessible from one side. The shaft is mounted before magnet assembly to ensure mechanical stability of the rotor during assembly. As dimensions are larger, cooling down of a long and heavy shaft is a difficult and energy-intensive task, so heating of the lamination stack with a batch oven is used to create an opening clearance for mounting shaft and lamination stack. The rotor is then transported to the unmagnetized or magnetized magnet assembly station. For unmagnetized magnets, a distinct amount of magnetizing power is necessary for preassembly magnetization. Small batch sizes force manufacturers to use magnetized magnets therefore. The assembled magnets need again to be fixed. For large motors, this is done at an extra fixation station after the magnet assembly process. For preparation of the fixation material, a casting system is provided for missing the resin and the reactive hardener. The rotor itself is standing in the fixture and sealed on the downside and the cylindrical lamination stack surface (e.g. sealing paint) to avoid spilling of resin out of the lamination stack during fixation.

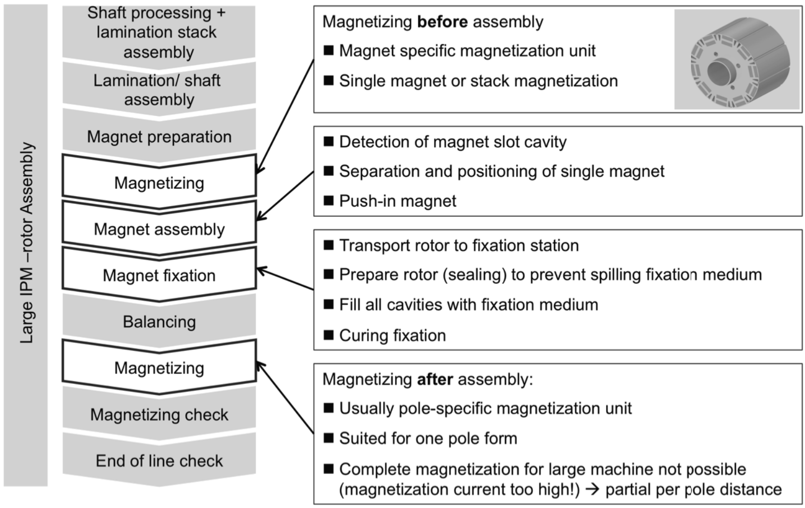


Fig. 19. The IPM assembly process chain for large motors

For high requirements towards lifetime of the larger motors (e.g. train motors working with high vibration forces), the rotor is fully cast with resin, sometimes even in combination with mechanical clamping systems or even fixation screws. The fixation is finished, when the resin is fully cured. This can take up to several hours. After assembly and fixation of the magnets the rotor is again cleaned and balanced. Magnetization after assembly is not always possible for large drives, because of the required high magnetization energy and is therefore done partly for each pole segment. The magnetization unit must turn and position the rotor correctly. The last steps are the final check of the magnetization and the preparation for the end of line check.

3.2 Scenarios for small, middle and large batch sizes

Planning of assembly lines for rotor variants incorporates the evaluation of three batch size production scenarios [68], to understand and detect the overall necessary investment as well as the needed workers for each scenario. The whole rotor process chain can be searched for optimization potentials.

Thus a calculation tool has been developed for calculation of the necessary assembly time, as well as expenses for machines and materials. Cycle calculations start with three batch sizes for small, middle and large batch sizes for possible manufacturing scenarios.

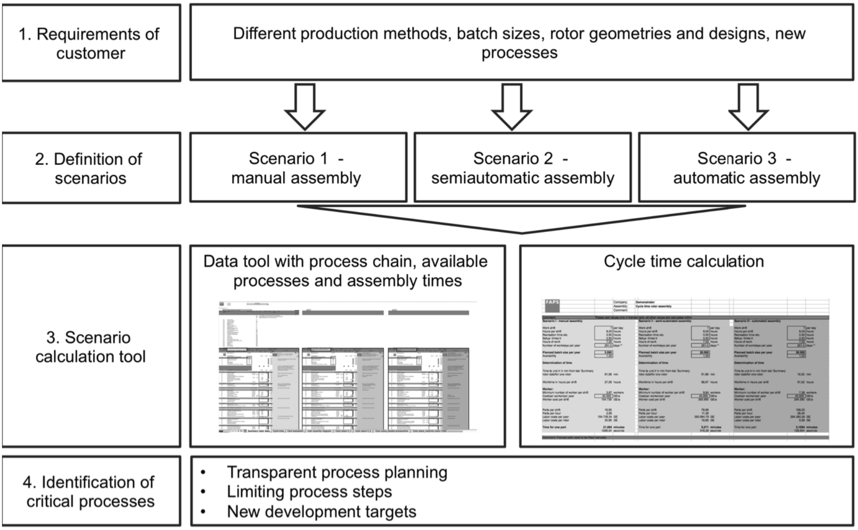


Fig. 20. Three scenarios have been evaluated for manual, semi-automated and automated production of rotors.

For calculation of rotor manufacturing line capacity and expected cycle times, information about available processes for each step is collected in a scenario tool (see Fig. 20). Three scenarios show up technical boundaries and potentials:

- A manual scenario: the batch sizes are small and ranging from 1 up to 5000 parts per year. This is the typical setup for pioneer applications with new customer specific motors enabling new or substituting already existing technologies with high efficient servo motors. It applies to prototyping scenarios as well as to customer specific motor production. Most production steps are done manually keeping initial invests low while obtaining a high flexibility for changes. Magnets are bought premagnetized avoiding magnetizing stations and fixtures.
- The semiautomatic assembly scenario: this scenario is valid for producers with existing and increasing production batch sizes between 5000 and 50000 motors per year. In this case, initial work places have already been designed and the producer looks out for improvements and optimizations of the existing workstations. As the number of produced motors increases, requirements

towards part quality and productivity demand new developments (e.g. switching from magnetized to unmagnetized magnets) and changes of the magnet supply path in rotor production.

- The full automatic assembly scenario: in this case one variant of a rotor needs to be assembled in large quantity (>50000 motors/year). The process chain needs to be adapted and analyzed to achieve an automatic production line for manufacturing large traction drives for electric cars. For automation, a broad knowledge of all inset materials (e.g. magnets, lamination stacks, adhesives, additional assembled parts), all processes (e.g. magnetizing fixtures, concatenation of stations) and high invest for the process stations is necessary to achieve shortest cycle times combined with low failure and scrap rates.

The gathered rotor data information of the created tool calculates the cycle time and capacity of the workplace scenarios based on the following data blocks. It does not explicitly include a benchmark for innovative modes of operation for included processes.

- Assembly station: a calculated process step, which is summarized under a station name.
- Material costs: magnets per rotor, lamination stack, fixation adhesive (or resin), shaft material, additional mechanical pressure plates and balancing materials
- Base: includes the referring unit of the inset value: “per lamination”, “per rotor”, “per shift”
- T_e: the execution time for the work step [s]
- T_r: the setup time for a distinct work step [s]
- Wage: the base wage [€/h]
- Necessary workers per shift: number of necessary personnel for achieving the wanted batch size
- Comments: explanations for the chosen processes

3.3 Summary

For both SPM and IPM assembled rotor configurations, the need for process developments has risen. The process parts for both designs have been presented within three process chains and described. The most significant target processes are magnet assembly and secondly detection and measurement of the magnetic field during the process. For a detailed evaluation of the influence of each process step a calculation tool for magnet assembly lines has been set up including all necessary information for scenario comparison. Three distinct scenarios have been described and potential developments have been shown.

For the first scenario, handling the magnetized magnet material is a major boundary for manufacturers for establishing an optimized process. Handling and gripper systems are required for a hands-free magnet handling during assembly.

4 An Electromagnetic SPM Gripper – the ELMAG

The demand for magnet assembly and handling solutions has shown up as key part for the manufacturing process of the rotor. For each production scenario, the assembly time needed for every single magnet demands a parallel assembly of multiple magnets at once. This limits the variability and flexibility of the assembly process. Otherwise the definition of the magnet handling process for single magnets promises developments comparable to Surface Mounted Devices (SMD) electronic circuit production systems: the understanding of the assembly for flexible pick and place systems has led to automated high-speed part placing systems. Solutions for handling permanent magnets and placing them on SPM rotors are presented in the following chapter.

4.1 A flexible magnet gripper solution

A basic mechanical approach with two actuated permanent magnets to generate gripping forces has already been designed by [69]. The permanent magnets are rotated by pneumatic actuators ("Pneumag") within two positions and create a high summing field in north or south pole direction. The handled workpiece magnet is depending on its position strongly attracted or pushed away. With this principle, a basic arrangement for placing magnets on larger rotors has already been shown and discussed.
The concept for the gripper system should fulfill the shown prerequisites:

- Handling multiple magnet materials and magnetic field strengths
- Adaptable towards round or polygonal rotor surface geometries
- Variable automation level: Manual triggers (in manual workstations) or integration with PLC controls (semi and fully automated)
- For magnetized or unmagnetized magnets
- Bipolar operation modes for both polarities

In contrary to the already developed system of [69], the gripper should allow more flexible use with differing magnet materials (e.g. also magnet materials with lower remanent flux density than NdFeB, which tend to be demagnetized by strong external magnetic fields) and provide an adjustable gripping field for additional adaption. It should be able to handle magnetized and unmagnetized permanent magnets. For the use of magnetized magnets a dual-polarity system should be possible to avoid a tool change during rotor pole changes. In typical manufacturing workplaces, several tools must be used for geometric and variant specific adaption through the production process and must be designed for long term and cycle use [70].

The first prototype of magnet grippers used mechanically rotated permanent magnets to create the magnetic field of the gripper. This is represented by the positions with strong pulling or pushing force seen from the magnet. For the development of the new system, a passive use (this means without magnetic field) should be established requiring additional intermediate states without magnetization or only partial magnetizations.

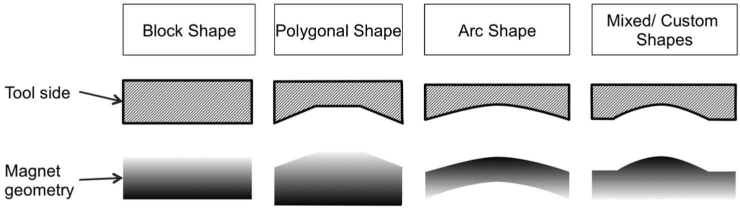


Fig. 21. For SPM assembly, adapted tool shapes for flat, round and polygonal magnet geometries are necessary

Another important characteristic is the ability to handle all geometric types of permanent magnet shapes (see Fig. 21). The main distinction is between arc and block shape. The gripper surface needs to be adapted to the geometric dimensions and force of the variant magnet. Additionally, capabilities for polygonal shapes or custom shapes enlarge the possible setups of the handling system.
Fig. 22 lists the built gripper concepts. VACMAG, PNEUMAG and EASMAG grippers have been developed by Junker [58] until 2007; the later established gripper concepts improve the handling and provide the following features:

- VACMAG (Vacuum-Magnet-Gripper): this gripper was developed for pick and place operations with unmagnetized magnet bodies and is built up similar to gripper systems for placing of SMD IC´s. [58]
- PNEUMAG (Pneumatic-Magnet-Gripper): here, two magnetic actuators turn permanent magnets to create a distinct pull- or push force against the work-piece magnet; for magnetized and unmagnetized magnets [58]
- EASMAG (Electrically Articulated Source Magnet Gripper): within this concept, the magnet shearing process has been introduced, the gripper and mechanics are controlled electrically for both magnetizing states [58]
- PASMAG (Passive Magnet Gripper): a ferromagnetic core is used as carrier for the magnet; for magnetized magnets [71]
- ELMAG (Electromagnetic Magnet Gripper): an electromagnetic core establishes a monopole field for holding and release of the permanent magnet; for both magnetizing states. [72]

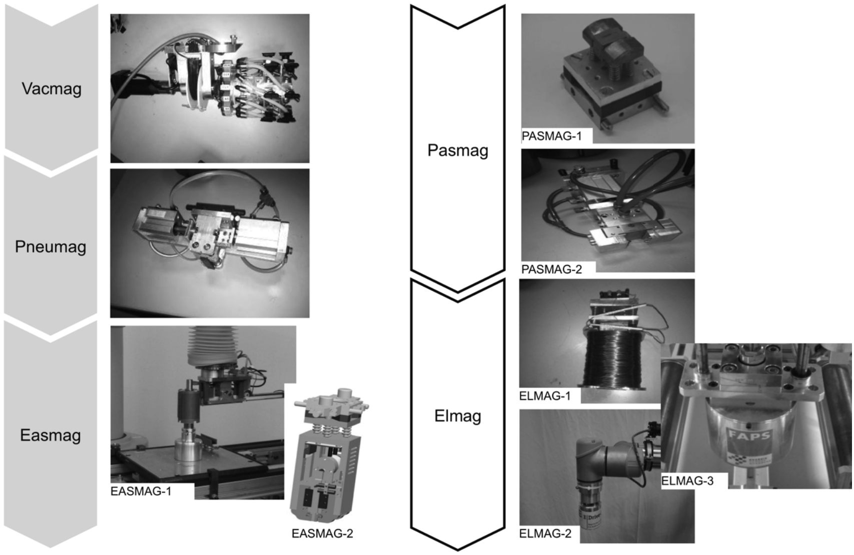


Fig. 22. Grippers for handling permanent magnets for SPM [58]

The grippers for magnet handling incorporate the physical approaches to hold the magnet with a vacuum (VACMAG), with permanent magnets (PNEUMAG), with mechanical actuators (EASMAG), ferromagnetic parts (PASMAG) or with electromagnetic force (ELMAG). Fig. 22 shows the initial designs on the left realized by [58], the Vacmag, the Pneumag gripper and the Easmag-1 gripper. The grippers realized in this work start with the Easmag-2, the Pasmag and Elmag grippers (see Fig. 22 on the right side).

Magnet-placing failures have to be regarded for the grippers (see Fig. 23). Each failure can lead to complete breakdown of the magnetic field of the rotor and dramatically influence the function of the whole assembled motor. Magnet damages are caused through unwanted snapping of the magnet to the gripper and the surface of the rotor, influences of parasitic magnetic fields or adverse placed ferromagnetic parts. This failure is found, if the fixture of the rotor is not exactly aligned with the handling device during an automated assembly. Four types of unwanted production failures occur during magnet placement:

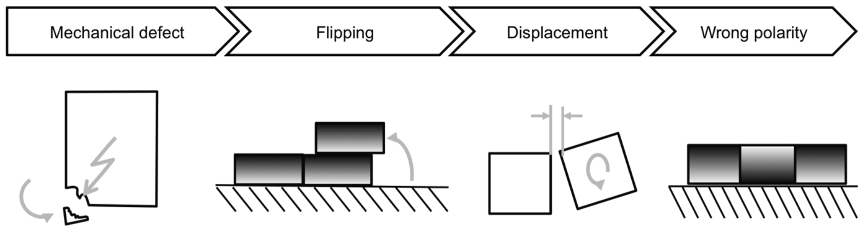


Fig. 23. *Permanent magnet failures and damages during handling and assembly*

If the gripper has a suspension system, the placing position is set deeper onto the rotor surface with additional deviation. This method simulates the thumb of the worker, as it will push the magnet onto the surface. As NdFeB magnets are very brittle, broken magnets and the resulting small magnetic particles are widespread on the rotor surface and require intensive cleaning steps or sometimes the take-out of the rotor workpiece. Magnet flipping is another unpredictable behavior, if the fixation and radial force of the magnet are too small against nearby assembled magnets. After retracting or pulling of the gripper device, the magnet flips away and is settling on top of other magnet rows. Displacement can occur due to an angular twist of the magnet body during curing of the fixation or glue. A wrong polarity occurs if the magnet is not properly checked for right polarity. Therefore checks for the right position and pole number are necessary.

4.2 The PASMAG gripper concept

The passive application with the PASMAG-1 gripper system evolved out of the development of the Pneumag gripper system. If a magnet is placed and the polarity of the Pneumag gripper is inverted, the magnet can be strongly displaced, when the glue between magnet and lamination stack surface has not cured enough. The alignment of the gripper without suspension and a fixed flux collector design of the gripper lead to oblique arrangement between magnet and rotor surface during the assembly. If the end position is set too deep onto the rotor surface, or the workpiece surface has been altered during the placing process, the gripper can be mechanically damaged or the magnet cracks.

The PASMAG-1 demonstrator is designed with a center steel core and a ball tool support enabling the tool head to skew around the suspension. Two slides are attached preventing a twist of the magnet on the tool and therefore a displacement. Main advantages of a passive magnet gripper system are:

- Rugged design with few, simple parts
- Easy and fast to implement

- Fail safe function: if the handling device fails, the magnet will remain at the gripper tool.

Fig. 24 shows the PASMAG-1 concept and the resulting demonstrator gripper. The placing head needs to be customized to the size of the magnet, as well as the guiding slides. Furthermore the necessary tool path is shown for a multi-magnet pole-placing scenario, with several magnets forming a pole with lamination stack pole separation. On mechanical pole separations or already placed magnets the guiding slide can move up and the magnet can be set onto the already set magnet. Each magnet is held as long until the magnet is cured enough to avoid loosening.

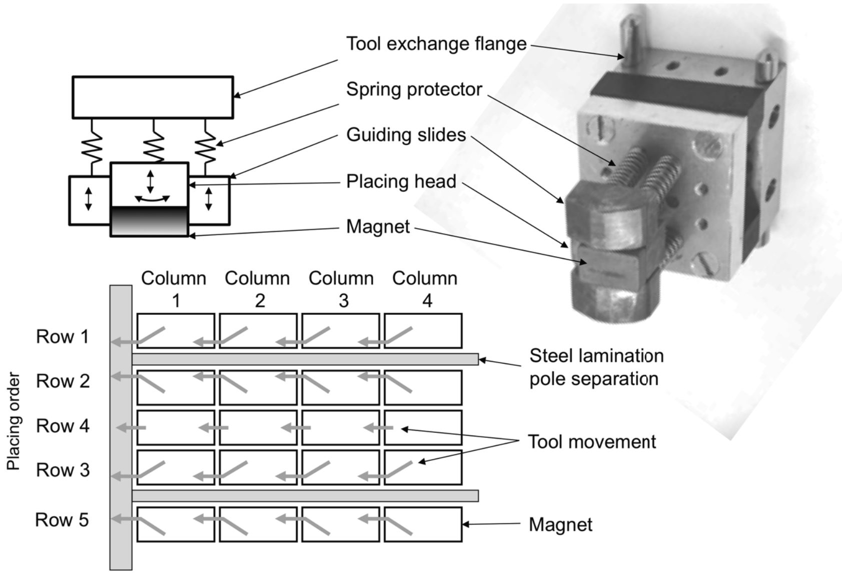


Fig. 24. Top: PASMAG-1: A passive mechanical gripper can be used for placing magnets. Bottom: The path planning for a rotor surface with three poles is given.

The permanent magnet can be set manually or within a supply rail for each placement step providing a constant magnet positioning. For a fully automated assembly an unwanted snap of the magnet onto the gripper must be prevented. With the guiding slides, contriving the magnet in between and providing a straight alignment on the placing head is difficult.

The second gripper using a ferromagnetic core is the PASMAG-2: the ferromagnetic carrier of the PASMAG-1 is advanced, as the core is decoupled from the gripping system and a standard two finger gripper system is established for gripping the block.

The block is then used as carrier and stays on top of the magnet, until the fixation is cured enough to take the carrier away. The use of known standard parts to reach an automated placing method by using a two-finger gripper is the main consideration for this solution.

The magnets are placed in a fixture tablet row (see Fig. 25). The gripper sets the carrier-block on top, as it slides horizontally onto the magnet surface. During this combination process the magnet can slightly lift and snap onto the carrier. The aligning process is nonetheless as correct as the matrix tolerance between the magnet and the fixture.

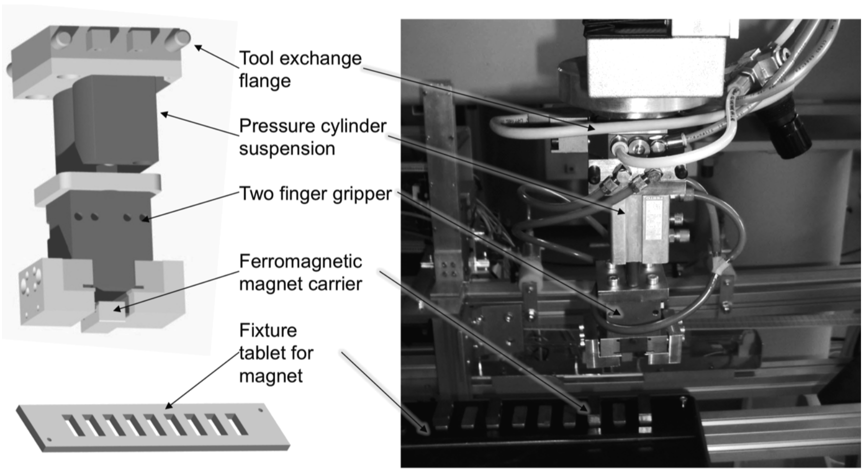


Fig. 25. The PASMAG-2 integrates a flexible tooling with standard automation equipment.

The system is integrated into a 3-axis system, so angular displacements cannot be rectified by an additional rotation of the tool head. For path planning, seven steps need to be defined (Fig. 26):

- **Approaching magnets:** the gripper is positioned towards the supply area and positioned with gripper open.
- **Collecting carrier:** a carrier block with attached permanent magnet is taken from the fixture tablet. If none is prepared, the gripper can also set the carrier on top of a separated magnet.
- **Approaching workpiece:** travelling to the rotor with rapid movement
- **Positioning:** exact positioning with feed rate

- **Place and shear:** placing the magnet and shearing the carrier block over an already placed magnet, this produces a ferromagnetic clamping and the magnet is connected with already assembled magnets
- **Open gripper:** opening gripper and releasing the carrier with feed rate
- **Gripper take off:** travelling off with rapid movement to supply position

Depending on the supply path and the necessary curing time of the fixture system, only a small set of simple ferromagnetic magnet carriers is necessary. Three to five blocks are needed for two-component glue systems (e.g. Loctite 326). The first set carrier may to be taken away after two additional magnets. During this time, the glue system is cured enough to hold the placed magnet in position. The carrier block is sheared away from the magnet surface. This avoids an unwanted stripping of the magnet.

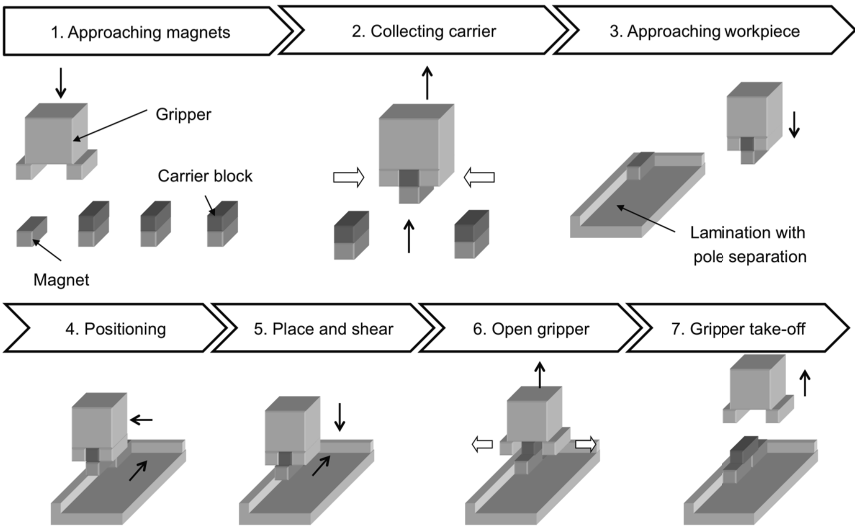


Fig. 26. The assembly path with the carrier block method

The system shows flexibility towards block and arc shaped magnet shapes and magnetizations, as the method is based on the difference of the B-field between carrier block and magnet contrary to magnet and rotor surface. The better the geometric connection between magnet and gripper tool, the stronger the carrier holds the magnet.

4.3 The ELMAG gripper concept

The ELMAG (electromagnetic gripper) establishes an unipolar electromagnetic field and can grip magnetized and unmagnetized magnets. This principle uses a ferromagnetic core bar with a surrounding coil to produce a strong magnetic field at the end of each core side and has been patented during this research work [72]. The necessary polarity change is switched by inverting the current direction through the coil. A toolset for calculating the magnetic flux and force has been developed for calculating available space for the gripper (e.g. if magnets must be placed inside a rotor bell). Important design factors are the right power supply (standard power systems with voltages between 12- 24 V preventing dangerous touch voltages in case of winding failure) and an electronic H-bridge controller for a decent PWM-control of the gripping force.

Electromagnetic grippers are widely known for transporting and handling ferromagnetic parts in production. The concepts for this type of grippers include a bipolar functional principle with easy termination by supplying the coil with a constant current. For permanent magnets, this principle is not usable, as two polarities lead to pushing and transversal skew forces.

An electromagnetic gripper with one polarity suits the needs for handling permanent magnets. It combines the idea of the PASMAG and PNEUMAG devices and leads to the new electromagnet concept with an electromagnetic actuated core, forming a monopole- bipolar structure. The magnetic circuit is opened and only one active part is used (see Fig. 27) as only one magnetic pole is used, whereas the other disturbing pole is omitted, such permanent magnet grippers only have one polarity.

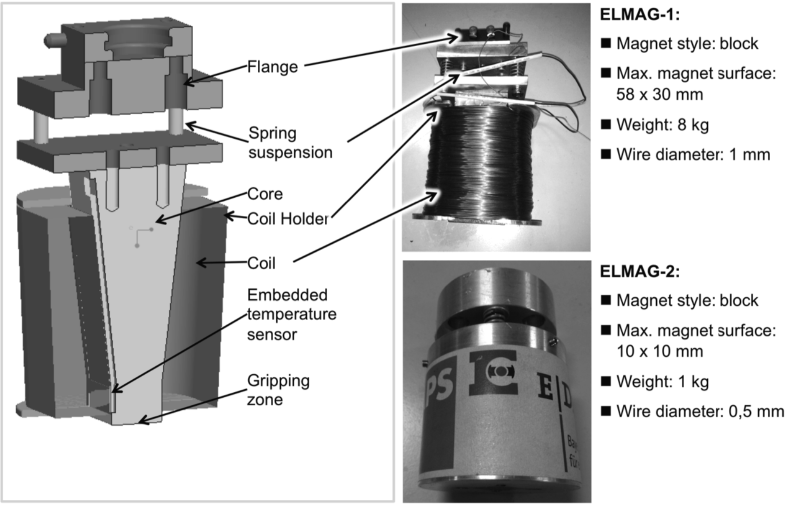


Fig. 27. ELMAG grippers with prototype for larger magnets (ELMAG-1) and an application for small robotic applications (ELMAG-2)

With this type of gripper unmagnetized as well as magnetized permanent magnets can be processed with a 5-steps pick and place assembly process operation as it is realized for placing electronic components on PCB boards. Instead of the pneumatic/vacuum gripping principle for electronic SMD parts, the ELMAG gripper involves the generation of a strong monopole permanent magnet field, that can be used for controlled take-away, transport and exact placing of magnets. The process for handling unmagnetized and magnetized magnets is therefore just slightly differing. Fig. 28 shows the workflow for unmagnetized magnets:

- **Magnet separation:** presenting one magnet at a definite take-away position
- **Attaching:** approaching and positioning the gripper over the magnet body
- **Activate the gripper field:** as the permanent magnet is unmagnetized, the outer field can be chosen freely for a magnetic transport. In case of gripper designs with high field generation in combination with „weaker“ ferrite or AlNiCo magnets, the field may be chosen as the wanted polarity for the assembled pole. In this case, an “On-Gripper-Magnetization“ could be considered, but has not been realized.
- **Approaching and placing:** positioning the magnet on the workpiece, e.g. gap-free towards other already assembled magnets
- **Mounting the magnet:** pressing the magnet into correct end position, e.g. hot- curing glue or two-component epoxy-resin

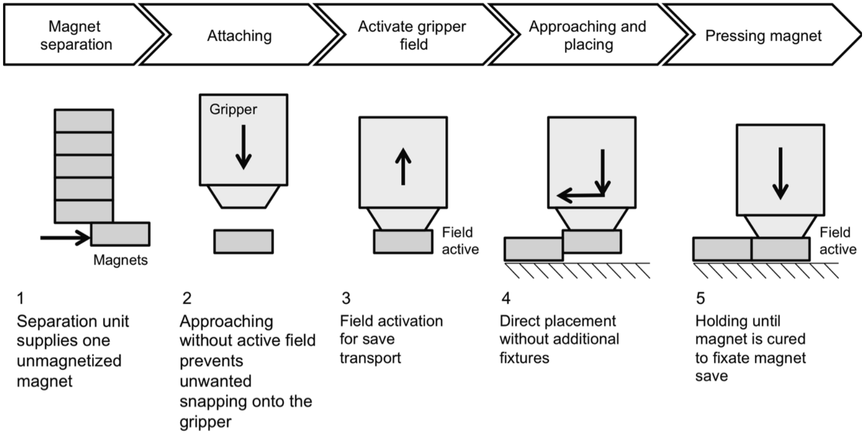


Fig. 28. The handling process for unmagnetized magnets with the ELMAG gripper concept is divided into five main steps.

The handling of unmagnetized magnets is not the expected application goal for the ELMAG gripper. For small or flexible batch size manufacturers expenses for magnetizing equipment play an important role for product calculation, the handling of already magnetized magnets is important and shown for the ELMAG system in Fig. 29. The handling process can therefore be translated into five decent steps.

- **Magnet separation**: In this case, the coercive forces of the magnet have to be considered for the design of the separation unit. When using magnetized magnets, the process for attaching to the workpiece magnet as well as the placing and retracting of the gripper need additional attention. The electro-magnetic field of the gripper is used to support the magnet assembly steps:
- **Attaching** the magnet with the inverse poled gripper
- **Reverse the gripper polarity**
- **Approaching and placing**
- **Pressing the magnet** onto the work piece and reverse pole again

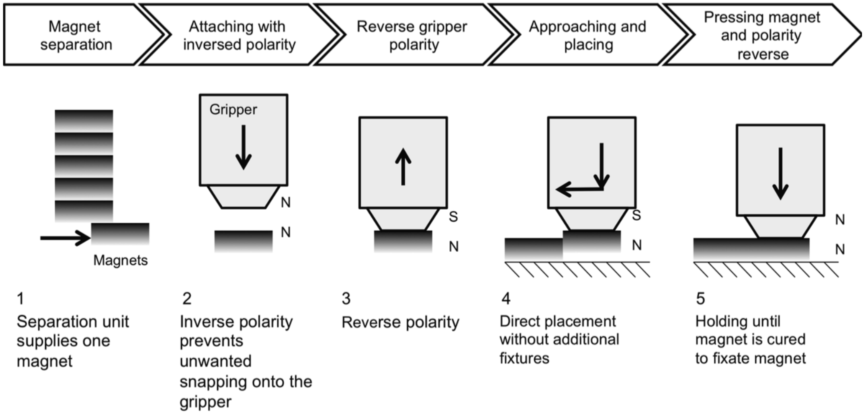


Fig. 29. The assembly process with the ELMAG gripper system consists of five steps.

One major disadvantage of the gripper system is the mechanical interface between core and gripper area. The gripper has to be replaced completely if the magnet shape or the dimension of the magnet changes. Tapering the magnetic core is described in [73].

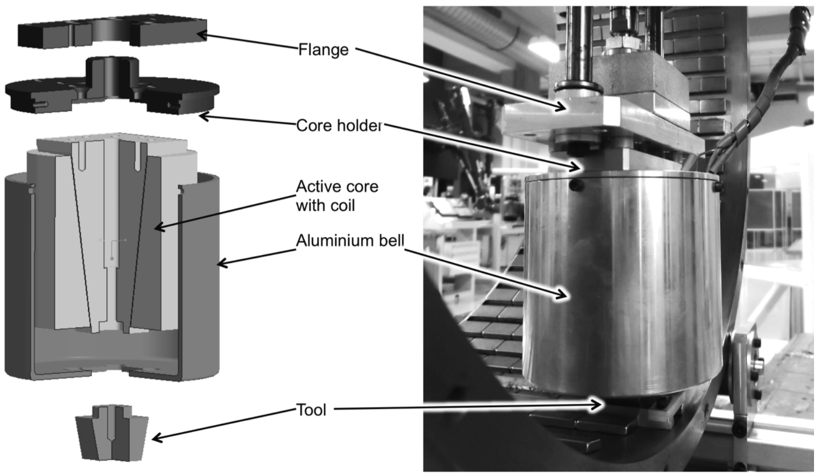


Fig. 30. The ELMAG-3 gripper is equipped with an exchangeable tool end to provide flexibility for all magnet shapes.

The ELMAG-3 represents the latest development. It includes an exchangeable tool, which can be adapted to the necessary magnet shape. Magnetic core and fixture stay the same (see Fig. 30).

With this gripper, a universal tool is created with the following features and advantages:

- Integration into automatic production lines possible
- Simple and fast gripping characteristic
- Fully controllable magnetic force creation
- Fail safe, as the magnet will be held by the ferromagnetic gripper core, if the current switches off
- Simple and rugged design, supplied by standard DC voltage supplies
- Compact size
- Easy control of current and current direction (2 outputs from PLC or driven manually)
- Can be combined with temperature and Hall sensors for magnetization check additionally
- One core fits for multiple tools
- Very low tool cost (only new tool inset)
- Fast exchange of tool (only one screw)

Fig. 31 gives an overview about capabilities of the presented PASMAG-1, PASMAG-2 and the ELMAG gripper:

- **The operation mode**: The gripper devices are distinguished between magnetized and unmagnetized handling (e.g. if the gripper just has to place unmagnetized magnets with a simple pick and place operation).
- **The failure mode**: In case of machine or workplace errors, a safe handling procedure ensures, that magnet material is not contaminating the workspace. For magnetized materials unwanted snapping to other components of the machine is not wanted.
- **The take-off mode**: For wrong or misplaced magnets the take-away from the rotor surface is an additional operation mode for the gripper system. Removing unmagnetized magnets (which have been set into glue) is less complicated than removing magnetized material manually.

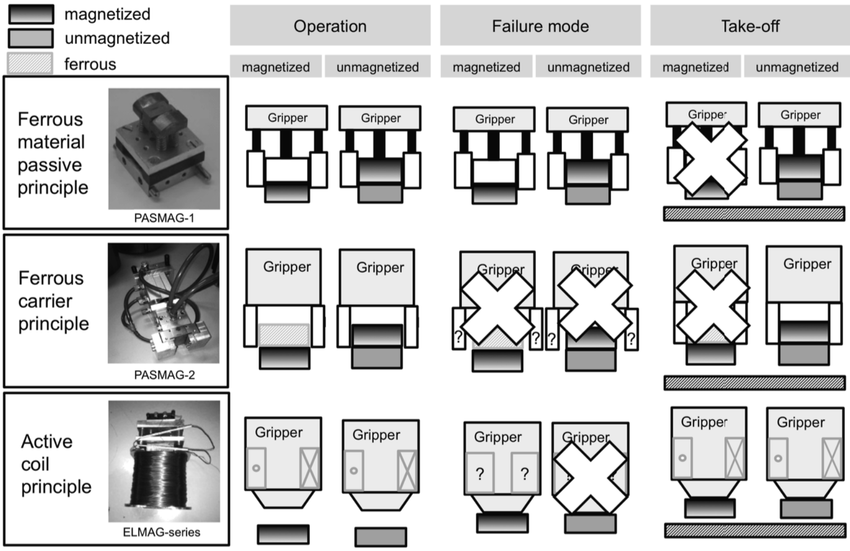


Fig. 31. *The developed gripper solutions differ in operation, failure modes and take-off capabilities.*

The results show advantages for an active system. All three gripper types can handle magnetized or unmagnetized magnets. Disadvantages are detected for the take-off operation with magnetized magnets for the PASMAG-1. The attracting forces between rotor and magnet can be higher than between magnet and gripper. A take-off is then not possible. For the PASMAG-2 with carrier block, a failure of power supply can lead to unwanted opening of the gripper for both magnetization states and the take-off operation for magnetized magnets can show the same behavior as the PASMAG-1. Passive operation is not suited for take-off of magnetized magnets due to the missing additional magnetic forces to lift of the magnet from the rotor surface. The active coil of the ELMAG system provides operation for both magnetizing states of the magnet without change of the gripper. If unmagnetized magnets are used and the power is switched off, the magnet body falls off the gripper. The design and development process of the ELMAG gripper principle can be demonstrated with three variants of electromagnetic grippers (ELMAG1-3) and the use in manual and semi-automatic assembly stations has been discussed with manufacturers of electric motors and research [71].

4.4 Basic ELMAG electromagnetic coil setup

The design path for calculating the circuit of the ELMAG gripper includes three main parts shown in Fig. 32, split up into the FEM simulation, the coil calculation and the realization. The design of the coil is limited by requirements of:

- Available voltage: For excitation of the necessary magnetic field, standard industrial switching supplies with low voltages (5- 24 Volts) can be used to ensure safe manual handling during operation.
- Allowed current: Depending on the available voltage and the electrical design of the coil properties
- Available wire: the wire gauge has to be chosen as large as possible for higher ampacity
- Available space: The size of the gripper/ the available space in the assembly area can influence the design of the ELMAG gripper

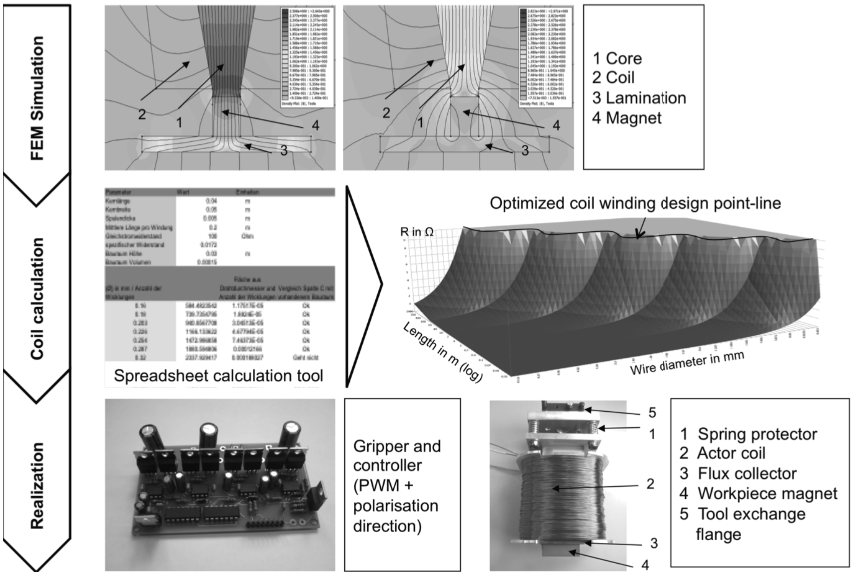


Fig. 32. The design steps of the electromagnetic gripper are simulation, calculation of the coil and the realization of the hardware.

The core geometry has been simulated with FEM solvers (e.g. Femm [74]) and trapezoidal core structure with flux accumulation to create a high push and pull force against the work piece permanent magnet [71]. Therefore harder silicone enriched metals are better for generating the wanted field intensity as core material for the ELMAG solenoid. The main disadvantages are availability of the materials as well as the cost. For the prototypes, standard steel cores (material: S235JRG1) are chosen to build up the demonstrator grippers.

Fig. 33 represents the model scheme of the basic ELMAG parts. A bell, consisting of non-magnetic (aluminum) parts protects the inner solenoid system. The core is the basic part for generating the magnetic force with a monopole end. Compared to known standard lifting magnets, the magnetic circuit is not closed. Around the steel core, an insulation material (bobbin) is mounted with the solenoid.

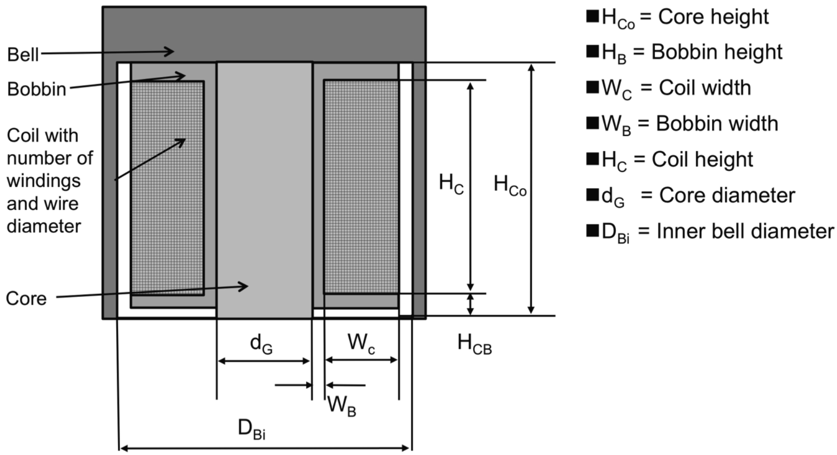


Fig. 33. A model for calculating the ELMAG gripper helps to understand the principle.

With a trapezoidal or tapered shape [73], the flux lines can be accumulated and intensified towards the tool interface in contact with the magnet surface. The angle is chosen empirically by FEM estimation, because an accurate calculation tool has not been available. Fig. 34 gives a comparison between the magnetic flux in a straight and a tapered core. The straight core is saturated over nearly the full length, whereas the tapered core merges the flux to the workpiece center. This flux concentration is used to collect as much flux as possible to create a strong gripper polarity against the workpiece magnet.

In the second step the parameters for the winding of the gripper are calculated regarding resistance and number of windings. With these calculation basics, the ELMAG can be constructed for various surface mount applications and be implemented in various workstations for manual and automated use.

The calculation model of the gripper works with basic calculations, that the core and the coil are designed as cylinders. The design characteristics furthermore include the parameters for:

- Working voltage: the supply voltage for operation of the gripper
- Ampere turns: the number of turns, which are necessary for creating the magnetic field
- Maximum temperature: allowed temperature for the insulation system
- Size of the winding slot: allowed size around the winding core

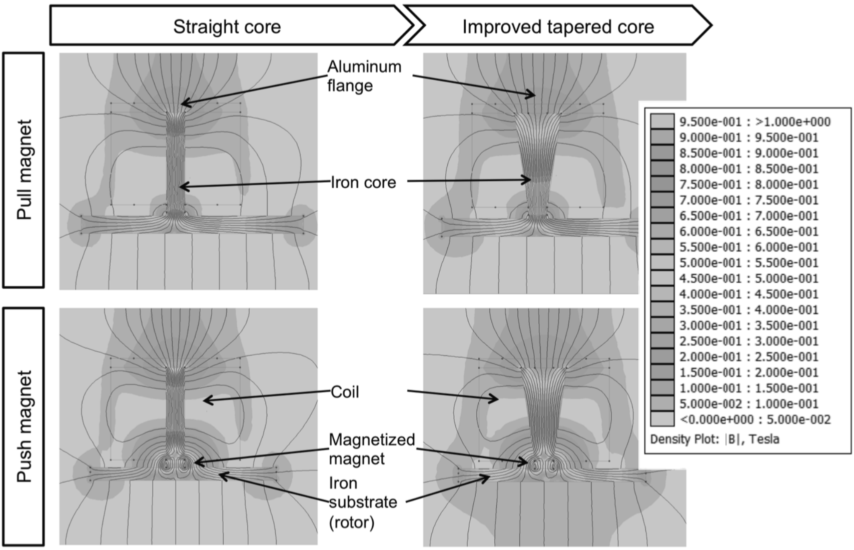


Fig. 34. The core of the ELMAG is tapered for improved flux guidance.

The calculations can be merged in three subroutines, the calculation of the winding area, followed by the determination of the wire size and finally completed by the temperature evaluation. Fig. 35 starts the calculation with all necessary geometric components. For the shape of the coil, optimized height (y_{opt}) and width parameters (x_{opt}) can be taken from [75].

Tab. 3. Additional abbreviations for the calculations in Fig. 35

Abbrev.	Explanation	Abbrev.	Explanation
a	PM-length	A_w	Winding area
b	PM-width	W_{Cmax}	Maximum allowed coil width
x_{opt}	Optimized coil width	H_{Cmax}	Maximum allowed coil height
y_{opt}	Optimized coil length	W_{Copt}	Optimum coil width
A_{Wmax}	Maximum allowed winding area	H_{Copt}	Optimum coil height
$l_{Coremax}$	Maximum core length		

With the size of the permanent magnet (a, b) the ELMAG core diameter is calculated. The second step is the optimized coil width and height (W_{Copt} and H_{Copt}). With these values, the winding area can be determined regarding the geometric boundaries of the defined gripper bell width and height (W_{Cmax} and H_{Cmax}).

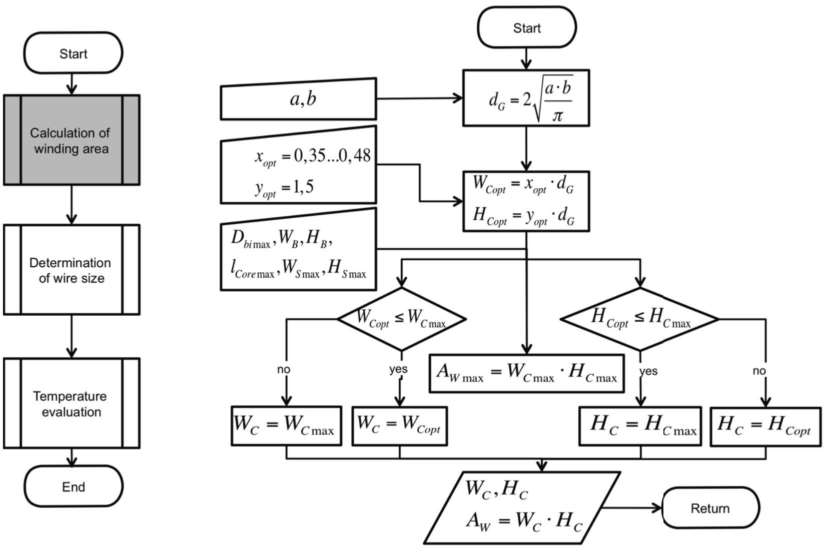


Fig. 35. For the determination of the ELMAG winding area, all geometric parameters are taken into account.

With this design, the flux requirements and the necessary wire for the winding are determined. The length of one average conductor winding (l_m) regarding the available winding space is defined and integrated into the formula for the copper diameter. Fig. 36 shows the dependencies between flux, number of windings and the required current. The flux is taken from the FEM simulation and includes the wanted pulling force for holding the magnet. When the copper diameter is calculated, the winding production (layer-, orthocyclic- and orderless winding) is considered in the calculation of A_{WCu} and compared to the winding area (A_W). The result is then again reiterated with available dimensional space. If the values do not match, ampere-turns and available current need to be set. For maximum current usage, no additional serial ohmic resistors should be used, because they would limit the available excitation voltage. Therefore the current estimation always directly depends on the resulting ohmic resistance of the solenoid coil (assuming a static excitation of the coil – switch on/off). The resulting ohmic resistance of typical Average Wire Gauges (AWG)-wire sizes for given length is attached to the appendix.

Tab. 4. The abbreviations for the calculations in Fig. 36 and Fig. 37

Abbrev.	**Explanation**	**Abbrev.**	**Explanation**
d_{inner}	Inner coil diameter	U	Operation voltage
Δ_ϑ	Temperature difference	A_{wmax}	Maximum allowed winding area
R_{Warm}	Hot resistance	d	Diameter of isolated wire
ϑ_{max}	Maximum allowed temperature	N	Number of winding turns
d_{outer}	Outer coil diameter	I	Current
l_m	Average conductor length	iso	Isolation thickness
d_{Cu}	Copper diameter	A_{WCu}	Winding area copper
ρ_ϑ	Electrical conductivity at temperature	A_W	Winding area
ρ_{20}	Electrical conductivity at 20°C	d_{Cu}	Copper diameter
α	Heat transfer coefficient	A_W	Winding area
ϑ	Temperature	P_T	Heat loss power
ϑ_A	Ambient temperature		

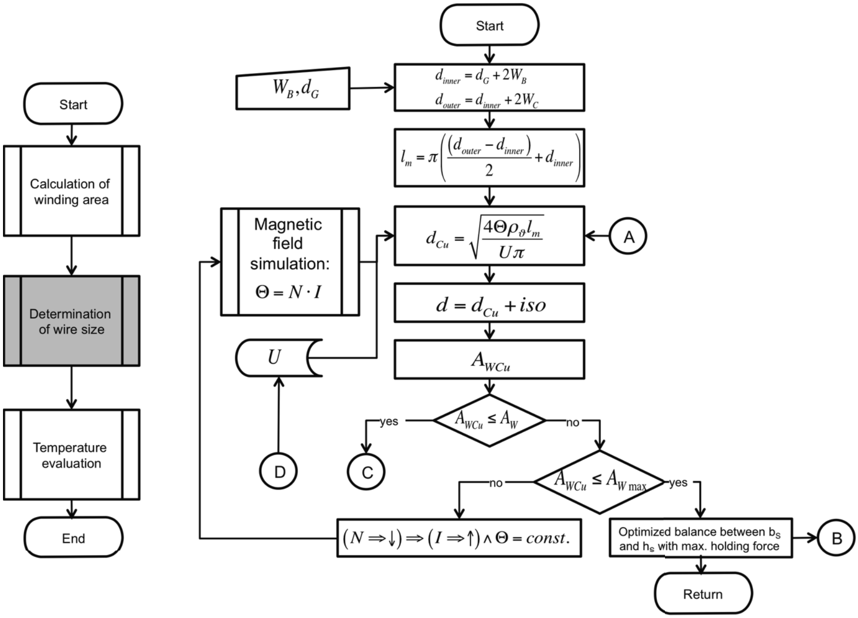


Fig. 36. The wire size is determined by including the required field.

If the current is chosen too high, the solenoid will heat up and destroy the winding insulation. Fig. 37 therefore gives the additional calculation steps for evaluation of the expected temperature. Including all calculation steps and comparisons, the gripper is ready for production.

The electrical conductivity is calculated for the selected wire. With this value, the resistance (R_{Warm}) of the ELMAG coil can be evaluated. With this resistance and the operation current (I), the heat loss (P_T) of the coil is given and can be computed within a temperature simulation. The peaks of the temperature simulation are then compared to the temperature limit for the used selected wire and insulation material. If the temperature does not fit, the winding calculation is repeated with another wire size, otherwise the coil magnet is ready.

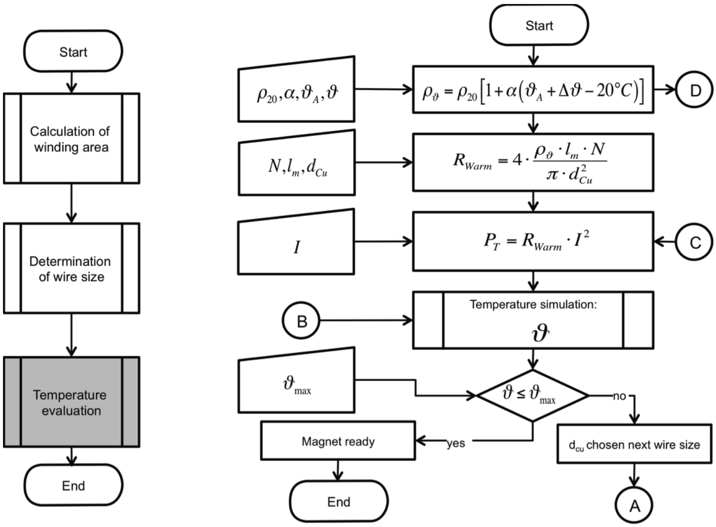


Fig. 37. Evaluating and regarding temperature ensures save operation of the gripper.

The core is insulated and preassembled with the flange part. Afterwards it can be wound with the required wire length on a standard winding machine for rotary winding products. The number of windings, as used in the prototypes varies between 3500 and 5000 with wire diameters between 0,5 mm to 1,2 mm. For this amount of wire turns this means strong wire tension on the wound solenoid. The windings have been dripped with layers of glue during the winding process and have been cured to ensure a safe takeout off the winding machine. The electrical interface has been realized with a self-designed 4-quadrant DC motor stage, which is able to switch the direction of the current through the solenoid by standard control signal levels. Furthermore, Pulse Width Modulation (PWM) control of the solenoid is possible and can reduce the created field intensity by lowering the median excitation voltage.

For use in the lab and the placement experiments, a manual control has been added for turning the magnetic field on/off and reversing the field polarity with switches. For automatic systems this can be implemented into a small cabinet with PLC-control. The ELMAG-3 has an additional temperature sensor (PT-100) inside on the solenoid core material for the possibility of temperature monitoring. The first results showed moderate heating of the prototype, as it has been constructed with mechanical safety coefficients, so the temperature sensor has not been read-out for the experiments. If a boost or overload function (e.g. for easier take-off) from the rotor should be realized, temperature monitoring should be activated for coil protection. An aluminum cup-bell is used as shielding against mechanical influences on the winding structure.

4.5 Summary

In this chapter, various gripper types for handling permanent magnets in magnetized or unmagnetized state have been presented. The development has shown that the generation and control of an electromagnetic gripping principle provides the best solution for permanent magnet placing, especially if gap-free mounting and flexibility for varying types of permanent magnets is necessary. The ELMAG system has been presented with the calculation for the gripper coil. Grippers with adapted force characteristics for the required magnet sizes and forms can be derived and be built up.

5 ELMAG Gripper Integration in SPM Assembly Workplaces

The technology of the electro-magnetic gripper system is suited for workplace integration. Complete workplace redesigns are not necessary, but improvements within existing process stations significantly change the way rotors are produced. When magnetized permanent magnets are used at the workplace, production methods become very complicated for the worker. In this case, additional precaution has to be spent for shielding the magnetic field, persons with heart injuries must keep safety distances to permanent magnetic materials and the worker has to take care of the permanent magnet behavior during assembly (pulling forces in interaction with other magnets.

The standard method of assembling synchronous rotors, e.g. for industrial robotics or linear motors is the placement of the magnet onto the surface of a ferromagnetic core. The magnets are set on a layer of glue, which is applied before or during the assembly process.

Manually handled permanent magnets require close attention throughout the assembly process. The available equipment does not avoid dirt contamination and the magnetic force of the workpiece magnet in interaction with other magnets is hard to handle. New handling approaches for magnet assembly are needed.

In this chapter

- implementations for the use of the ELMAG gripper for SPM applications
- workplace analysis with MTM-UAS systems
- a workplace demonstrator for SPM inner rotors
- a workplace demonstrator for outer rotors

are presented.

Based on the work of [58], the assembly of magnetized magnets has been investigated. For traditional production lines of this type, unmagnetized magnet bodies are used, requiring a final magnetization step establishing the wanted field intensity. Motor designers have to develop customer specific motors and drive systems with integrated and biased frequency inverter/motor combinations. This leads to a number of variants whereas the product lifecycle is shorter and batch sizes vary in broad ranges. For the assembly line, this means an increased toolset combined with a limited number of workplaces.

Demanding electro-motor applications furthermore involve complex flux guiding (e.g. for reducing torque ripple) complicating the use of magnetizing equipment. Larger coil-sets for magnetizing rotors are necessary regarding rotor lengths and rotor diameters. If magnetizing in “one shot” is not possible, a skewed magnetization is also possible by assembling skewed segments of premagnetized magnets. On the other hand, the development of a variety of customer specific variants is technically challenging for production systems with one product.

As a result, the range for small to middle batch size production is focused for the next generation of magnet handling workplaces and flexible solutions are necessary to support the basic assembly process. Fig. 38 shows the concepts for SPM workplaces with inner and outer rotors. These concepts and the resulting workplaces are presented in the following chapters.

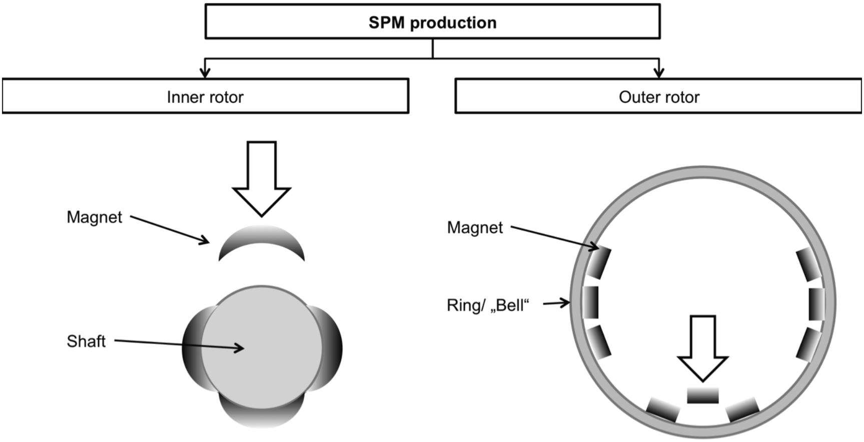


Fig. 38. SPM solutions for inner and outer rotors have been developed and demonstrated by prototype workplaces [71], [76].

For placing the permanent magnets, a gripper and handling strategy has been developed [72], [77]. For operation, the gripper must include features for handling varying NdFeB magnet sizes, strengths and shapes. For an easy application in motor prototyping for small to middle batch manufacturing the gripper must furthermore be able to be used by hands in manual workstations as well as in combination with robot manipulators.

The development with the first automated assembly attempt in [58] has led to a new approach, to enable a cost effective and a possible automatic use of the developed gripper system [69], [71], [76]. As practical approach for analyzing the assembly scenarios, Methods Time Measurement (MTM) is used as an analyzing system for workplace generation. Looking at a typical assembly scenario (as shown in Fig. 39) the following challenges are given:

- The workplace concept is for small batch synchronous rotor production, aiming a yearly production of about 5000 pieces/ year.

- The permanent magnets are already magnetized. In-house magnetizing instantly increases production costs for the product, as additional magnetizing fixtures are necessary.
- The process therefore starts with unpacking a stack of permanent magnets.
- To prevent unwanted flipping of the magnets, ferromagnetic tables are used, where the stack can be deposited or the magnet can be separated.
- As the stack is handled manually during the unpacking and separating process, the magnet bodies need to be cleaned before assembly. This can be combined with activating for the glue process.

5.1 Workplace for placing permanent magnets on the surface

If fully automated solutions should be applied, high variant changes and initial costs have to be met and all technical risks for introduction have to be eliminated. The ELMAG gripper has been launched in a workplace design with a new approach. It focuses on small prototype to medium scale manufacturers, where a lot of variants have to be produced at one magnet assembly workstation. A manually driven, scalable workplace, combined with a new developed permanent magnet gripper system is presented. The workplace has been calculated with principles of MTM [78], [79], [80]. Furthermore, a scalable version of the workplace towards an automated design presented, keeping the demanded variant change flexibility combined with low system costs for handling and placing magnetized magnets.

Fig. 39 shows a typical workplace layout for small to medium batch size SPM magnet assembly. The worker takes the glue, applies it on the surface of the rotor, takes a magnet from the preparation table and sets it carefully onto the rotor surface. As equal-poled permanent magnets show serious unwanted transversal forces against each other (e.g. in one pole row), the worker has to hold the magnet on the rotor in place until the glue is cured enough. Then the steps repeat for all other work-pieces.

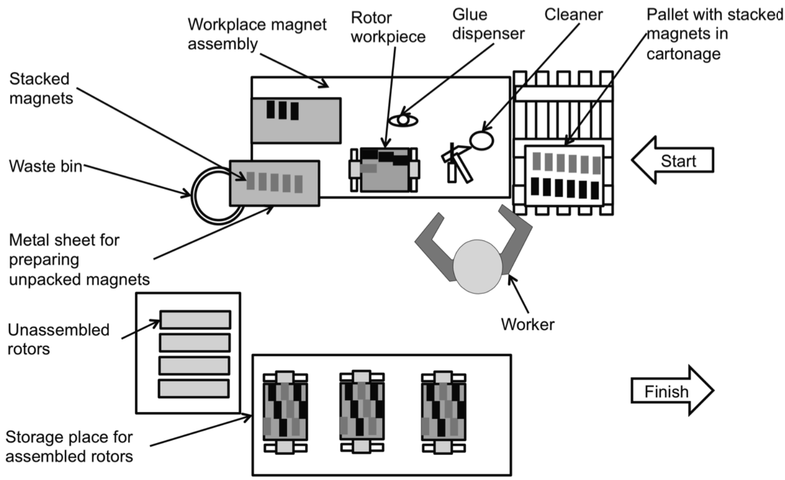


Fig. 39. Workplace layout for small lot size permanent magnet assembly

Accordingly, the MTM-UAS analysis shows the corresponding (ideal) assembly times for each presented step [81]. For comparison, a test case with a four-poled rotor with four magnets per pole is taken. The single steps have been analyzed with the MTM-UAS System [82] [83], as this system is suited for flexible production with change of variants. As the magnet forces are higher within the magnet stack, the UAS-system allows the use of process times (PZ) so even rough calculated work steps can be inserted. For the separation of each magnet therefore a process time of five seconds (equals 139 time measurement units -TMU) is estimated. Depending on the size of the magnet this can be much higher, when the worker needs more time to separate magnets, which have been delivered without spacers or he needs additional time for safe arranging on the preparation table.

Dosing of glue is done with standard squeeze bottles without additional dosing system. If too much glue is applied, residual glue has to be removed instantly avoiding cured glue bumps. These are quite hard to remove and critical for hitchless assembly of pole rows. The assembly time for placing of the magnet is considered with four seconds of placing time adding an average of 20 seconds long process curing time period ensuring safe glue curing to hold the magnet. Depending on the chemical composition of the glue, tempering the magnet/rotor combination can fasten the curing process.

The calculated assembly time for the presented processes is given in Fig. 40 and summarizes to about 15 minutes with a main time of 92 % in a 7,5 hour shift. As for every MTM-UAS calculation, an additional time is added to provide a personal allowance of 8 %.

Topic:	Magnet Assembly 1
Assembly:	Workplace with glue/ gripper combination
Comment:	Rotor variant 4 pole/ 16 magnets

Part / Work Pattern	**Code**	**TMU**	**Quantity**	**Sum in TMU**
Walk to pallete (1m)	KA	25	2	50
Bend down to palette	KB	60	2	120
Take magnet stack (8 pieces) out of cartonage	AG2	65	2	130
Place it on the table	PA2	20	2	40
Unpack	PZ	278	2	556
Collect packaging	AB2	45	2	90
Walk to bin (and back- each 1m)	KA	25	2	50
Throw away packaging	HB2	60	2	120
Separate magnets for preparing	PZ	139	16	2224
Visual control	VA	15	16	240
Take cleaner and equipment	AB2	45	2	90
Clean the magnet	ZC1	30	16	480
Walk to rotor (0,5m)	KA	25	16	400
Take glue	HB2	60	16	960
Place glue applicator exactly	PC1	30	16	480
Apply glue	ZC1	30	16	480
Visual control	VA	15	16	240
Put back glue	HB2	60	16	960
Walk to magnets (0,5m) and back	KA	25	16	400
Take magnet away from panel fForce!)	AK1	50	16	800
Place magnet exactly on rotor	PZ	111	16	1776
Hold and correct (process time depending on glue type)	PZ	556	16	8896
Visual control	VA	15	1	15
Take cleaner and equipment	AB2	45	16	720
Clean glue residue	ZC1	30	16	480
Put back cleaner	HB2	60	16	960
Sum				**21757**

Assembly time according to MTM-analysis	782,63	Sec.
Additional time in % **10**	78,26	
	860,89	

Assembly including extra time **860,9** Sec.

t / piece	Allowance %	Availability %	Pieces / h	Hours / Shift	Number of shifts day	Pieces / day	Work days/ year	Pieces / year
860,9	0,92	0,9	**3,5**	7,5	1	**26,0**	230	**5973**

Attention:
8 % Allowance means a value of "0.92" in the table !

Fig. 40. The MTM-analysis structures the work process and uncovers steps, which are time consuming.

To improve and develop the workplace towards a scalable process station, the process times shown in Fig. 40 must be minimized. In contrary to a fully automated system the approach builds up on already existing assembly environments.

For the workplace enhancement, the following components of the automated system can be rearranged:

- A manually driven kinematic positioning system supports the placing process of the permanent magnet
- The magnet separation system reduces the time to prepare the next magnet for assembly
- The electromechanical gripper supports the whole magnet placing process by a safe handling of the magnet during placement moves and the placing process itself
- A small enclosed NC control system for exact angular adjustment of the rotor to position the rotor shaft with exact angular positions; this enables also skewed positioning of magnets

An important feature is the manual driven handling system, on which the processing gripper system is attached. Parallels can be found for the exact manual placement of SMD-parts [84], where the worker manipulates the work piece by a manual guided two-axis system (XY-mimic) with a variable Z-axis actuator for placing. An additional axis to turn the magnet is not necessary, if the magnet is held straight with the gripper system. The concept for permanent magnet placing is similar.

The worker guides the actuator manually. The height can be pre-adjusted for every rotor by a hand wheel with numerical height counter. To apply the placing force, the gripper is attached to a second pressure cylinder pressing the magnet down in negative Z-direction. As shown in Fig. 41, the placing step holds the magnet with the gripper with a slight offset over the rotor surface and prevents an unwanted snap onto the rotor.

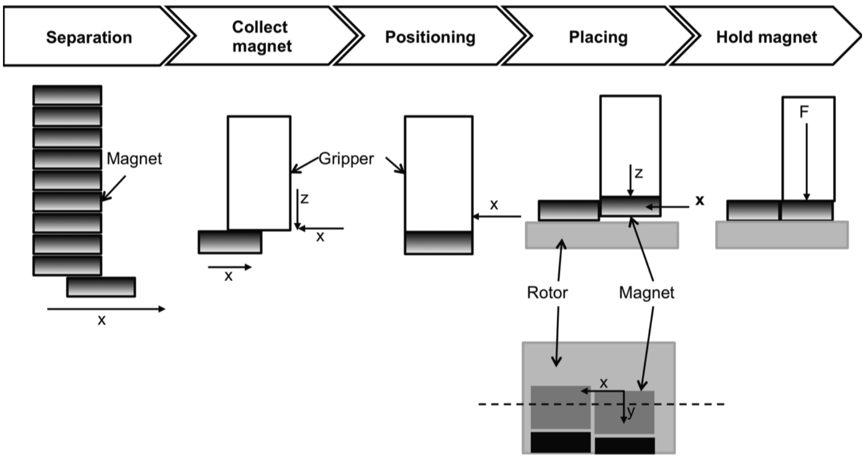


Fig. 41. The kinematic model can be derived from the five process steps for magnetized magnet assembly.

In theory, a movement only in X- and Z-direction should be sufficient, if all process components are placed directly center-line of the rotor. The gripper assures a spin-free transport of the magnet preventing an angular displacement by transversal forces. If magnet separators or semi-automatic gripper changing systems should be used, the additional Y-axis enables additional placing positions (as shown in Fig. 41). The pressure cylinder of the Z-axis applies the necessary holding force in the last step and releases the gripper from the magnet. Therefore the polarity of the unipolar gripper is changed automatically. During the assembly process, the worker activates the gripper with two knobs (e.g. known in press systems).

The magnet separation system consists also of a pneumatically actuated pressure cylinder moving the inset permanent magnet stack forth and back against a variant specific ferromagnetic cavity. With a simple add-on dosing unit, unwanted waste of glue can be significantly reduced and attached directly besides the gripping system. The glue can be directly applied before or after a placing process without releasing the gripper system and additional movements.

Depending on the rotor design, the angular placement of each magnet differs or must be reached exactly. For this reason, the rotary position is adjusted by a NC-controlled servo-axis combined with a high-resolution encoding system and a mechanical brake unloading the servo drive. The angular position is automatically set after each gripper release action or can be separately switched forth or back with a two-button foot switch. The final concept for the improved workplace is shown in the following Fig. 42.

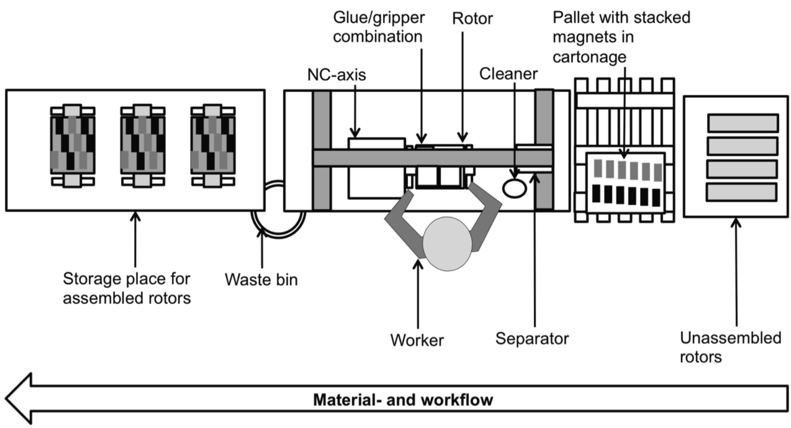


Fig. 42. The optimized layout substitutes several work steps and improves the process.

To show notably changes, the concept was also analyzed with the MTM-UAS system. The results are shown in Fig. 43. The test rotor conditions are the same. Even the long and material depending holding time for the permanent magnets (8896 TMU) has been taken over. With the new workflow, the total assembly time is notably reduced from 860,9 seconds down to 679,1 seconds. This equals a time reduction of around 22 percent.

Topic:	Magnet Assembly 2
Assembly:	Workplace with glue/ gripper combination
Comment:	Rotor variant 4 pole/ 16 magnets

Part / Work Pattern	Code	TMU	Quantity	Sum in TMU
Walk to pallete (1m)	KA	25	2	50
Bend down to palette	KB	60	2	120
Take magnet stack (8 pieces) out of cartonage	AG2	65	2	130
Place it on the table	PA2	20	2	40
Unpack	PZ	278	2	556
Collect packaging	AB2	45	2	90
Walk to bin (and back- each 1m)	KA	25	2	50
Throw away packaging	HB2	60	2	120
Take stack	AB1	30	2	60
Place stack in the separator	PC2	40	2	80
Walk aside (50 cm, one step - here for two magazines)	KA	25	2	50
Take gripper	HB2	60	2	120
Move to separator unit	ZA2	15	16	240
Visual control	VA	15	16	240
Place gripper	AB1	30	16	480
Collect magnet	AB2	45	16	720
Move gripper	ZC1	30	16	480
Place glue/gripper applicator exactly	PC1	30	16	480
Apply glue	ZC1	30	16	480
Visual control	VA	15	16	240
Place glue/gripper applicator exactly	PC1	30	16	480
Place magnet exactly on rotor	HC1	50	16	800
Hold and correct (process time depending on glue type)	PZ	556	16	8896
Take cleaner and equipment	AB2	45	16	720
Clean glue residue	ZC1	30	16	480
Put back cleaner	HB2	60	16	960
Sum				**17162**

Assembly time according to MTM-analysis	617,34	Sec.
Additional time in % **10**	61,73	
	679,07	
Assembly including extra time	**679,1**	Sec.

t / piece	Allowance %	Availability %	Pieces / h	Hours / Shift	Number of shifts day	Pieces / day	Work days/ year	Pieces / year
679,1	0,92	0,9	**4,4**	7,5	1	**32,9**	230	**7572**

Attention:
8 % Allowance means a value of "0.92" in the table !

Fig. 43. The improved workplace layout enables capacity potentials of 22 percent.

Material delivery is possible from behind the workplace. The unpacking of the magnet stacks is the same, the semi-automatic separation and presentation of the permanent magnet reduces process time as it is moved to ancillary time of the workplace. The handling system moves can now be directly addressed by the MTM-UAS move cycle commands (e.g. “ZA” for separator moves, “AB” command for placing). The exact alignment of the magnet is now simplified for the worker in practice.

The production capacity of the workplace is increased against the non-optimized layout by 35%. Adaptions for further variants are necessary for the gripper and the separation cavity, if e.g. the geometric form of the permanent magnet or the size changes. This can be realized with a gripper changing system and specific inlays for magnet variants. A prototype demonstrator of the workplace has been build up (Fig. 44). The mechanical design consists of linear guides in XYZ direction. The pre-adjustment of the Z-height (with offset) can be set with a spindle. To demonstrate the numerical control of the system, an open source LinuxCNC [85] is operating the servomotor and PLC program.

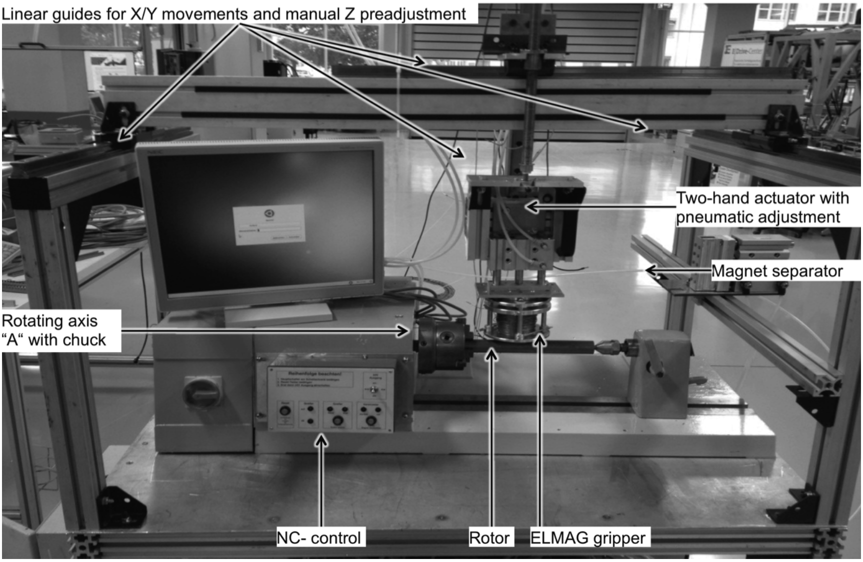


Fig. 44. The prototype demonstrator for SPM assembly

The magnet separator is constructed for cup-style NdFeB permanent magnets. The 24 V voltage bus supplies the electromechanical gripper and is also used for the servomotor. The holding force is pneumatically adjusted with a standard choke connected to the cylinder supply. The rotor itself can be manually clamped into a standard chuck ensuring high positioning accuracy and clamp force.

The mechanical parts of the workplace can be upgraded towards a semi-automatic respectively automatic workplace when necessary, to raise production capacity additionally. This can be realized by adding servo axes for the linear guide system and furthermore the integration into the existing CNC. Further developments include the integration of a sensor system for measuring holding forces or placing positions. These features improve the use for small shops reducing the barrier from manual to automated workplaces.

5.2 Workplace for placing magnets on outer rotors

Besides the assembly for inner rotors, offering a good accessibility during assembly, torque motor concepts (e.g. for small water mills) use SPM technology on the inner side of a rotor bell. This includes a high number of poles, which need to be set freely on the inner side. Fig. 45 shows a demonstrator model concept for a direct drive with customer specific pole counts.

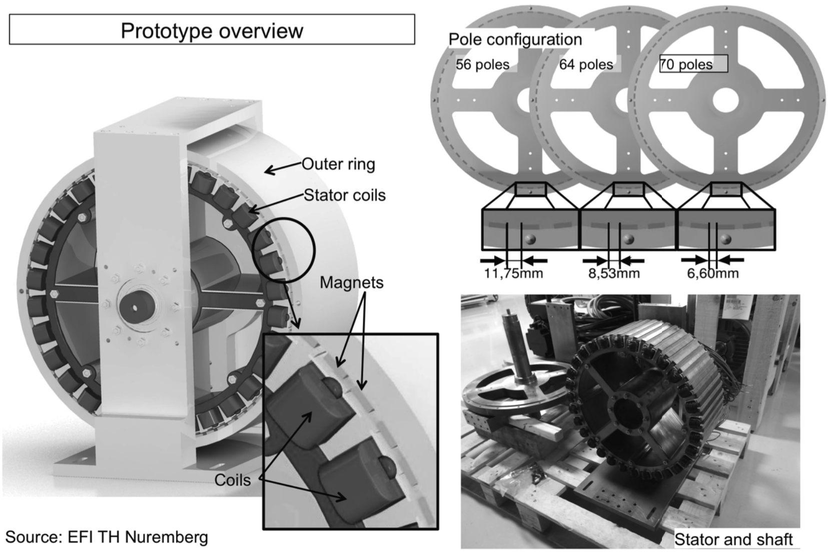


Fig. 45. The outer rotor of a prototype generator can be assembled with three pole configurations.

For the magnetic configuration, three settings are allowed, including 56, 64 or 70 poles. For the demonstrator, a distinct set of magnets has been provided to achieve the maximum pole count of 70 poles.

The outer runner needs to be assembled with magnetized permanent magnets, as it would be planned for small batch sizes. Furthermore, customer specific variants are planned, which should also be assembled on the workplace. For the workplace concept, an MTM UAS analysis has been developed for a rough concept of the workplace, including

- the ELMAG-3 gripper system
- an analysis of the assembly process workflow
- a manual handling device for separating and placing the magnet

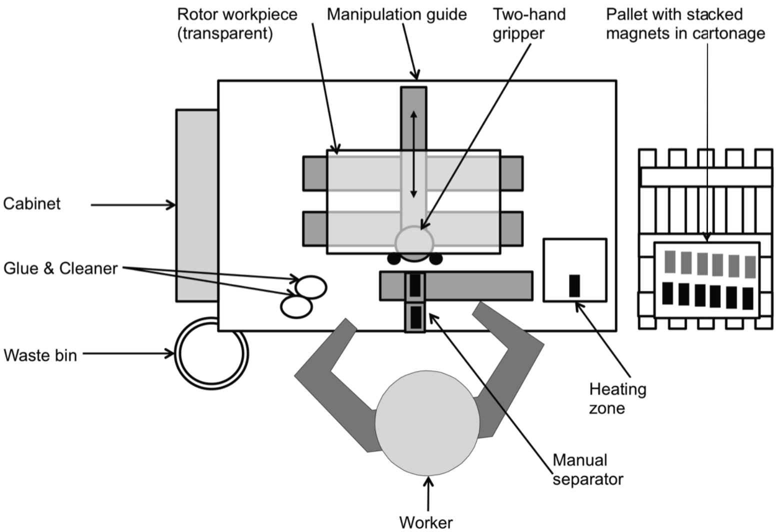


Fig. 46. MTM-UAS Analysis: Outer rotor fixture with ELMAG gripper system.

In Fig. 46 the workplace concept for the MTM evaluation is shown. The worker has all necessary equipment within his near gripping range. A control cabinet for the workplace (pneumatics, additional axes, PLC, heating system, dosing control, additional magnet check) is mounted at the side of the working table. The workpiece itself is too heavy for being lifted by the worker, so the manipulation guide can be loaded with a crane directly above the workplace fixture. The gripper is again equipped with a two-hand activation system and a control dashboard for adjusting the necessary polarity manually. The worker loads staples of magnetized magnets right in front into a manual or semi-automated separation unit. An additional improvement for curing the glue system is added by a heating zone, where every magnet is heated to a temperature of 60-80 °C. In case of manual dosing of the glue, the worker can place it on his left including the activator system.

In the next step, the workflow of the desired workplace has been determined. The workflow concept starts with an inserted rotor ring in the workplace fixture. The second step is a premounted pole adjustment ring. This fixation is only needed once at the beginning, so it is not taken into account for the assembly process.

As the correct magnet assembly is not possible without a fixture and the prototype rotor should be mounted, focus has been set on versatility towards variants. The resulting time for assembling 490 magnets for the 70-pole rotor has been calculated for 8 hours.

The time calculation includes the preparation and separation of the magnets as well as unpacking actions. The gripper ensures a hands-free operation of the magnet itself introducing significant improvements for placing quality and cleanliness of the glued parts. On the other hand the worker is able to handle even larger magnetized magnets easily to the assembly point.

Compared to the workplace that has been built up for inner rotors, a CNC axis for automatic positioning is left out to simplify the workplace design. Costs for wiring and an extra cabinet are therefore prevented. An MTM-calculation also has helped to ensure an easy workplace layout without unnecessary gripping lengths during the assembly process. Everything is centered around the rotor and easily achievable for the worker.

The longest time amount in the process is the curing time for the glue. Therefore the need for further investigations towards modern fixation systems is clearly shown and can influence the overall assembly time significantly.

The workplace is shown in Fig. 47. Similar to the linear guided workplace presented for inner rotors, the outer rotor concept incorporates as few automated parts as necessary to achieve an easy entry for manufacturers with low degrees of automation.

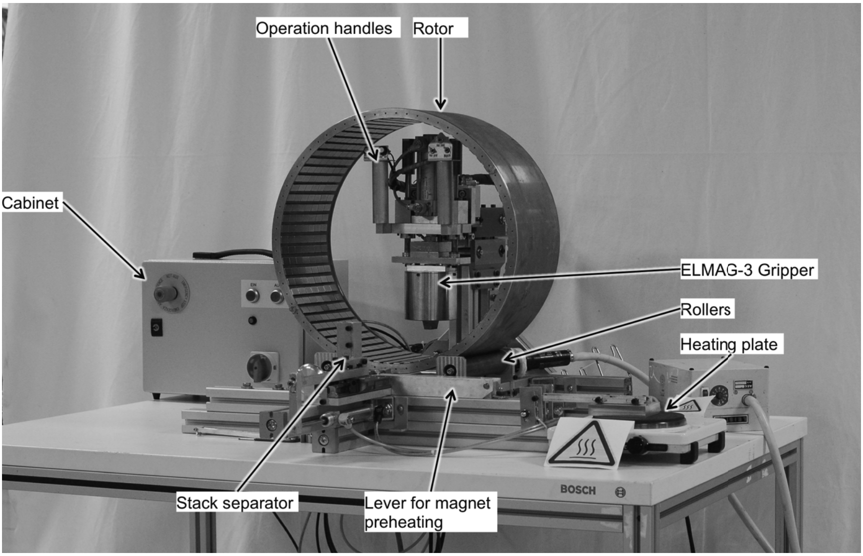


Fig. 47. The realization of the workplace for outer magnets incorporates an adapted ELMAG-3 gripper system.

The workplace is built up on a standard table and fits completely on a size of 160 x 80 centimeter. The rotor ring is placed on two rollers, which also support the right orientation of the pole. The magnet stacks are set in separately and directly in front of the worker. The process is implemented automatically with an actuated magazine if larger magnets are used, or even separated with a manual push/pull operation. The separated magnet can be transported with a lever onto a heating plate placed on the right.

Therefore the lever can leave the separated magnet and can therefore take back another already heated magnet back. With the two handles the worker pulls the placing unit out of the rotor to the take-away position, activates the gripper and carries the magnet with the gripper into the ring back to the assembly position. The gripper itself ensures a zero skewed transport of the magnet until it is placed and cured.

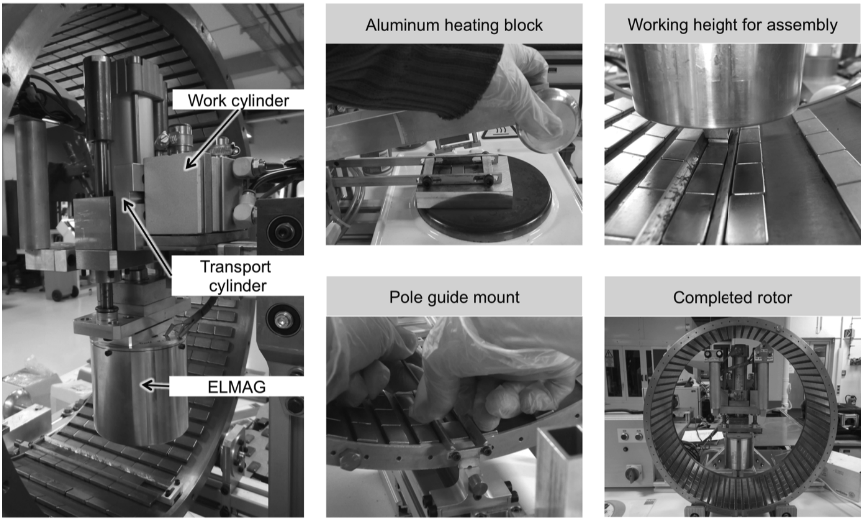


Fig. 48. Fixture details for the assembly process with the workplace for the outer rotor.

Attention has been given to the two stages of the pneumatic system (see Fig. 48). Two cascaded pneumatic cylinders are involved in the assembly process: The first is the transporting cylinder for rough movements in the work area (gripper lift height > magnet height). This cylinder is set to leave a minimum residual distance to the rotor, if a magnet is attached to the gripper. 0,2 mm distance has shown good results and save operation in the assembly area. The second work cylinder is additionally connected between the workplace frame and the transport cylinder, lifting or pushing the gripping system up and down. The work cylinder compensates the missing residual distance. Compared to a fully manual assembly it replaces the manual operation of the worker to hold the magnet and presses the magnet onto the rotor surface until the glue is cured enough to hold the magnet.

During the assembly tests with the real workplace and the prototype rotor, the workplace concept has been validated. The results of the MTM-UAS analysis and observation times fitted nearly completely. The flexibility of the workplace enables additionally variants of the prototype (e.g. changes in ring geometry, magnet heights and sizes, pole counts) rotor without a change of the workplace at all. The only necessary change is the adaption of the gripper tool contacting the magnet surface: If the shape of the magnet surface changes, a suited tool needs to be mounted.

5.3 Summary

In this chapter, flexible workplace approaches for placing permanent magnets have been shown. For low to medium batch size production, the presented systems can help to raise production capacity and product quality of magnet assembly, where fully automated production cell concepts fail to work.

By using the well-established MTM-UAS system, main production processes and differences between concepts can be reviewed neutrally. In the case of the assembly of magnetized permanent magnets, it is possible to build the bridge between manual and automated production by implementing a scalable system.

In the realized prototype demonstrator system for inner and outer rotors incorporating a new gripper system (the ELMAG), all necessary and suggested components are set up fulfilling the requirements for flexible production of variant types with minor setting up changes. A magnet separation system and the innovative electromechanical gripper system as well as a simple NC system permit a remarkable increase in production capability. Furthermore, scalability of the system is ensured by developing the workplace concept and enables further development with the reverse approach by using an upgradable manual workplace.

6 Solutions for Inserting Magnets in IPM- Rotor Designs

The IPM design of electric motors is in focus of motor producers for the last years. Magnetic excitation is also realized by permanent magnets but compared to traditional surface mounted application the magnet material is inserted into slot cavities. For achieving an electromagnetic optimized design, the assembly of one permanent magnet pole is a discrete magnet system consisting of several single magnets stacked together. Compared to one magnet/ one pole configurations, the splitting of the pole into several sub-magnets prevents eddy currents induced in magnets. Contrary the planner of the assembly workspace or line wants to use as few parts as possible to achieve a short assembly time. An optimized production solution is supported by one single shaped magnet for each pole.

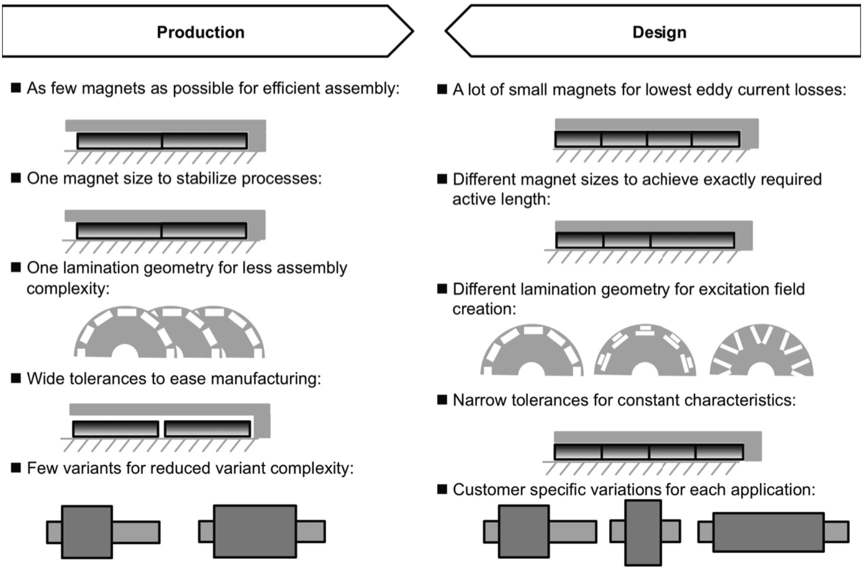


Fig. 49. Production and design require contrary strategies for electric motor composition.

The main differences between motor designers and production planners are given in Fig. 49: The number of various shapes and optimized magnet flux guidance leads to altered parts. Assembly structures vary within the production cycle for the lamination stack.

6.1 Rotors with IPM-design offer enhanced magnetic circuit designs.

For today's high-energy permanent magnet motors, not only surface mounted permanent magnets are used. Permanent magnet exited motors with buried, interior or internal magnets show several characteristics, which are required for e-mobility concepts.

This design inhibits several advantages compared to the surface mount method:

- Round rotor shape and therefore smaller air-gaps are possible
- Electromagnetic overload of magnet during operation possible, e.g. for boost function
- Rotor assembly has good mechanical stability
- Use of reluctance moment
- Motor designs with less magnet material, but higher local power density possible compared to SPM-motors
- More magnet material per pole and therefore higher power density possible compared to SPM-motors (stacked magnet versions, see Fig. 50)

Contrary to SPM rotors, the steel lamination stack determines the outer shape of the rotor for IPM motors. Therefore a complete round shape rotor with small air gap can be designed, which is technically hard to realize with surface mounting technology types because of tolerances within the magnet and the fixation with reinforcing fiber-tape.

The magnetic field is slightly influenced by the surrounding steel of the lamination stack causing small flux leakage. If a magnetic field occurs, which is higher than specified (e.g. a short cycle overload of the motor), the magnet is better protected. The surrounding steel lamination stack has an important function for motor maintenance, as it also protects the brittle magnet material when the rotor is pulled out of the stator.

With buried magnets, the reluctance moment can also be used for expanding the working range with less magnetic material compared to surface mounted motors. The permanent magnet field can furthermore be focused for each pole by stacking the magnet material above each other. Compared to SPM-designs, the magnet field can be increased with higher flux density. Regarding the air gap and the available space, an IPM motor can hold up more magnet material per pole, as it is using the lamination core additionally. These aspects lead to a steady development for this type of motor.

The round outer diameter of the lamination stack is creating a more perfect rotor form, than the on-wound fiber for fixation. As the core lamination space between outer rotor diameter and shaft is unused, more permanent magnet material can be integrated than in surface mounted designs. Therefore, the coercive field strength between stator and rotor pole can be locally increased and the reluctance effect be used.

6.2 Basic IPM rotor configurations

Typical IPM motor designs can be structured in four manufacturing concepts, as shown in Fig. 50. The IPM rotor is assembled with magnets of the same size, or with two or more differing sizes for advanced generation of the magnetic flux. Strategies for assembly and handling need to be changed regarding pick and place paths and increasing complexity. Four scenarios for magnet assembly geometries are possible and divided into assembly with magnets of same or differing sizes and straight or angular positioning of the magnet:

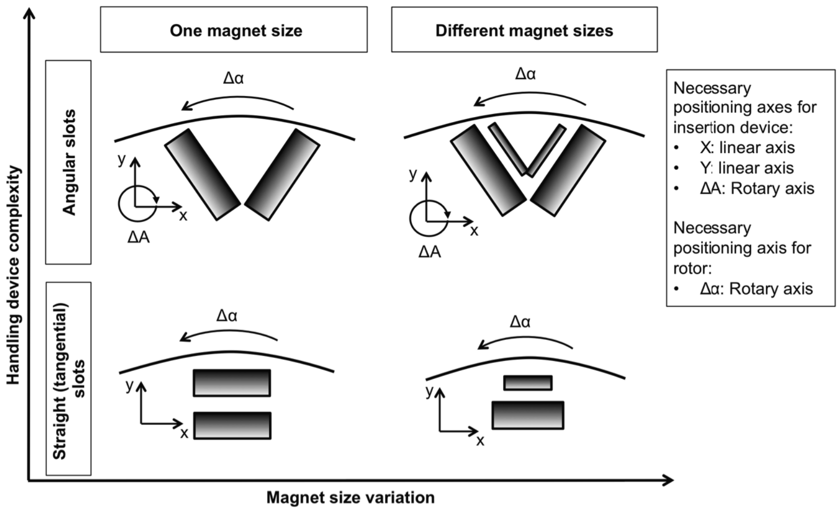


Fig. 50. IPM rotor - magnet configurations and the necessary axes-configuration

Straight slots/ same size: In this case the magnet has to be built into the lamination stack facing outwards perpendicular to the radial center point (= tangential to the outer surface). The slots have the same size, so only one gripper or handling fixture is needed to insert the magnets. If the rotor lamination stack is rotated, then only one linear movement is necessary to position the handling device. A simpler assembly variant is the use of only one magnet slot per pole. This reduces the Cartesian positioning of the slot to only one position.

Straight slots/ different size: A slightly changed layout of the sheet shows two magnet slots, requiring sets of magnets at the same time, or sequentially one size first after each other by changing the fixture or inset of two parallel grippers.

Angular slots/ same size: The magnet position can also be arranged in a “V”-form to achieve a higher flux concentration in the rotor. The handling devices for inserting the magnets have to be individually positioned four times. If one handling device for placing all magnets is used, a free gantry space kinematic with additional rotating axis is necessary.

Angular slots/ different size: The most complex assembly design incorporates at least two or more sizes of permanent magnets in combination with positions in “V”-form. For this purpose a single fixture with a fixed matrix can be used to insert the magnets all at once or in several distinct stages. A flexible solution can be made of a gantry style or robotic handling device combined with sensor integration for the detection of the slot cavities.

6.3 A pattern recognition algorithm for rotor cavities

An important assembly step for placing magnets in the lamination stack is the knowledge of the exact assembly position. Deviations in the magnet cavity depend on the geometric magnet quality and designed around 0,2 mm to ensure a safe magnet insertion process. In combination with chemical fixation (e.g. adhesives, epoxy) the remaining gaps are filled. For traditional prototyping and low batch size productions, fixtures with narrow tolerances are provided and the worker compensates the deviations by iterated balancing during fixture preparation.

For detection of an empty cavity, two ways of in process recognition are possible:

- Tactile measurement with mechanical instruments
- Non-tactile measurements regarding optical and ferromagnetic active-methods (inductive sensors)

Tactile measurements require a numerical controlled approaching process that additionally adds onto the total assembly time. Direct contacting of the workpiece can lead to damages of the workpiece, so precautions towards maximum allowed contact force and mechanical locking need to be taken into account for this solution. Possible sensors are e.g. mechanical probe sensors for distance detection to the lamination stack or variant specific piston elements fixing the workpiece in a defined position.

For non-tactile measurement methods mechanical locking can be prevented. Possible sensor principles are inductive or optical sensors. Inductive sensors have a distinct switching distance, so e.g. the sensor can be used as probing instrument, while the rotor is turned mechanically, until a cavity has been detected. As the detection must be set customer specific, the system needs to be recalibrated for every variant.

Optical systems promise the best approach:

- No need for direct mechanical contact, so the sensor can be placed at distance
- Large possible sensor area
- Various extraction of characteristics for fault detection possible
- Differing and complex shapes can be recognized and computed.

For the planned workplace implementations, the following workflow for implementing a visual cavity detection sensor has been developed:

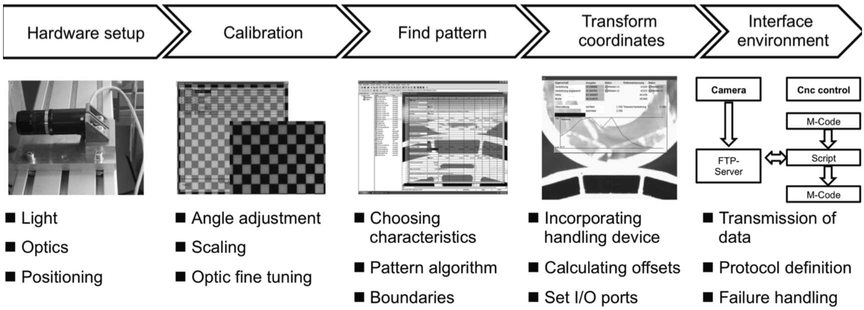


Fig. 51. The method for implementation of the cavity detection takes five steps.

As shown in Fig. 51, the implementation is divided into subdivisions. First of all, the camera system has been chosen as an intelligent system with an own image processing stage [86]. The hardware setup of the camera includes the selection of the right illumination for the lamination specimen, as well as the mechanical fixation position in the handling system. Involving varying focus lengths, the distance to the rotor lamination object compared to the achieved image section can be varied. After hardware setup, the calibration of the object is most important for correct scaling factors. The image is repeatedly fine-tuned avoiding additional angle disposition. The optics system is set perpendicular to the lamination stack surface.

Programming and implementing the vision algorithm is accomplished within the sensor software “InSight” of the inset camera system of Cognex. It starts by choosing the visual characteristics of the specimen. The program should not only detect the cavity itself, but also decide, which cavity is the correct one, detect additional failures (lamination stack failures) or even detect workpiece identification codes to set the correct program. The pattern algorithm for detecting the pattern of the cavity can be as described next:

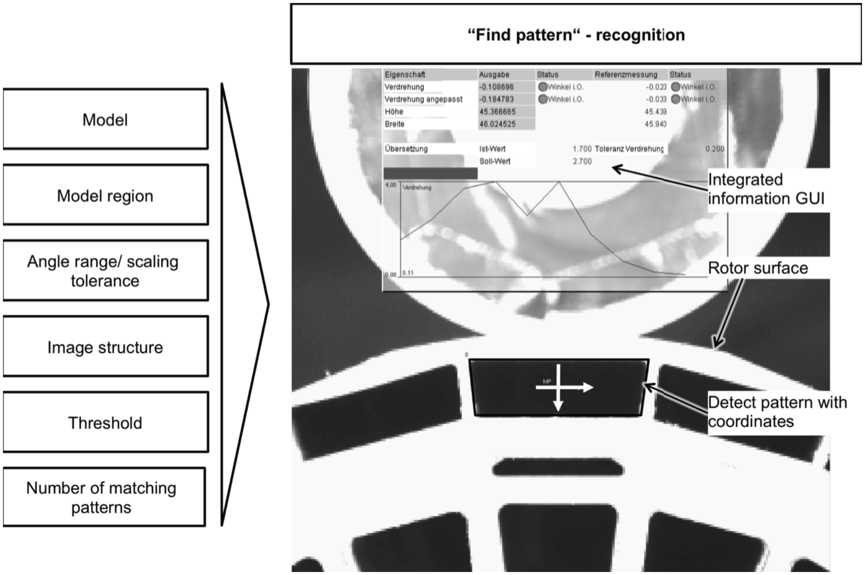


Fig. 52. *Finding the right pattern for cavity detection incorporates pattern characteristic features.*

The settings of the "Model"-parameter specify training parameters and an area of pixels should be detected. The "model region"- parameter excludes parts of the picture, which are known to show non-relevant information by omitting these parts during calculation. The parameter "angle range" determines the +/- tolerance to a rotation of the measured rotor object. For non-compromised and fast detection, the angular displacement should be chosen between 0 and 90 degrees. The parameter "scale tolerance" reacts on changes in pattern scale due to lights changes or geometric tolerances. The "image structure" function sets the coarseness of the recognized pattern (e.g. in number of pixels) to avoid unstable pattern examination. With minimum and maximum "threshold" parameters the camera can decide, which kind of pattern should be investigated and which can be left over. Finally, the "number of matching patterns" tells the camera, when to stop the detection algorithm (see Fig. 52).

Connection to the machine or robot controller is achieved by establishing a FTP transfer protocol writing actual displacements into a text file. From there the iterative robot program calls a script loop reading out the values and integrating the coordinates into calculation of the movement process.

The transformation result of the calculated angular displacements is converted into degrees and millimeters and can be used by the handling device in two ways:

- Direct approaching the cavity and placing the magnet with direct implementation of the camera head at the placing system
- Iterative detection of optimal position by consecutive movements with the camera mounted indirectly besides the handling system.

Both methods have been implemented in stations for inserting magnets with a scara robot gripper system and an assembly station for inserting permanent magnets for larger rotor sizes (see Chapter 6.5).

6.4 A concatenated automated IPM production line

Depending on the design of IPM motors, the functional magnetic field of an IPM rotor can be achieved in three possible scenarios:

- Magnetizing the whole rotor after assembly
- Magnetizing single permanent magnets before assembly
- Supplying ready-for-installation magnets

The first scenario is to insert unmagnetized permanent magnets into the slot cavities followed by fixation of the magnets. Magnetizing can then be arranged at an assembly stage, where it does not affect other assembly steps such as balancing (the magnetic field can attract chips resulting from automated negative balancing due to drilling or milling) or the additional assembly of surrounding parts (the worker/ the machine needs shielding). Also curing of magnet fixation must be regarded, if chemical (e.g. glue or epoxy resin) is used. The magnetizing step is inserted at the end of the line, just before the rotor is set into the stator housing. This method requires nevertheless a huge capacity of magnetizing equipment including large toolsets for saturating the permanent magnet material with one or several magnetizing shots.

In the second scenario the magnets are supplied unmagnetized and magnetizing is done directly in production. Therefore the permanent magnet can be supplied directly without precautions to the line, e.g. in standard packaging. As the magnet has no magnetization yet, contamination with ferromagnetic particles is prevented and the magnetization step is postponed until the magnet is directly assembled. For preparation and separation of each magnet automated vibratory spiral conveyors or standard magazines for permanent machine feeding can be used.Tab. 5 lists the characteristics for the three mentioned scenarios. The integration of the magnetizing equipment influences the cycle time of the assembly station.

Tab. 5. Advantages and disadvantages of the three assembly scenarios for IPM magnet assembly

Magnetizing the whole rotor after assembly	
+ Easy integration into production line + Perfect for mass production of large batch sizes + Does not affect other rotor assembly steps + Shortest cycle time	- Expensive toolset - Difficult in case of saturation effects in the rotor during magnetizing - Cross-magnetization of already magnetized areas
Magnetizing single permanent magnets before assembly	
+ Smaller magnetizing equipment + Parallelizing process steps for magnetizing and magnet assembly + Faster magnetizing cycles by lower power requirements + Simplified tool shape + Flexible tooling, e.g. for different magnet sizes + Full control of magnetizing parameters + Building knowledge and know-how of magnetizing and magnetism + Good automated documentation possibility	- Medium cycle time for supplying one magnetized magnet - Complex implementation of equipment inline - Fixation process requires adjustment (e.g. curing time) - Additional (parallel) process station - Complicated automated assembly due to unpredictable field recognition
Supplying ready-for-installation magnets	
+ No additional expenses necessary for production equipment (magnetizing tools) + Magnet shape variants can be used without necessity of magnetizing tools. + Fast method for prototyping – no extra time for equipment establishing	- Danger of magnet contamination with dirt - Additional costs for unpacking and magnet preparation at the workplace - Process is only recommended for experienced workers. - Additional health and safety procedures in workstation necessary - Danger of magnetic material/ magnetic parts handling - Complicated assembly due to unpredictable field recognition/ repulsation of magnets out of the cavity

The third scenario is to order already magnetized magnets from the supplier. This process variant is used for small prototype series or small companies with high variants and high requirements towards magnetizing direction. The material needs to be unpacked and due to the high attracting forces between the magnets in stacks, the packaging needs to shield the environment against the magnetic fields. Additional ferromagnetic slides and padding layers are necessary and degrade the useful transport volume of magnet per package. Also, extra expense is needed for unpacking of the magnet material including the separation of single magnets. If spacers are used, the magnet to packaging volume ratio is below 0,4. The packaging includes then the spacers, which are (nearly) the same sizes as the magnet, the packaging for one stack, insulation material and the carton transport packaging.

6.5 A robot assembly station demonstrator for IPM magnets

A gripper prototype has been successfully built up for flexible mounting of magnets in rotor lamination stacks (Fig. 53). The IPM-1 demonstrator combines a vision system for fast detection of various cavity designs. With a new developed vision algorithm, the cavities are recognized automatically. The system is combined with a SCARA system reaching a large workspace covering a broad variety of rotor diameters. An exact fixation of the rotor lamination stack is not necessary, as the vision algorithm enables the automatic calculation of a motion compensation for the robot, which is then able to adjust accordingly.

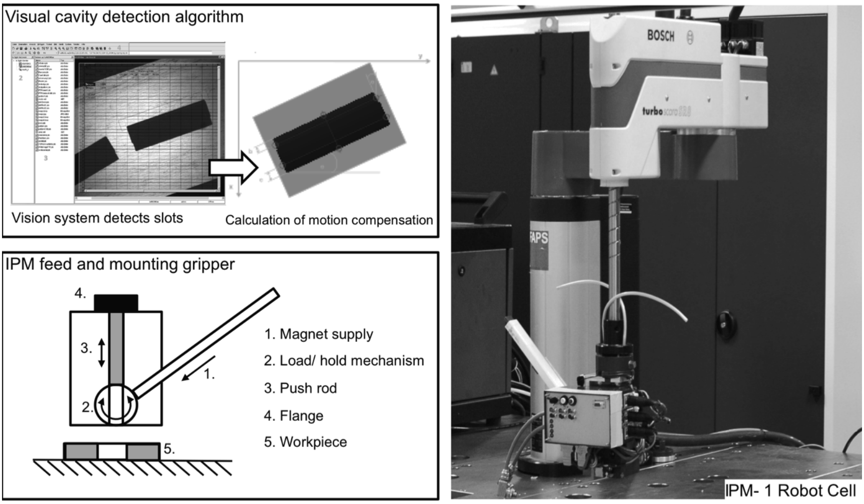


Fig. 53. For precise magnet mounting, a rotating magnet placing system is combined with visual cavity detection.

The work cell is loaded with lamination cores, e.g. on a standard workpiece carrier (Fig. 54). The presented camera system for cavity detection is mounted on the handling device and detects the incoming lamination stack orientation. In a second step, unmagnetized magnets are loaded via the magnet supply shown in Fig. 54. The gripper loads the magnet from the side by turning the load and holding mechanism. To avoid the magnet body falling out of the gripper, it is held by a piston until the gripper is placed properly over a detected cavity. The push rod is actuated by an electric motor and sets the magnet fully into the cavity.

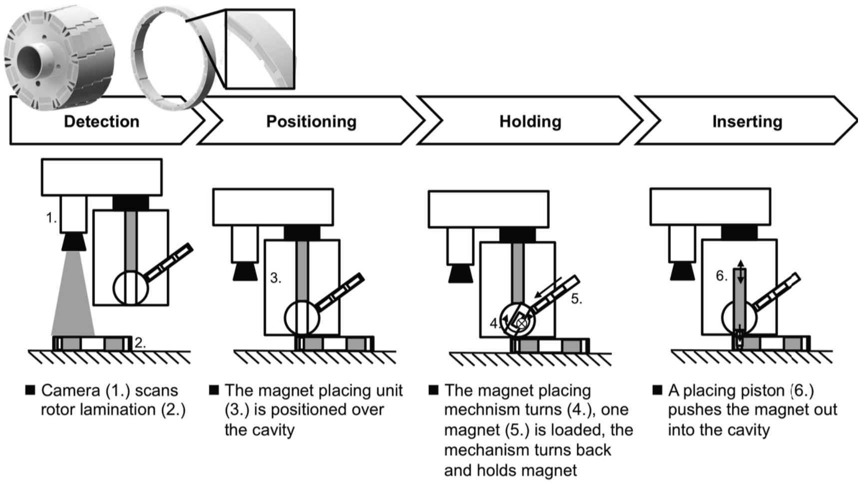


Fig. 54. The IPM feeding gripper sets permanent magnets freely programmable into lamination stack cavities.

The cell is suited for industrial automated production of prototypes and small batch sizes, as the robot program is easily reconfigurable for variants with changed pole and lamination stack types. The SCARA system can be easily integrated into manual fed or automated transport paths. Therefore the lamination stacks need to be fixed on a work piece carrier, ensuring defined delivery and an indexing possibility.

The gripper has been tested with unmagnetized magnet bodies and can be modified for inserting magnetized magnets, as this workflow is used for manufacturing skewed lamination stack type rotors or small rotor rings integrated into traction systems with larger diameter.

For rotors with straight cavities and an active length excessing the length of one permanent magnet body, the presented method with the placing gripper will not work, as additional friction between lamination stack and permanent magnet is recommending higher insertion forces. If the magnet body is magnetized and adds a reluctance effect between lamination stack and magnet, unwanted forces increase further.

This type of rotor, needed for larger drives, can be completed by two assembly strategies (Fig. 55):

1. Inserting each permanent magnet body and pushing it through the lamination stack to the final position
2. Inserting one magnet after another and pushing the magnet row until the opening of the cavity

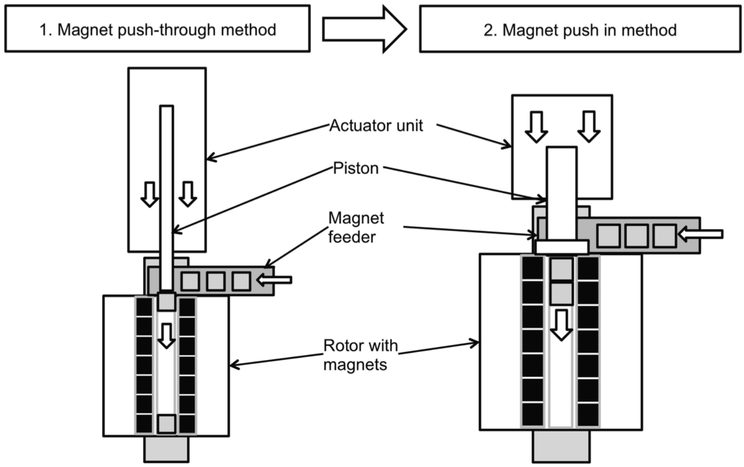


Fig. 55. Changing from pushing the magnet-through to push-in assembly improves the magnet insertion method.

The first method, pushing the magnet into its final position, requires a tool piston with the required length of at least the active length and the length for the necessary magnet feeder. The piston needs to fit into the cavity to push the magnet until the end of the lamination stack, so the mechanical stiffness is critical. As the piston stays in nearly direct contact with the core lamination, friction between piston and lamination stack can appear, if the rotor is not adequate aligned with the piston and causes then quick wear of the piston material. And at least, the piston has high travel paths to insert each magnet to its final position, increasing assembly time.

Assembly time can be improved by anticipating the push through process towards a push-in of the magnet. The magnet is therefore inserted until it is fully covered by the edge of the lamination stack. The following magnet is then positioned before the cavity and pushes all already inserted magnets one position further into the rotor. The main difference to the push-through method is the increasing insertion force of all magnets in the cavity. Contrary, the piston only needs to travel the length of one magnet back and saves therefore time. The piston diameter can be chosen larger, because it does not need to fit into the lamination stack. The assembly path is shorter and the piston itself not exposed to possible friction-wear.

For these processes, the evaluation of assembly force is important for determining the needed strength of the handling device. With a sample rotor lamination stack, the necessary process force for inserting the magnets has been measured. Fig. 56 shows the resulting forces. The first magnets show almost zero force, because they are “soaked” into the lamination core, as the magnets want to close the magnetic circuit. In the evaluation the first four magnets have shown this behavior, force has to be applied starting with the fifth magnet. For the evaluation, 30 magnets have been consecutively pressed into a test lamination stack with standard tolerances used in traditional manual assembly. The length of the lamination stack for the test has been 600 mm. With more than 15 magnets in a row the magnets sometimes catch in fine tolerances between the lamination sheets, therefore the force varies.

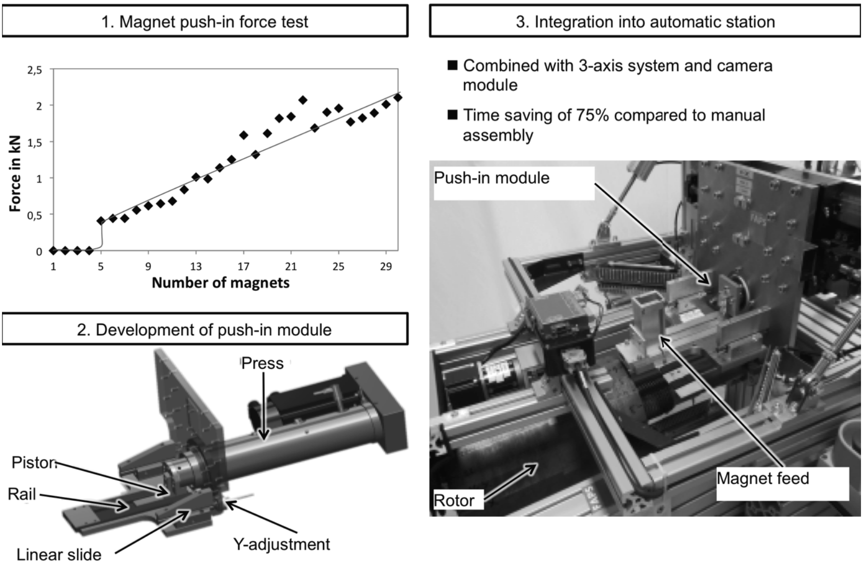


Fig. 56. The push-in force has been measured for the development of an automatic IPM rotor assembly station.

A calculation of the forces is difficult, as the permanent magnet is attracted to both sides of the lamination stacks. During the insertion of the magnet, it can change its attraction state from the contact surface towards the rotor shaft (lower cavity contact surface) to the outer shape (higher cavity contact surface). Additionally, the single magnets push each other in the cavity (during the assembly process without fixation) because of the superposing magnetic fields of each magnet. A simulation based calculation regarding the model of the attraction force of a single permanent magnet and the lamination stack has not been established yet. In this case the model must contain a multi-physical model regarding mechanical friction between permanent magnet, the lamination stack and magnetic attraction forces between each magnet as well as with the surrounding metal sheets of the lamination stacks

Compared to the gripper for inserting only one magnet into the lamination stack, the assembly piston for pushing-in several permanent magnets requires higher stiffness and strength. The concept has been developed and built-up as an automatic station for magnet assembly of larger IPM rotors. Contrary to the traditional manual induced push-through manufacturing method a reduction of 75 % assembly time has been achieved within a complete automatic process [87].

6.6 Summary

In this chapter, technologies for IPM assembly have been presented. Starting with basic design characteristics for determining the right handling axes and devices. For automatic positioning with a robot, the coordinate positions of the cavity must be defined. A cavity detection algorithm has been presented and implemented. The permanent magnets need to be fed into the cavity; therefore an IPM gripper system concept has been developed. As complete system, the cavity detection algorithm and the IPM gripper are combined with a SCARA handling system. A second solution is presented for larger rotors. For this assembly, a press module is linked with a Cartesian positioning device.

7 Measuring Magnetic Fields of Permanent Magnets in Production

Apart from the assembly process, a raising demand for magnet quality control is necessary, to ensure product functionality and constant quality output. As rotor production quantities are increasing, cycle times need to be shortened and customers demanding full traceability of each component of the product.

Several faults appear during the lifespan of the magnet from production until motor failure during operation [88]. Starting with delivery at the factory and initial magnetization, the safe transport of the magnet needs to be supervised. Measuring the magnetic fields in the supply chain inside the assembly is another application field for evaluations. After assembly of the magnetic material and the fixation thereof, knowledge of the resulting field is necessary for detecting deviations in supply and assembly processes. For larger generators in small to large size power plants also maintenance purposes are becoming important requiring periodic surveillance checks of the rotor magnet field during maintenance cycles.

Standards for hard magnetic material testing are based on qualifying single permanent magnets within custom made measurement devices for full material characterization. The IEC 60404-8.1 is the worldwide standard for testing permanent magnets.

Tab. 6. International magnet qualification

ASTM A977	Standard Test Method for Magnetic Properties of High-Coercivity Permanent Magnet Materials Using Hysteresisgraphs.
IEC 60404-5	Permanent Magnet (Magnetically -Hard) Materials - Methods of Measurement of Magnetic Properties.
IEC 60404-7	Methods of Measurement of the Coercivity of Magnetic Materials in an Open Magnetic Circuit.
IEC 60404-8-1	Specifications for Individual Materials. Section One - Standard Specifications for Magnetically Hard Materials.

Testing of the magnetic fields also characterizes the manufacturing methods. If one process is running out of the specified parameters, the resulting magnetic field is not reaching the designed optimum. Another quality criterion is the change of suppliers to optimize the product or supply strategy. Measurements and checks of the magnetic field support therefore a constant production quality observing material mixes and material deviations.

The permanent magnet part of the motor is subject of changes during the further development of a product, so testing applications for production need to keep pace:

- Magnetic poles built together from separate magnets can be replaced by a single sinter part and is magnetized multipolar
- The permanent magnet size is changed towards larger or smaller fractions of the original magnet size
- The permanent magnet form can be changed (e.g. from bread style to round arc style)
- Change magnet material, including material formula (e.g. composition) or even a shift in materials (e.g. from SmCo to NdFeB)

Challenging requirements towards measurement of permanent magnets arise, if the rotor is not manufactured at the same manufacturing site as the stator, or if the supply form changes from supplier to in-house magnetizing. Influences of manufacturing and fixation methods on the quality of the resulting permanent magnet field must be evaluated regarding the resulting field propagation. Sintered magnets can vary in geometric tolerances and magnetic properties between batches, so the design specs must be checked continuously for constant magnetic field properties during manufacturing. And at least the magnetic components must be tracked from production to the finished product. Traditional methods for magnet checks include therefore:

- Polarity checks before and after magnet assembly
- Geometry check for correct size
- Visual checks for material cracks (e.g. broken magnets) or defects in the coating (e.g. scratches, right thickness of coating, right color)
- Screening and evaluating of magnet suppliers before start of production with lab techniques (determining hysteresis loop, flux density magnetizing/ demagnetizing)
- End of line testing of motor performance when totally assembled
- Mandating the magnet supplier for certification and checks for customer specifications (size, form, magnetization).

Furthermore the measurement methods have to fulfill not only laboratory requirements while accompanying the manufacturing process [89]. Automated processes demand inline measurement cycles within seconds for an entire qualification of processes and products. The following chapter represents concepts for measuring permanent magnet characteristics parallel to or inline in rotor productions.

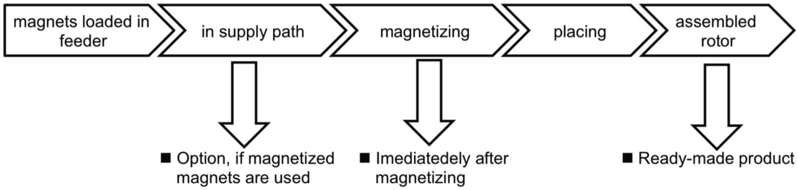


Fig. 57. Magnet checks can be integrated into three positions of the production line.

For a production workplace there are three distinct process steps for magnet checks possible (see Fig. 57). The insertion of magnets into the feeding or gripper system can be observed. The supply path, the whole process of providing the magnet to the workplace, can be monitored after unpacking and enables checks for single magnets. For unmagnetized magnets the process step of magnetizing is a proper way to check for magnetic characteristics. And finally for both supply strategies (magnetized/ unmagnetized); the magnetic field check at the end of line gives an opportunity to test magnetic properties.

Therefore the following chapters show realized solutions for workplaces with new types of measurement sensors to expand inline-testing capabilities. The first two evaluations have been done with a two-dimensional hall sensor array and a magneto-optical system. Two innovative line hall arrays, the “LINMAG-1” and “LINMAG-2”, for permanent magnet and rotor inspection enable new testing strategies. Sensor systems need to be positioned along exact movement paths including robots and programming. The concepts and developments for testing kinematics are also shown starting with linear systems up to complex 6-axis robotic motion systems.

7.1 Magnetic field detection and measurement categories

Production magnetic field measurements of single magnets or a resulting field of a rotor can be arranged depending on the necessary information (Fig. 58). The simplest evaluation of ferrous parts is the detection of magnetism. Standard automation grippers or custom fixtures are not primary designed for dedicated use with magnetic parts, or it interferes with the magnetic part and distorts the measurement. The relevant equipment can be tested for magnetic influence. Each manufacturing site provides standard equipment for rough detections of magnetism and polarity, in most cases by manual guided test equipment [90].

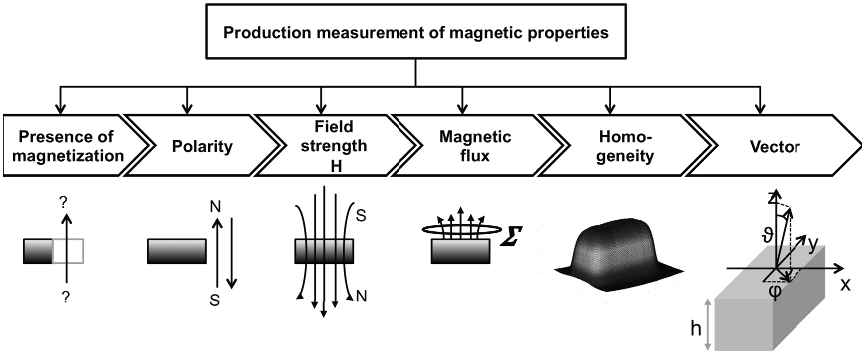


Fig. 58. The measurement of magnetic properties is split up on the wanted characteristics.

Performing a polarity check is one of the simplest checks in assembly lines. For larger rotors this check is performed to ensure the right polarity among magnets belonging to one pole. For SPM-style rotors, even a repair of faulty assembled magnets is possible, whereas for IPM-style magnets wrong polarities lead to a replacement of the whole rotor.

Measuring field strength and flux density involves more elaborate testing equipment with sensors and profiling equipment. Characteristic values represent the polarity of the magnet and the right amount of magnetization. The stray field of the rotor can also be evaluated. For correct field detection, the measurement positions need to be declared, measurement equipment installed and a routine for automatic database storage of all necessary values established.

The homogeneity of the magnetic field involves correlation and representation tools for automatic detection of the assembled field. These examinations can also be used as feedback loop for motor designers. For manual inspections the worker is able to imagine the invisible field components in a way to judge the quality of the assembly work.

Beyond the physical detection of magnetic values, characterization by analyzing coherent data points is the most sophisticated area of magnetic measurements. Compared to the development of optical vision sensors and the combination thereof, magnetic testing can also determine magnetization vectors or exact positions of multipolar-magnetized materials (e.g. encoder magnets) with highly developed algorithms.

The detection and calculation of magnetization vectors for single magnets or bulks of assembled magnets creates advanced measurements for magnet characteristics for both manufacturing as well rotor designers.

7.2 Near field and far field measurements

For time varying electromagnetic fields, a near and far field region can be defined. Distances larger than $\lambda/2\pi$ (λ is wavelength) are considered as far field, distances smaller as near field. A distinct difference between near and far field measurements of permanent magnets is not described yet. A main distinction between measurement methods must be made with sensors placed as close as possible (near field) or distant to the source of a magnetic field e.g. the permanent magnet. In the near field measurement configuration, local characteristics of a permanent magnet or several magnets can be evaluated. For rare earth permanent magnets, the measured field intensity reaches several hundred Millitesla. This is the typical application for hall sensors, opto-magnetic sensors or field coils [91], [92], [93]. Very sensitive anisotropic magneto-resistance (AMR) and giant magneto-resistance (GMR) sensor probes get saturated in this constellation, but can be used, if prerequisites are kept regarding the maximum field density for measurement [94]. Coil measurements are used with integrators, where the sum flux of the complete rotor can be measured [95], [96].

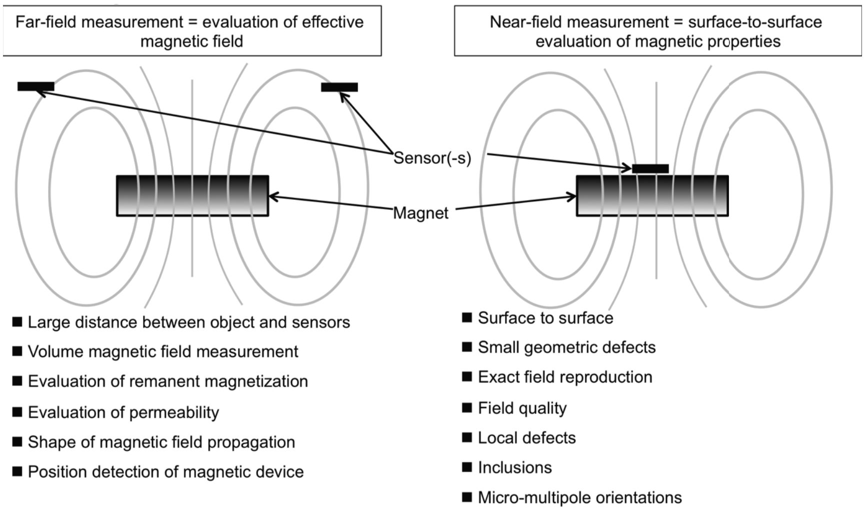


Fig. 59. A difference can be made between near- and far-field measurement of magnetic fields.

The definition for near- and far-field measurements is not set by definite values in literature (Fig. 59). The two terms are distinguished as evaluation of the effective magnetic field (far-field) and a close surface-to-surface measurement for evaluation of explicit magnetic properties at a distinct position. Far field measurements are used to determine the characteristics of the magnetic system from a distance. As magnetic fields sum up and overlay each other, a resulting vector field is measured. The result is used to determine e.g. the position of the magnet or the direction of the magnetic field. The measured field strengths are low. Therefore very sensitive AMR and GMR sensors are used [97].

Near field measurements (called: surface-to-surface measurement) are taken directly as close as possible at the specimen. The field strengths are much higher and saturate sensitive sensors easily. For these applications hall sensors and integrating induction methods are used.

Advantages of far field measurements:

- the possibility to determine the magnetic characteristics of large magnetic designs at once (e.g. main magnetization direction vector).
- a safe distance from the specimen during the test

Whereas near-field testing offers

- exact magnetic field values at predefined locations on the object
- predictable test conditions with specimen interaction
- precise localization of values possible (e.g. field strength of single magnet)

Near field measurements provide deepest insights into the active field of the permanent magnet. Therefore requirements for near field measurements have to be defined for production lines. The magnet is measured in an open loop circuit. This means its magnetic field is not closed when tested in the supply path or assembled on the rotor surface. So the typical flux densities on the magnet surface are between ±250 mT to ±450 mT. The geometry of the magnet is either a block or arc type magnet. The kinematic for measuring on the surface must be able to test perpendicular to the surface. Furthermore, active lengths and cycle times demand high integration of sensors into PLC and kinematic programs to achieve fast sensor readouts.

7.3 Measuring magnetic field components

Various sensor sizes and types are developed for customer specific applications and magnetic measurements are widely used in commercial (e.g. angle position sensors for gas pedals) and industrial (hall switches for servo motors) products [73], [98].

An important characteristic for manufacturing is the available cycle time and the necessary environment for measuring magnetic fields. A highly available and cost efficient sensor is necessary for broad acceptance in productions lines. Additionally the integration is important for complex sensor systems with integrated automatic positioning, measurement and readout. Fig. 60 characterizes the equipment for magnet inspection.

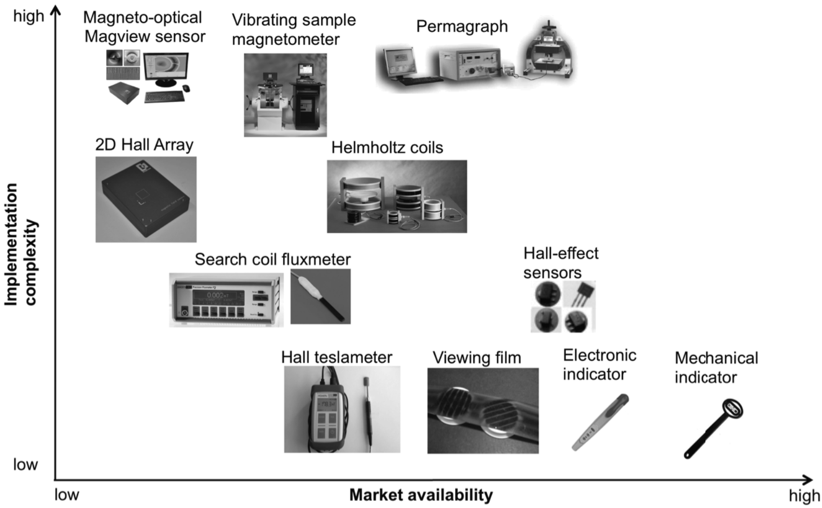


Fig. 60. For measuring permanent magnets parallel to or in manufacturing, testing equipment is available on the market [98].

Mechanical indicator

A permanent magnet with colored poles can rotate in a hand-fixture. By approaching a permanent magnet surface, the indicator magnet reorients and the polarity can be easily determined. This device is used for simple polarity checks of any magnet.

Fig. 61. Left: Electronic pole identifiers indicate the shown field with LEDs, Right: Mechanical pole identifiers turn a magnetic indicator

Sometimes an alternative mechanical solution can also be found as magnet pole finder or identifier. This type of device consists of a small universal mounted bar magnet (cheap AlNiCo) which is attracted with the counter poled magnet side towards the test sample. As the magnet will turn around while the pole finder is moved, it is used as demonstrator for the three dimensional effect of permanent magnet fields. Production sites conditions can be harmful to the fragile mechanical design of the pole finder; the detection magnet is influenced by the strong fields of rare earth magnets.

Electronic indicator

An electronic and more robust indicator solution consists of hall elements in a battery driven mobile pen-style device. The polarity is in this case presented with two LEDs. Within a small hysteresis loop around zero-field no field indication is shown. In the circuit of the device, a small hall switch is placed to activate either an LED indicating the magnetic north or south- pole (with red/green combination). The circuits use Schmidt-trigger circuits with a hysteresis threshold around ± 10 mT for response to magnetic fields. The device is also used as a rough quality/ correct polarity change check directly in the production site. If manual steps determine permanent magnet production and handling, the indicator is the choice for handling magnets, as it is easy to use and portable.

Viewing film/ magnetic detector foil

This foil can occur with name designations (e.g. “sensor foil”, “magnetic detector foil”) and visualizes polarity reversal of permanent magnet material. The visual image is reached by a greenish translucent suspension with Nickel particles enriched. Magnetic domains with high flux densities appear as dark areas whereas lower flux densities appear light. The foil is very flexible and can be cut without losing function characteristics.

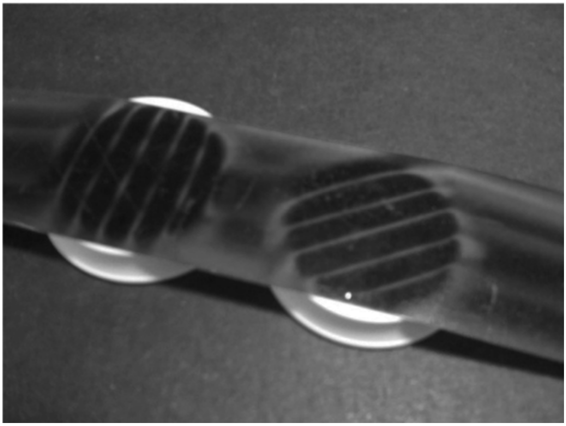


Fig. 62. Detector foil with representation of multipolar magnetized sample magnets shows the change of the magnet polarities. [99]

The detector foil is well suited for quick visual presentations of field distributions on magnetic surfaces and to check materials for magnetization at all.

Hall-Teslameter

One of the most common in-field instruments is the hall sensor equipped Teslameter. The measurement range of the hall sensor can be adjusted. More advanced developments integrate EEPROM ICs with the right calibration for the probe inside the housing or the connector. This enables automatic calibration of the readout device. The manual operated probe of a teslameter (sometimes also called "Gaussmeter") is used for occasional checks of magnetic field density. The probes are distinguished into axial and transversal measurement direction (Fig. 63).

Transversal probes are used for direct surface measurements (e.g. permanent magnet surface). Axial type probe configurations are used for detection in small cavities or for axial flux measurements of coils [100].

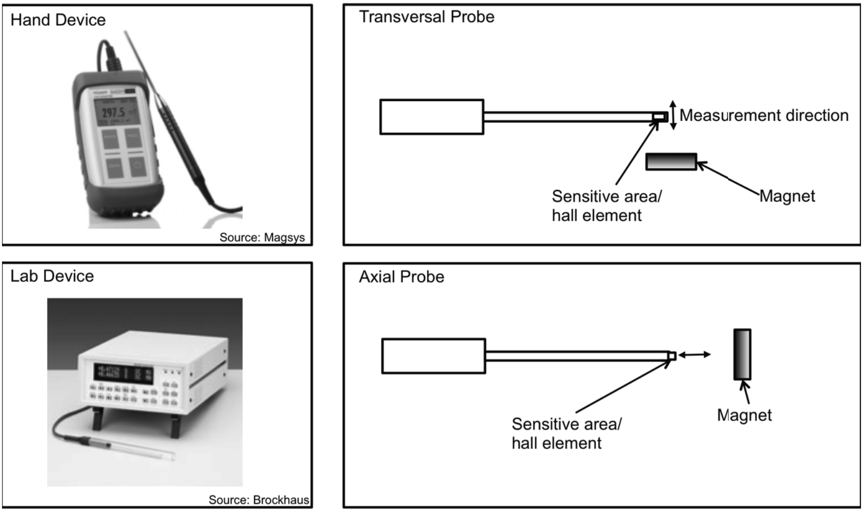


Fig. 63. Upper left: Example of manual Teslameter;
Lower left: Example of Lab Teslameter [101], [102]

Tesla- or formerly known gaussmeter belong to standard process equipment for measuring permanent magnet fields. A hall sensor probe is build onto a carrier PCB board. Probes can be built as axial or transversal design, depending on the type of necessary measurement. Bipolar measurements are presented with negative values for south and positive values for detected north-poled fields.

Better devices offer additional PC-interfaces (USB, COM) for direct value logging in combination with a PC and distinct calculation programs. Biasing of most modern devices is stored in the probe shaft within an EEPROM IC. Additionally the correct signal conditioning is applied in the probe too, so alternating probe geometries can be used with one read-out device.

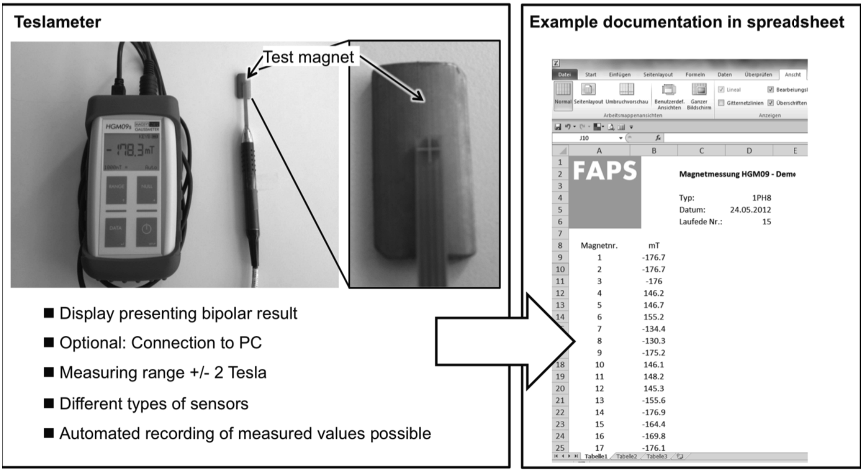


Fig. 64. The manual teslameter is used for discontinuous magnetic field checks.

Hall effect sensors

For applications with requirements for internal sensor read-out, or distributed measurements, hall sensors are available as Hall element or integrated as hall-IC. The hall element itself is delivered as SMD package with four connectors and is connected as Wheatstone resistor bridge. For accurate read-outs, the sensor can be fed with constant current or voltage. Temperature compensation is necessary to prevent thermal drift of the sensor element. This compensation in combination with additional amplification is used as unipolar, bipolar or linear Hall-IC. The basics, characteristics and application circuits are very well described in the works of Popovic [103], Ramsden [92] and companies [104]. Hall elements are widely distributed, as they are used in brushless DC motors for commutation detection, as well as position detection in numerous industrial and common goods.

Search coil fluxmeter

For detecting and evaluating of magnetic fields induction based measurement search coil devices have a long tradition. These sensors are made of small coils surrounding a decent amount of flux and can be built up as axial or radial measuring types. For calculating, an integrating stage is necessary causing long conversion cycles, when measuring a larger amount of measurement values. Search coils are customer and product specific designs and used as single sensor (e.g. fluxmeter). The coils are also found in hysteresis-graphs. Building a sensor array means therefore additional design, where the single sensors itself can be freely arranged.

Helmholtz coils

A type of search coil is presented with the Helmholtz array. It is built up as a parallel pair of identical circular coils spaced one radius apart. The winding of both coils is oriented, so that the current flows through both coils in the same direction. The coil is able to operate in both directions: actively, it generates a very homogenous field. When it is used as passive receiver coil, very accurate measurements can be integrated in combination with an integrator. For the measurement, the permanent magnet must be moved between two coils and the summing flux change is integrated. A common way to do this, is to flip the magnet around 180° or to take the magnet out of the sensing area.

2D hall array (MagCam)

The 2D hall array has been presented in 2009 and incorporates a plain 2D sensor array with 128 x 128 hall sensors and measures the magnetic flux in a plain sensor area of 12,8 x 12,8 mm [105]. The sensor has a serial USB interface, so read-out and measurement interpretation can be taken with standard PC components.

For testing permanent magnets in rotor manufacturing, the sensor area promises to detect the full field of the magnet in a single or multiple shots. A solution for permanent magnets larger than the sensor size is “stitching” several pictures together. With MagCam, permanent magnets supplied to the workplace can be observed. The dense hall sensor matrix enables close near field measurements.

Magneto-optical sensor (MagView)

Magneto-optical systems consist of an optical magneto-sensitive filter disc and an industry camera to record the transmitted light. Vision software tools can be implemented and detect non-trivial failures in permanent magnets and the resulting field. As vision systems require high data capacities, a lot of information is created during one measurement process. The implementation and system learning is furthermore quite work-intensive. As rotors have a radial field distribution, the two-dimensional flat sensor geometry is not suited for already assembled rotor designs or arc-style magnets. Possible adaptions of this sensor principle for round shapes could bend the sensor geometry or implement CMOS lines combined with external rotation of the rotor to readout the complete object.

The magneto-optical principle can be used for detection of various defects concerning the destruction-free quality check of ferrous products (e.g. chamfers and notches). The work piece is therefore excited with an induced magnetic field. The optical system is emphasizing breaks of the flux, which can then be easily analyzed by standard vision systems. The scalability of the magneto-optical filter material enables new sensor designs, e.g. bent structures for radial measurements of rotor geometries. The resolution of the system is depending on the inset vision system.

Vibrating sample magnetometer (VSM)

The vibrating sample magnetometer has become standard in various laboratories for open magnetic circuit measurements of permanent magnet samples. As shown in Fig. 65, the VSM uses an actuator combined with a stiff sample holder lever to vibrate the sample between a set of magnetizing coils while detector coils measure the flux change, which is direct proportional to induction voltage across the terminals of the measurement coils.

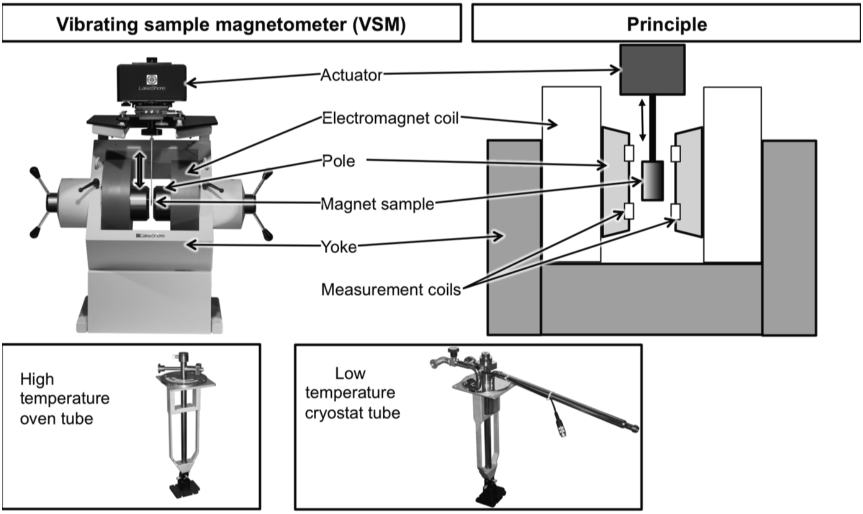


Fig. 65. The vibrating sample magnetometer fully characterizes permanent magnets within an open circuit measurement. [106]

The system suits very well for small probes of magnetic material. Therefore this device is found in production accompanying laboratories and used for characterization of small fraction of material for material studies, magnetic layers, Ferro fluid measurement, material research (soft-magnetic components and small permanent magnets). The poles around the sample can be heated or cooled down with tube adapters. A specialist manually has to operate the preparation of the sample, the loading of the machine and the test itself.

Perma- or Hysteresisgraph

The classical instrument for permanent magnet characterization is the Hysteresisgraph (also called "Permagraph" after the manufacturers product name). The system includes all necessary equipment for complete hysteresis recordings of permanent magnet materials: A yoke for perfect flux guidance is combined with strong height adjustable coils for application of magnetizing and demagnetizing fields. The flux through the material as well as through the air gap is measured by two integrated field coil probes (see Fig. 66) [107].

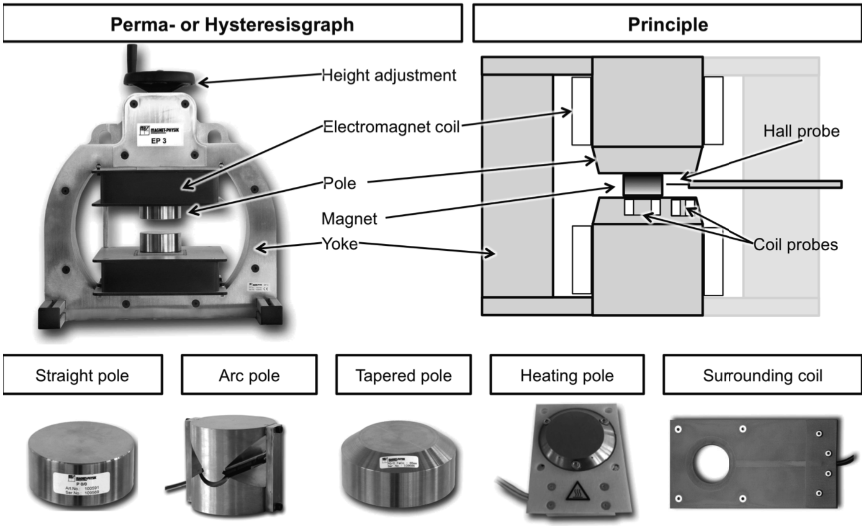


Fig. 66. The Hysteresisgraph fully characterizes permanent magnets [108].

An additional hall probe is inserted for measuring the field strength in the air gap. Adaptions to magnetic geometries or working conditions are achieved by custom pole geometries. Straight poles are standard, whereas tapered poles are necessary for mounting heating adapters and j-compensating surrounding poles [109]. Arc magnets are measured with segmented pole pieces. This measurement method is the standard for quality tests beside the production and characterizing permanent magnets from suppliers. A specialist does the measurement handling manually, adjusts the fixture of the yoke and manually performs the measurement cycle.

The presented measurement principles are manually operated, except of the hall sensors. The simpler devices for detecting magnetism and polarity are used along the whole production chain for punctual measurements. The more complex devices for full magnet characterization are designed for single laboratory checks of magnet production batch sizes. For inline measurements of resulting fields there are still no sensors or measurement principles. For complex measurements in production or directly for each product, hall sensors fit exceptionally well, because they are widely available and offer small build sizes for integration into complex machines. Sensor arrays can be arranged fur multi-punctual measurements. For modern permanent magnet motors the possibility for a high number of distinct measurement points enables new insights (e.g. complete field mapping of rotor, measuring stray flux and checks for field homogeneity) and feedback from manufacturing methods (e.g. differing heights by fluctuating glue heights, using magnets from two batches) to the function of the rotor.

7.4 Sensor integration concepts for inline measurements

Polarity checks are performed for finding misplaced or wrong placed magnets. Most common uses are to control visible marks for the right side of polarity or the check of larger pole areas for synchronous motors. A better solution is the documentation of the right field strength for every magnet. This ensures that all magnets are magnetized and all magnets have the same field strength.

The integration of sensors is almost entirely based on the combination of multiple hall sensors. Fig. 67 gives examples for single probe measurements, where a single measurement device is placed with a handling device. Commercially available systems provide a three axis system for measurements in Cartesian, or with an additional rotary axis, in cylindrical coordinates [110].

The concept of a robot based system “ROBOTESLA“ has been formed in this work and will be presented in chapter 8.3. The second column represents the innovative field for multi probe measurements. Known applications are found for magnetic flux leakage measurement, e.g. for checks of welded tubes [111], [112]. The missing magnetic flux is introduced with an exciter coil and resulting stray flux measured with a hall sensor pickup. This idea has been developed for permanent magnet rotors with the “LINMAG-1 and -2“ and will be also presented in chapter 8.4.

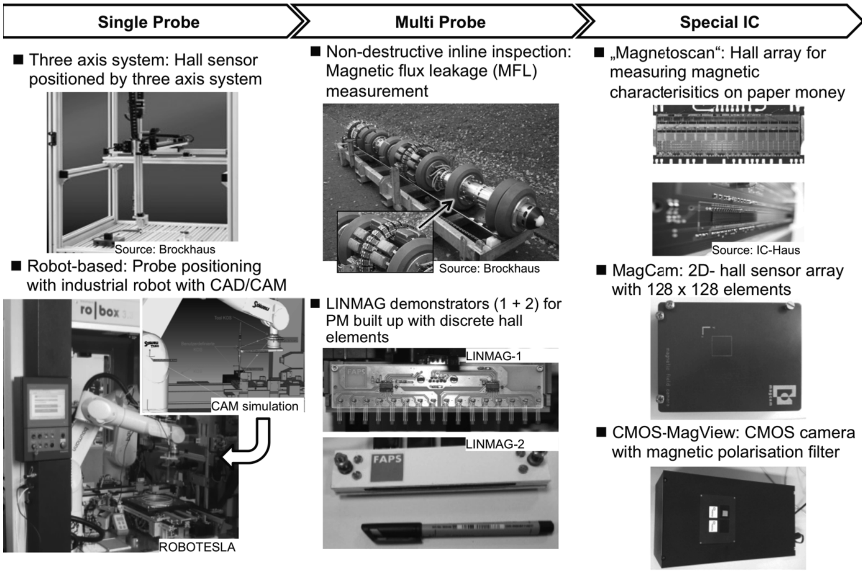


Fig. 67. Magnetic field measurements are distinguished into three main subcategories.

The third category includes sensors with integrated read-out circuits (IC), interface, supply and temperature compensation functions. These ICs are developed for measurements of plain surfaces and for distinct application fields. The Magnetoscan has been presented for detection of magnetic security dots on bank notes [113]. The MagCam sensor has been developed for evaluation of sensor magnets, e.g. for detection of the alignment of multipolar magnetizations. The CMOS-MagView system based on magneto-optical filtering is an integrated approach for non-destructive testing, e.g. for detecting cracks in welded tubes made of ferromagnetic steels [114].

7.5 Measurement sequences for inline magnet testing

The collection of measurement scenarios and possible devices requires the right strategy for designing a test. Fig. 68 summarizes the possible strategies for the use in permanent magnet rotor testing. Hall sensors for punctual evaluation enable four scenarios:

- Single point measurements: Distinct points are measured inside a predefined volume. A single sensor is moved and positioned.
- Multi-line measurements: Several row-scans are combined; the sensor array can be used for differing sizes and lengths.

- One-line measurements: A row of sensors is moved above the specimen magnet or rotor. The sensor array can be designed for the necessary rotor length.
- Measurement of planar patterns and combination of several patterns: This enables large area measurements.

Performing the rotation is done in two ways either automatically or manually. For the automatic move of the rotor specimen, a servo motor is used and the encoder signals is redirected to the measurement program as counter. In manual mode, at least one extra encoder is necessary for determination of the actual position to decide whether to toggle a measurement or not.

Additionally to planar surfaces, the challenge for rotors is the evaluation of the cylindrical surface. A distinction between line and arc geometry of the sensor array is necessary. If the rotor is turned, the line geometry stays at its distinct place and determines the circular field, while the rotor is moving. For applications incorporating the 2D area sensor array this is a disadvantage, because only one perpendicular sensor line array towards the centerline of the rotor will measure a correct field value. The other values of the sensors are therefore neglected.

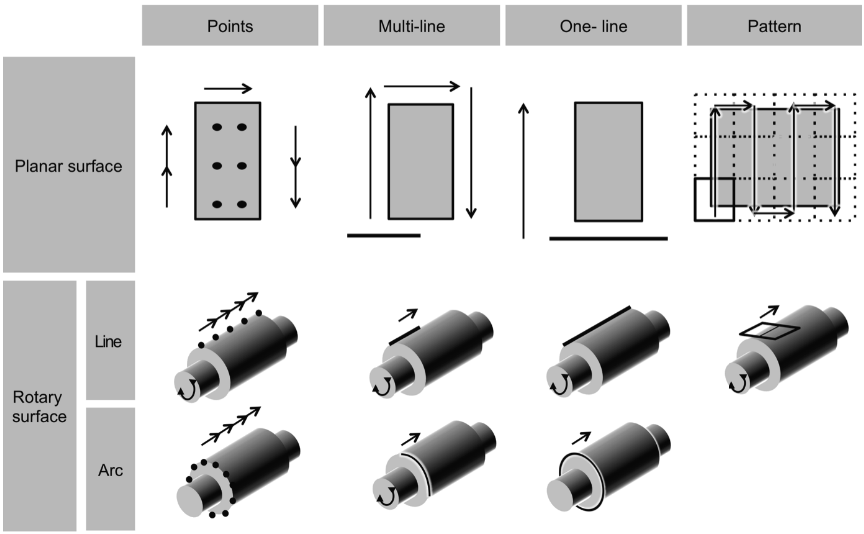


Fig. 68. Integration of multi-point-scans for measuring magnetic fields for electric motors

Arc geometries are suited for rotor variants with constant diameter. The advantage of point-wise ring- or high-resolution measurement is the simple handling of the sensor and the rotor stays in its supplied position. A compromise is the design of an adapted arc geometry sensor for a distinct product. If the sensor line array would be too large for handling, or the rotor cannot be reached with a sensor ring. This is e.g. the case, if the rotor is maintained in a large motor and only pulled out for tests. For variants with differing diameters or shapes the sensor can be built up flexible and bendable, with forming elements or adjustment fixtures and set the necessary arc geometries.

Four main process steps describe the design of the sensor array (Fig. 69). The first step includes all necessary planning and preparation, including boundary conditions for the magnetic field test. If quantitative measurements are needed, calibration of the measurement chain is possible with reference parts ("golden" parts), etalons (these are calibrated reference magnets) or Helmholtz coils.

Measuring is the second column and describes the basic process steps for testing the magnet in or before assembly. The system can be designed as automatic station, or as manual station with manual inserting of the magnet and setting the correct height.

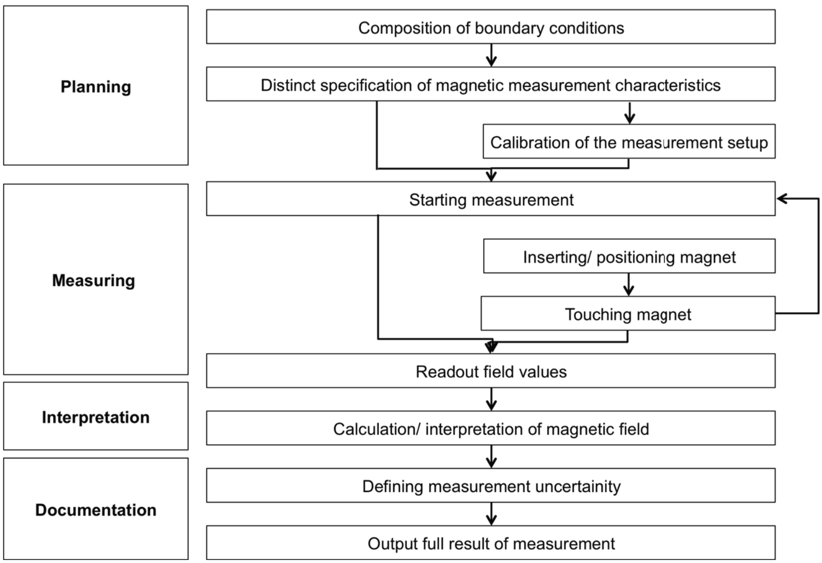


Fig. 69. Measurement of magnetic fields is categorized into four main parts [115].

The interpretation of the measured values is the third row and requires sensitive knowledge of the system and the required results. For the parallel read-out of measurement values, the interpretation needs to mesh the collected points and calculate e.g. homogenization factors for the measured field. As magnetic fields behave always three- dimensional and interact with their environment (e.g. screws) exact results take a lot of implementing care in the calculation stage.

Documentation of the results is standard for production. It should provide a full presentation of the magnetic field check and additional information for complete recovery of the production batch (e.g. responsible worker, date, temperature).

7.6 Summary

In this chapter, the fundamental measurement devices for testing of permanent magnets have been introduced. Innovative compositions of punctual hall sensors enable the integration multi-point-scans for electric motors, not only in the laboratory. Therefore concepts for sensor positioning have been discussed as well as the standard procedure for magnet testing.

8 Realizations of Magnetic Measurements

Sensor arrays enable parallel measurements of multiple points at once and expand the functionality of the shown flux- and teslameters. Currently, two devices based on the hall and the magneto-optical principles are available:

- A 2D- hall sensor array (also: ”MagCam”) [116]
- A 2D CMOS-camera system (also: “MagView”) [117]

In the following chapters, these devices have been used for tests and implementations into automated systems. These devices lead to the development of the LINMAG- 1 and -2 and the ROBOTESLA-1.

8.1 Evaluation of 2D hall sensor array and magneto-optical system

Measurement devices with hall elements are known quite well for single point measurements. A two-dimensional hall sensor array, introduced in 2009, marks an innovative concept for quality control of permanent magnets. The array consists of 128 x 128 hall sensors with a precise distance of 0,1 mm [116].The active area of each sensor is 40 µm x 40 µm. The perpendicular magnetic field component is used for measurements.

Tab. 7. The 2D hall array is read-out in full two-dimensional or line mode [118].

	Number of sensors	Measurement time
Complete	128 x 128	0,82 seconds
Half	64 x 64	0,21 seconds
One line full	128	7,4 ms
One line half	64	3,2 ms

The hardware is serially connected via an USB port to a standard PC system containing the read-out and control software for test preparation, starting the measurement, as well as post-processing tools for saving and interpreting the values. For adaptions to increase the measurement speed, the camera can be read out in full or half resolution mode with read-out speed of 50 µs/sensor. Additionally, the command time must be added once with 1 ms.

The hall sensor array system enables process control and checks for permanent magnets within workplace cycle time and can be integrated into the magnet supply of the workstation (e.g. magnet check after taking out of packaging) and within handling path (e.g. after separating a single magnet). Magnetic fields of larger objects can be scanned very quickly.

For PM-rotor production the permanent magnet is bigger than the sensing area of the sensor. To measure the field of a larger magnet, several pictures of the magnetic field need to be stitched (see Fig. 68-“Pattern”) together or one line of the sensor is scanned over the surface of the specimen. For stitching the measured field values, each 2D picture of the hall sensor array is added to one complete picture together. The scanning process must be split up into multiple areas covering the area of the specimen.

Concepts for using the MagCam sensor in stitching mode are:

- moving the magnet (e.g. for assembled magnets on rotor)
- moving the sensor (e.g. for large magnets or distributed measurement positions)
- combination of moving magnet with moving sensor

The magnet can be set into a fixture and moved around the sensor in distinct steps of 12,7 mm in x and y direction. The sensor must be set in the right height or lies on the bottom. The fixation of the magnet can be difficult while it moves, as only the side flanks can be used to grip the magnet. This means the magnet can fall off the gripper. Fixing the magnet on the other hand simplifies the automatic movement of the camera over the surface of the magnet. For this case a three-axis system was established. The sensor is adjusted at the z-axis and can be referenced by an approximation switch automatically onto various magnet heights.

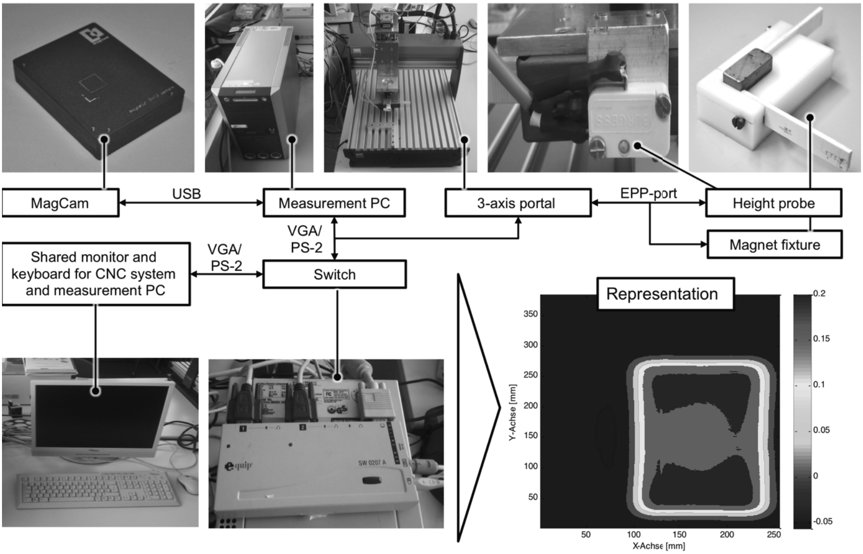


Fig. 70. For static and dynamic measuring with the MagCam, a read-out program and a handling device for positioning have been combined.

The MagCam is connected to a standard PC including the readout software (see Fig. 70). One monitor is shared for both the MagCam measurement-PC and the machine controller so the necessary control and representation setup is made within one terminal. The three-axis system is equipped with a non-magnetic fixture made of plastic. The magnet is set-in manually and fixed with brass screws. Additionally, a height probe is included for save approaching the rotor surface.

8.1.1 Hall sensor array in the magnet supply process

The entry point for an automated check of the magnetic field is the permanent magnet feeder, if a test should be established. The magnets are delivered at the workstation and are stacked together before magnetizing. The magnets are then separated. This process step enables a good/bad check or a flux check for the magnet. When the magnet is fed into the handling station, it has to be held to avoid unwanted snapping towards peripheral ferromagnetic parts or other magnets.

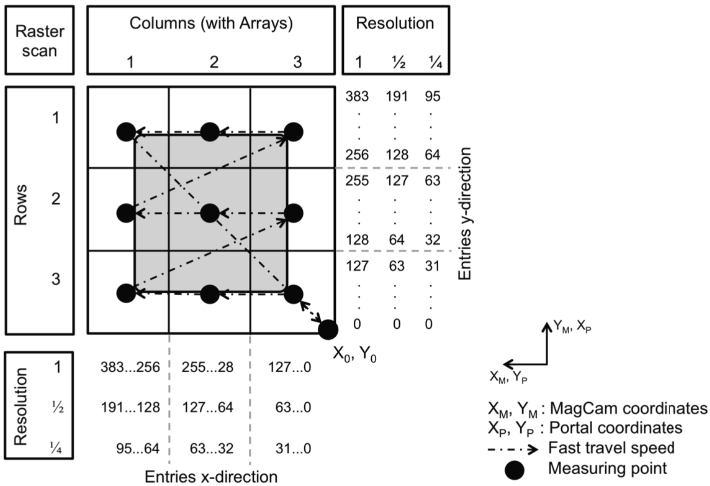


Fig. 71. The raster scan method takes two-dimensional "pictures" of the magnetic field at distinct points.

Measuring permanent magnet fields with the MagCam enable two working scenarios: In the first scenario the specimen surface is smaller than the sensor area. In this case the magnet only needs to be positioned accurately on the surface and the sensor array reads the complete flux of the magnet in one measurement step. For this reason, positioning frames can be mounted directly on the sensor to match exact positions. With automated software calculation scripts the measurement is evaluated. The camera remains therefore fixed and mounted directly into the workplace, e.g. in an automated magnet feeding system, or as quality check station for magnetized encoder wheels.

In the second scenario the magnet specimen is larger than the sensor array (see Fig. 71). The measurement is split up in several “pictures” and stitched together. Starting from a zero point, the MagCam is positioned with distinct steps of 12,7 mm apart. The resulting image is calculated and given out for further examination. A critical point is the absolute positioning of the MagCam sensor with the handling device.

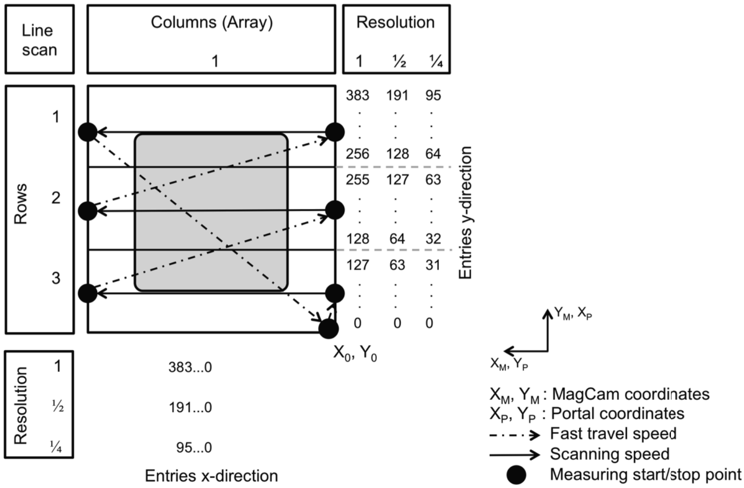


Fig. 72. The line scan method draws a one-dimensional-line along a distinct path to record the magnetic field.

A second scenario and method has been developed and implemented: The line scan algorithm. Following the initial examples for the line scan prototypes [119], new software has been provided for test purposes [118].

Fig. 72 presents the method for line scanning of the specimen. The sensor starts at a zero point and moves along axis "Y". All other lines are taken with an offset of 12,7 mm from the zero point of axis "X". Critical processes in this scenario are the adjustment of a constant speed during the recording of the line measurements and the absolute positioning of the line with the handling device. For specimens with very large geometries or flexible measurement scenarios with several distinct places, this method is suited.

With the presented two measurement concepts the following influences have been examined:

- Sensor moving speeds for line scanning
- Influence of temperature
- Influence of corrosion
- Magnet assemblies
- Changed sensor resolutions
- Hot/ cold effect
- Comparison with other instruments
- Stacking effect

8.1.2 Sensor moving speeds for line scanning

Contrary to the raster scanning, the line scan has the advantage to resolve the scanning lengths freely. Even endless conveyor tests can be designed. The MagCam only needs to be accelerated and decelerated once for taking one measurement and a continuous workflow is achieved. Therefore the scanning by using only one of 128 hall sensor lines can be used for integration into e.g. continuous supply paths with magnets travelling over the sensor or for measuring rotors while rotating the rotor surface under the sensor line. A calculation tool for the 2D hall sensor is provided for estimating the initial test speeds (see Tab. 8).

Tab. 8. Exact calculation of measuring time for 2D hall sensor array

Pixel time (per pixel)	0,048 ms
Command time	1 ms
Line time (= 128 * 0,048 ms + 1ms)	7,144 ms
Calculated maximum speed V_{max} (= 0,1 mm / 7,144 ms)	**14 mm/s**

Then the maximum speed of the measurement system presented in Fig. 70 has been evaluated with a magnet specimen of 30 mm length. Fig. 73 shows the difference in travel speed and the resulting length of the magnet picture caused by the measurement PC.

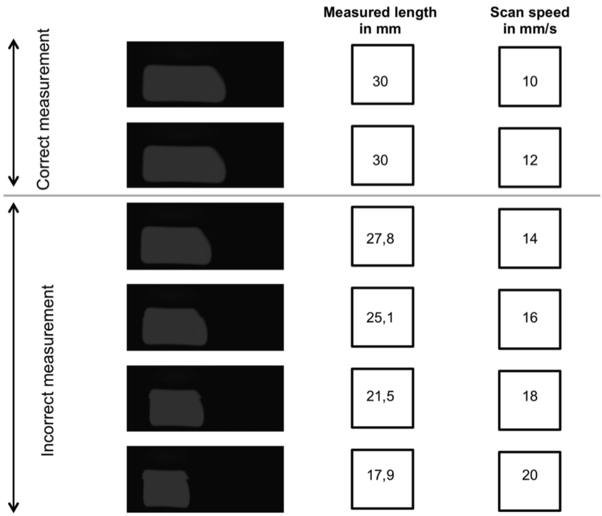


Fig. 73. The line scan with the magnet sensor depends on the right speed.

As triggering the sensor requires real time behavior of the operating system, frequently or randomly executed background services of the operating system, the bandwidth of the sensor interface and the overall performance of the measurement PC can lead consequently in loss of timing precision. Measurement points are not recorded and missing. The magnet is therefore not represented with the correct size. The proposed sensor movement speed of 14 mm per second by the sensor manufacturer has been evaluated as too fast for accurate measurements, so attention needs to be spent for similar systems. The resulting optimum speed is therefore 10 mm/s for the built up line scan system. Improvements are possible with faster multi core technologies, separating the real time application from the operating system kernel.

8.1.3 Influence of temperature on magnetic field

For modern permanent magnets, the influence of temperature on the magnet has an important impact on the achieved power density. Therefore tests with tempered magnets have been done to examine differences in the flux density. Fig. 74 shows the evaluation of temperature influence on nine equal magnet samples.

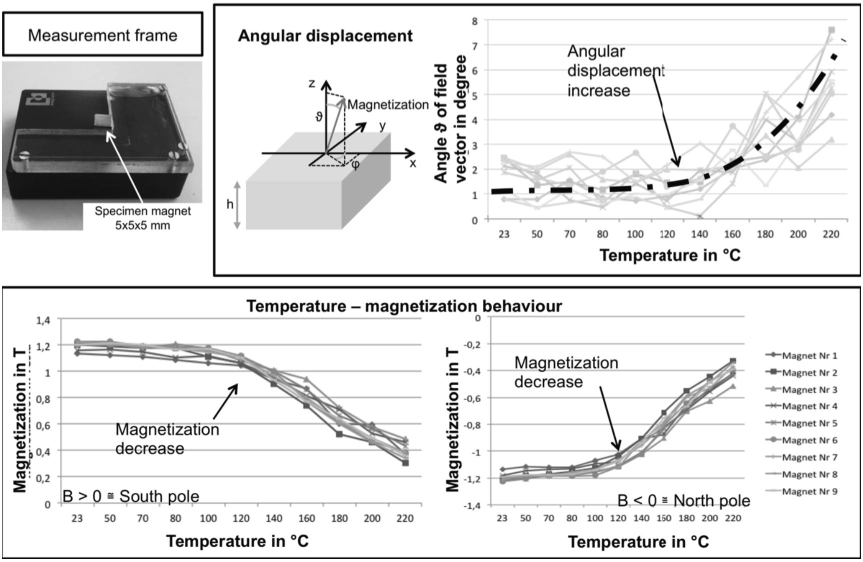


Fig. 74. Temperature influences and angular displacements of the magnetization can be measured with the hall sensor array.

As shown in manufacturer datasheets, the magnetic characteristics are degrading with increasing temperature [120]. For the resulting magnetizing angle, a trend for the evaluated specimens can be watched: The angle is increasing together with the working temperature and can be determined with the MagCam system.

The magnetization B_r of the magnet reproduces the expected change and degradation of the magnetic field for temperatures over 80 °C. The magnet distributor for the magnet samples has provided the magnet with a maximum working temperature of 80 °C. Therefore the detection with the hall array enables fast checks of the magnetization vector and the field reduction for hot magnets.

8.1.4 Influence of corrosion

As modern rare earth magnets include a large amount of Iron in their material base, corrosion is an important point concerning long-term stability of a magnetic system [121]. Therefore a salt spray test at room temperature has been built up with saturated Natrium Chloride lotion. The magnet specimen has been slightly sanded to watch the field degradation in case of a mechanical magnet defect due to inadvertence during assembly (e.g. scratches on the coating) or due to broken magnets.

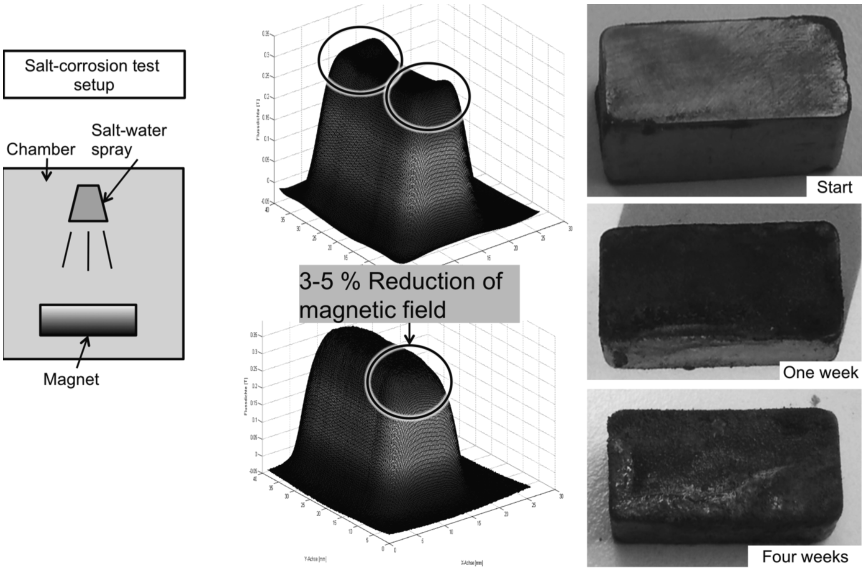


Fig. 75. *Corrosion has a deep impact on the magnetic field strength of NdFeB magnet materials.*

As Fig. 75 shows, the lotion has been able to impact the magnet with a visibly mechanical degradation of the magnet geometry. The resulting field at the beginning and at the end has been measured with the hall sensor array and shows a distinct reduction of the field area more than 0,25 T. The magnetic flux at the edges of the magnet is reduced compared to the initial magnetization state. The hall sensor array can therefore be used to detect magnetic degradation and check magnet assembly in e.g. linear motors to check the field weakening induced by environmental effects.

8.1.5 Magnet assemblies

Developers of electric motors who want to avoid eddy current generation in permanent magnets during motor operation request magnet assemblies, which are glued together by multiple smaller magnets. Each small magnet is coated and electrically isolated from the others, analogous to stacking of thin metal sheet laminations for the rotor and stator core. With the MagCam resulting flux variations of the coating transitions can be detected. Therefore a test specimen consisting of eight bar magnets has been evaluated. Each magnet has the dimension (length/width/height): 19,6 mm x 4,1 mm x 4,3 mm.

Fig. 76 presents the resulting field for the magnet specimen. The field distribution is waved, because every magnet forms its individual magnetic field. The resulting field distribution is equal to single body magnets:

- The field is slightly concave at the flanks.
- The field of the magnet has its maximum at the edges and lowers to the center.

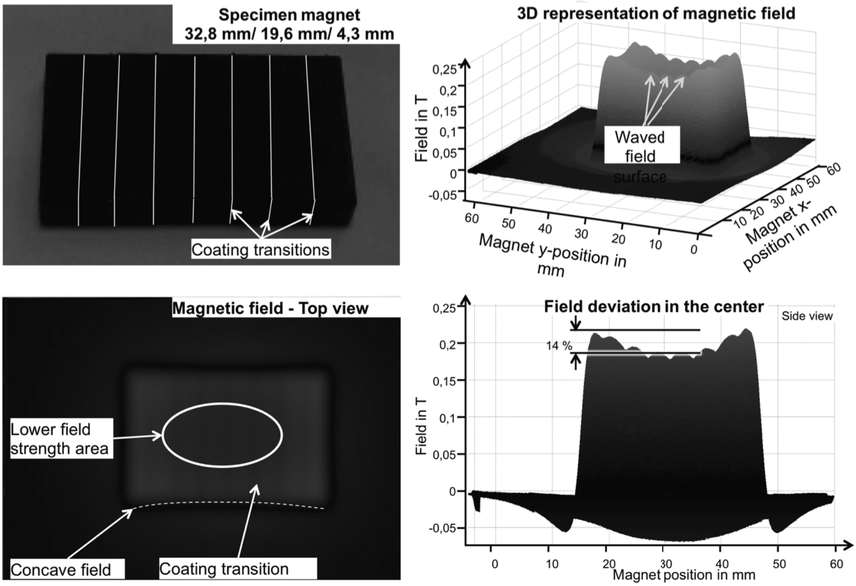


Fig. 76. Assembled magnets show similar characteristics as single body magnets.

The presentation of the results can be given as three or two-dimensional plot. Then the single magnet interconnections and the transitions can be seen clearly. The three-dimensional representation allows further detection of anomalies and identification of the wavy structure of the magnets working surface.

The tested magnet has a difference in magnet field strength on the surface of 14 % (referring to the centers minimum field strength). This nonlinear flux density distribution in permanent magnets leads to generation of harmonics and is subject to field fluctuations. It means in advance, that simulative modeling of such permanent magnets can be coupled with the hall sensor array measurement to refine and optimize the magnetic simulation model.

8.1.6 Hot- / cold side effect

The hot and cold side effect is caused by the production method of the magnet. The powder for the magnet body is pressed and the particles are aligned with an electromagnetic field. If the magnet is magnetized in the same direction as the aligned field, the measured magnet strength is higher than if the magnet is magnetized in the opposite direction [122]. For axial pressed permanent magnets this is e.g. a problem for assembly of homogenous undulators (a high-energy physics insertion device, e.g. part of a synchrotron storage ring) [123]. It reduces the magnetic field by about 7% compared to isostatic pressed permanent magnets and by 5% compared to transverse pressed magnets [122].

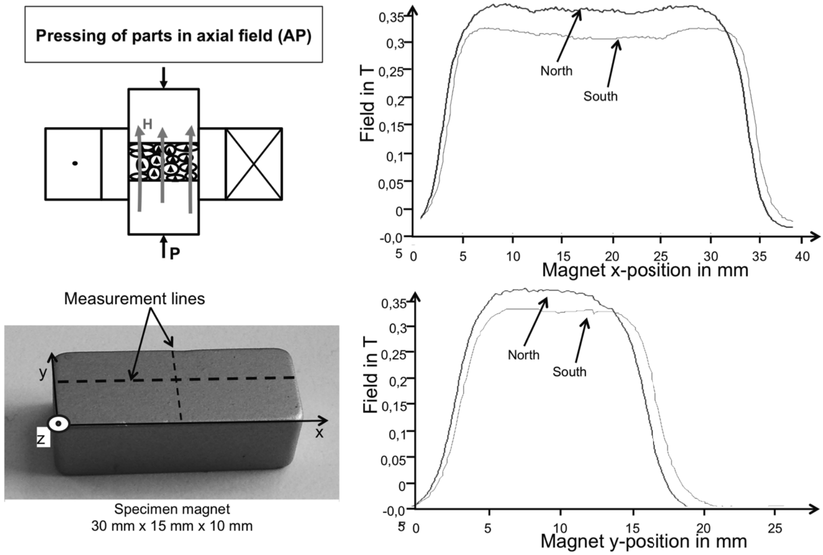


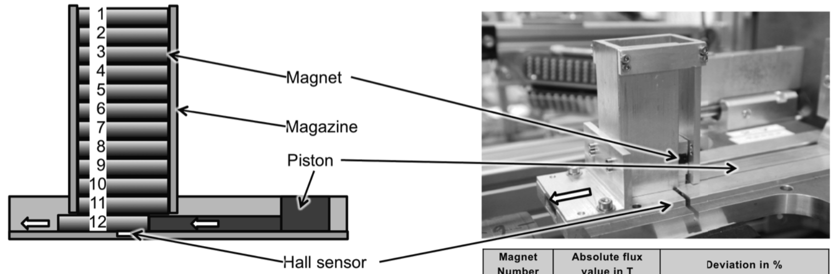
Fig. 77. AP-pressed magnets show a distinct hot-/ cold effect between north and south- pole side.

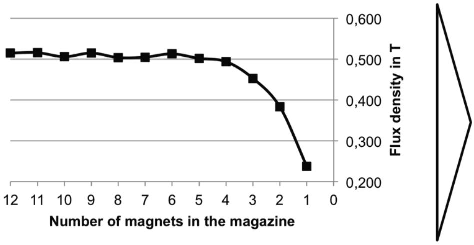
With the hall sensor array setup, the hot and cold side has been evaluated for a block magnet. The measurement line has been set in the middle of the magnet and the measurement has been taken with the line scan method. Fig. 77 shows a distinct difference. For single magnets of a whole stack even up to 12,5% difference have been measured. In this case, if the magnet should be assembled, the “north” direction should be chosen as active pole side facing the stator pole.

For existing magnet assembly workplaces, the integration of a pre-assembly hall sensor array station can detect the difference between hot- and cold side of a magnetized magnet. Sorting the magnets for correct and continuous hot side position can lead to a much more harmonic field generation for motors with block-style surface mounted magnets. Important for suppliers as well as applicators is the use of two types of block magnets in case of axial pressed magnets – with alternating magnetic pre-alignment during magnet production, to reach a hot side for south as well as for the north-pole magnets in the rotor.

8.1.7 Stacking effect

The measured field strength varies, if magnets are drawn from a stack of magnets. If the magnet should be checked in the supply path, a hall sensor can be placed directly under the stack. For the test, the middle position has been chosen, as the MagCam results have shown, that the flux density is lower in the middle position. Fig. 78 presents the stack inset in the magazine (aluminum); the hall sensor (a standard teslameter probe) is fixed under the magazine.





Magnet Number	Absolute flux value in T	Deviation in %	
1	0,238	Reference	-53%
2	0,383	+61%	-25%
3	0,453	+90%	-11%
4	0,494	+108%	-3%
5	0,502	+111%	Initial value 0,510 T ($Median_{5-12}$)
6	0,513	+116%	
7	0,505	+112%	
8	0,504	+112%	
9	0,515	+116%	
10	0,506	+113%	
11	0,516	+117%	
12	0,515	+116%	

Fig. 78. The flux density is decreasing in magnetized stacks.

If the magnets are set in as stack, the flux density does not change significantly during separating (reducing the stack height) and is higher than a single magnet until only five magnets are left, then the measured flux density decreases. The stacked permanent magnets represent longer magnet with a changed load point. If magnets are taken away from the stack, this “longer” magnet gets smaller and its flux values change. The flux measurements between a full stack and a fraction of the stack differ up to 53% from the median value of the stack. Therefore, a distinct measurement position with one separated magnet leads to much better results regarding the single magnet. Direct measurements can nevertheless be integrated as shown in Fig. 78 above as polarity and threshold measurement, or even as level detection for the available magnets in the magazine.

8.2 Magneto- optical sensor for defect characterization

Beyond the presented well-known hall sensor measurement principle, the diffraction of light by measuring with a magneto-optical sensor system is an alternative. New magnet sensor devices are developed for industrial testing, the principle of the sensor can be used in a huge variety of processes deriving from non-destructive material testing [117], [124], [125].

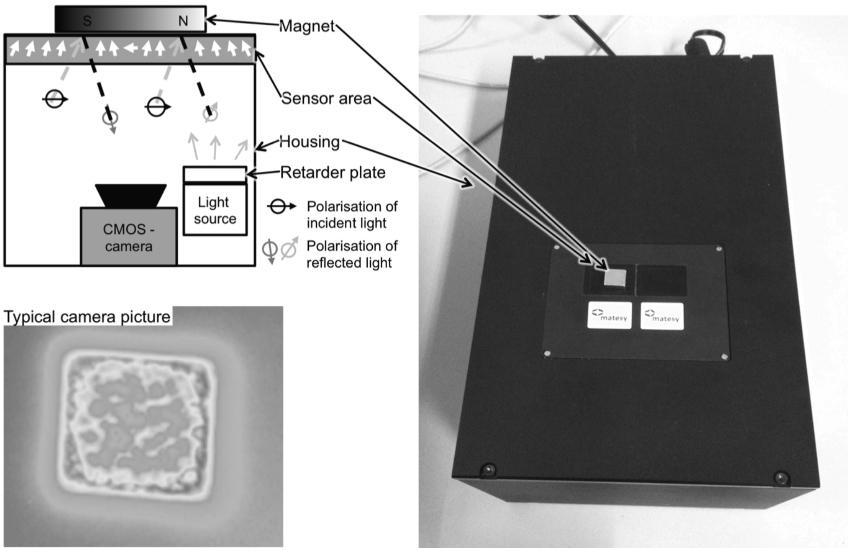


Fig. 79. The magneto- optical sensor can be used for detection of magnetic defects.

The magneto-optical sensor utilizes the Faraday effect describing the rotation of the polarization plane of linearly polarized light. The integrated CMOS camera views the sensor operating in reflection mode. A light source sends out light through a retarder plate, which is then polarized. The sensor forms a contrast depending on the local magnetic field strength. One polarity leads to a bright, the other in contrary to a dark image. The camera then detects the light, with a rotated polarization for the particular position. For comparison with the hall sensor devices, a prototype (see Tab. 99 has been evaluated with the small cubic magnet specimen (5 mm x 5 mm x 5 mm).

Tab. 9. The characteristics of the CMOS-MagView prototype system

Optical resolution	25 µm
Field range	Up to 167 mT
Active sensor size	15 mm x 20 mm
Size	230 mm x 150 mm x 60 mm
Weight	2 kg

Fig. 79 shows the working principle of the magneto-optical sensor. Compared to the hall sensor array, the resolution of the MagView sensor is four times higher, whereas the sensor housing is larger and the maximum field range is nearly ten times lower than the MagCam. The workflow for the measurement is the same as for the hall sensor array:

- The magnet is placed directly on the sensor.
- An image is taken and evaluated.

The resolution of the sensor system is variable, as a standard CMOS sensor is used to watch the resulting contrast picture. Therefore, also image processing software and high-resolution camera systems (up to several mega-pixels) are possible. Compared to the MagCam sensor with a resolution of 128 x 128 sensors on the chip area, the magneto-optical system offers new possibilities towards detection of very small material cracks in the coating material due to its higher resolution.

The principle of the sensor element allows the composition of measurement areas with sensor plate sizes for scanning complete magnets within one single step. During the measurements, the inset magnet specimen causes the sensor to saturate and produced a crossover on the sensor from the opposite pole side. The tested prototype sensor provided a small measurement range and is suited for detection of stray flux caused by cracks or air gaps.

8.3 The ROBOTESLA system

For flexible magnetic measurements with distributed spots to check around the surface of the rotor, a robot- based system has been built up. The station implements therefore the functionality of a single hall-sensor probe with the ability to reach every given point in the work area of a six-axis industrial robot. For this reason, a Stäubli RX-90 robot arm guides the hall sensor probe on the measurement paths. For the system (see Fig. 80), a CAD/CAM tool chain has been built up, to ensure an exact offline path planning.

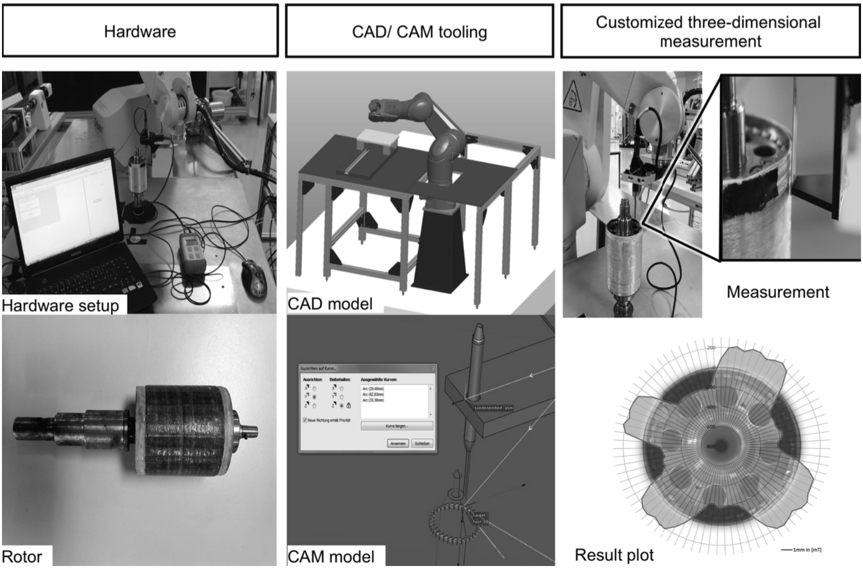


Fig. 80. The ROBOTESLA performs free three-dimensional measurements over a specimen.

For magnetic field measurements, programming all measurement points online by hand exceeds all economical time efforts and lacks flexibility for workpiece changes. For this reason, the robot is programmed with Famos Robotics [126], an industrial standard for creating platform independent robot programs. A CAD model of the rotor product and the robot cell can be implemented in the program. In a separate step the virtual work cell needs to be calibrated with the real work cell. After calibration, both cells share the same coordinates and the measurement path can be implemented virtually.

The robot system consists of a laboratory assembly cell and is expanded by a tool flange holding and supporting the hall sensor probe. The standard hall sensor probes are mounted on small PCB stripes and bend and break easily. A support holds therefore the probe in place.

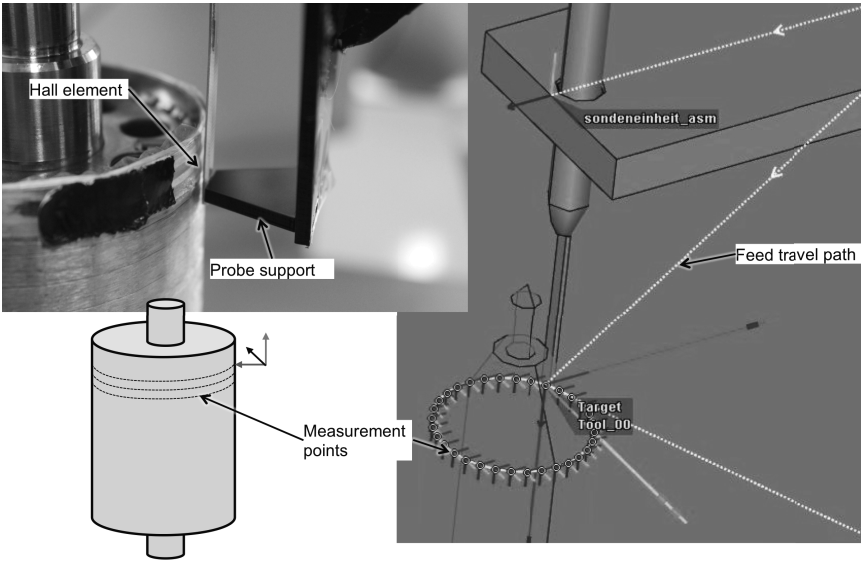


Fig. 81. With CAM based path planning complicated measurement paths can be realized.

The vector for each point can be set individually or comfortably as perpendicular standard vector towards the surface. As Fig. 81 shows with the rotor example, the virtual path planning strategy enables detailed setups. If variants need to be measured, parts of programmed paths can even be reused (e.g. tool changes, parametrical measurement paths, workpiece identification, measurement trigger, parts exchange). The offline programming offers a broad range of advantages:

- Faster path planning
- Exact positioning; the distance of the hall sensor can be adjusted
- Complex path generation possible
- Numerous path points easily programmable
- Flexible programming, even if the machine and the workpiece is not yet available

Depending on the type of work piece, the robot can also handle the part itself. In this case the robot arm positions the work piece towards a fixed measurement device. The ROBOTESLA station enables flexible stray and use flux measurements. Spline geometries around a specimen in the work area can be automatically calculated and be recorded. The offline capability of the measurement tool enables path planning strategies parallel to the development of the rotor and gives precise data for calculating the costs of the measurement process and resulting cycle time. Collision detection during programming is possible without damaging hardware components. Quick change of measurement programs is possible without the need of changing the kinematic system. Therefore also a simple creation of multiple distributed point sets for evaluation of critical workpiece areas or complex shapes can be programmed. Furthermore, the measurement can be done surface perpendicular or tangential. The measurement program just needs to turn the tool center point. With the robot system, standard automation components with good repeatability (depending on defined measurement parameters) and simple fixtures can be used.

The capabilities of a system for free positioning also challenges the precision of the handling device and its monitoring:

- The correct spline motion demands difficult monitoring and approval with 3D tracking sensors.
- The offline programming requires correct setup of the model and calibration with the real workplace.
- The quick change of measuring programs can lead to collisions between the work piece and the hall sensor probe in the workspace, if the wrong program is chosen.
- The robot guided sensor process is slower than a custom specific sensor arrangement for particular parts, due to the path travel of the robot.
- The precision of the handling device chain: the accuracy of pose or path is vital for the robot system, when it is programmed offline.
- Reaching all positions on larger rotors requires additional fixtures or larger kinematics.
- If necessary, an additional kinematic for turning the workpiece (e.g. rotary table) needs to be used.

The robot station is able to take a variable set of points around a specified specimen volume and is therefore suited for flexible workpiece measurements. The robot controller is linked to an additional read-out PC. On the PC two tasks can be prepared:

First, the robot controller has no own graphical user interface (GUI). It cannot be used for measurement path design, as the specific spline and control data cannot be computed manually in a decent amount of time. Therefore the PC is used for path planning and the resulting programs are sent to the robot controller.

The second task takes up the measurement values from the teslameter device and records them. The converted data can then be transferred via various interface types. The short cable length for the analog part of the sensor can be sensitive for EMC problems. Therefore the teslameter is directly on the arm of the robot to keep the analog signal path as short as possible.

If a lot of measurement points are taken, more possibilites for interpretation of the signal are given. For lab experiments, the use of state-of-the-art chart programs is sufficient but with an exaggerating number of values also the style of representation as well as the combination with measurement points has to be considered. The robot can therefore add its decent vector coordinates to every value, making a precise three-dimensional field computation possible. With this information also manually operated coordinate workplaces for magnetic measurements are possible if the probe is connected to a manually driven measurement arm with encoder position signals. The two systems (handling and hall sensor device) then need to be triggered. The measurement time is then determinated by the number of taken measurement points.

8.4 The hall line sensor concept – the LINMAG-1 and 2

For magnetic measurements of round surfaces, or large flat area, probing the work piece with a single hall sensor in a separate measurement station as described in [110] requires large cycle times, as one sensor is moved punctual along the rotor length. This is improved by an available system shown in [127] with a total amount of three hall sensors. To reach faster measurement cycles with high sensor resolution a custom designed sensor line array with discrete hall sensors has been developed.

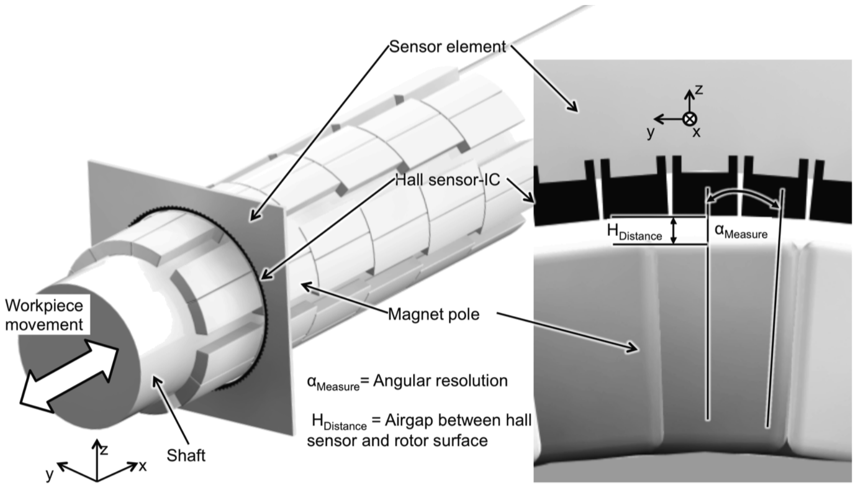


Fig. 82. The first concept covers a diameter specific ring type sensor.

Two applications of the line sensor elements are possible: A ring-line type sensor (Fig. 82) with one axial moved part (work piece or sensor) or a straight-line sensor with rotating work piece (Fig. 83). Both concepts have been discussed in [128].

The concept of a diameter specific ring sensor is shown in Fig. 82. The rotor is moved and positioned into a ring of discrete hall sensors. The concept can handle rotor lengths with the same diameter. The kinematic handling of moving the rotor through the fixed sensor is difficult, as the distance to each hall sensor element on the ring has to be kept precisely constant. A moving sensor in combination with a fixed rotor offers better guidance and tolerances. As the whole radius is read-out, a lot of hall elements are necessary at once to measure the field profile of the complete rotor. If less hall sensors are used around the rotor diameter resolution is lowered and the maximum permanent magnet field between two poles is not correctly measured. The method has been applied for patent under [129] as method for measuring stray flux in production of electric actuators.

The second concept of applying hall sensors is to arrange them in a line and move the work piece, e.g. the rotor. In this application, the radius of the rotor is not important for setting the distance of the measurement device, as it is adjustable. Fig. 83 shows a modular line layout with sets of hall sensor line elements, which can be combined flawlessly together for a desired length.

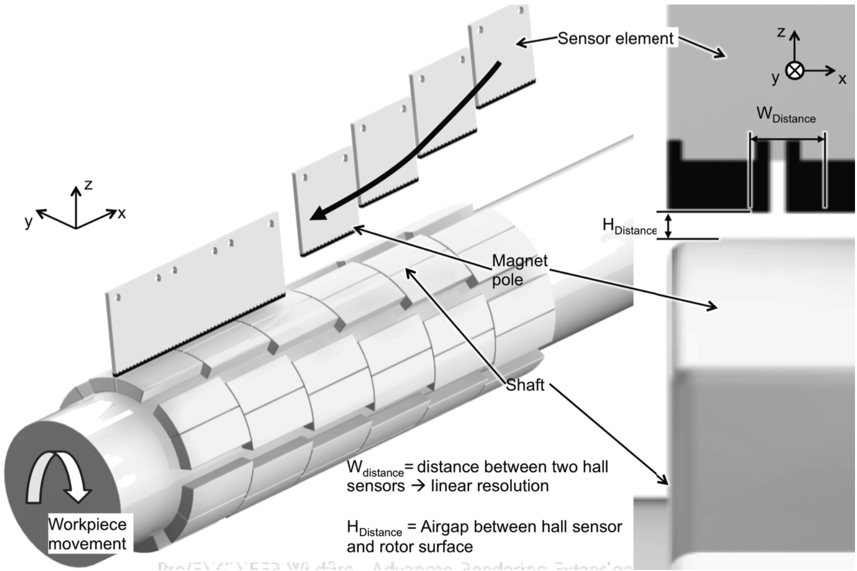


Fig. 83. The flexible line sensor consists of standard hall elements and can be combined to the necessary active length.

The main advantage is the correct measurement around the rotor radius. Even if only one hall sensor per assembled permanent magnet is used ($W_{Distance} \geq Length_{Magnet}$), the magnetic field of all permanent magnets can be measured for this line. For realization of a sensor for one- or multi-line measurements without sacrificing hall sensor elements (as in two-dimensional sensors, when only one line is read out), a line sensor has been developed with two demonstrator prototypes, the LINMAG-1 and -2.

The LINMAG-1 is built up with integrated THD hall sensor ICs, whereas the LINMAG-2 consists of SMD hall elements. Compared to integrated hall ICs the hall elements have a wider measurement range, but need more advanced read-out circuits. The number of hall elements has been expanded and created as PCB module.

The main goal of the development has been the evaluation of the resulting permanent magnet field deriving from production processes. The sensors have therefore been integrated into workplaces as proposal for production workplaces. Furthermore the workplaces can also be used for maintenance checks of permanent magnet assemblies of existing rotors.

8.5 The LINMAG-1 sensor

The LINMAG-1 design incorporates ratiometric linear hall effect sensor ICs from Allegro [130] and enables measurements for permanent magnets similar to the detector presented in [131] and [132]. The analog output voltage is directly converted by a 12-bit A/D converter-IC and sent via serial-peripheral interface (SPI) to an Arduino microcontroller for handling the SPI protocol and transmitting the value to a measurement PC. The PC based control [85] and the measurement program are implemented in one system avoiding additional hardware. In Fig. 84 the concept of the sensor read-out is depicted. The measurement itself is triggered by an encoder, which is directly connected to the rotor specimen. The rotor is then turned manually. For a given angle step parameter the readout of one line is taken automatically and added to a read-out ASCII-file. The result can be presented as three-dimensional plot.

The PC fulfills several tasks:

- Handling the measurement values from the controller
- Real-time handling of encoder triggers
- CNC positioning of sensor and rotor

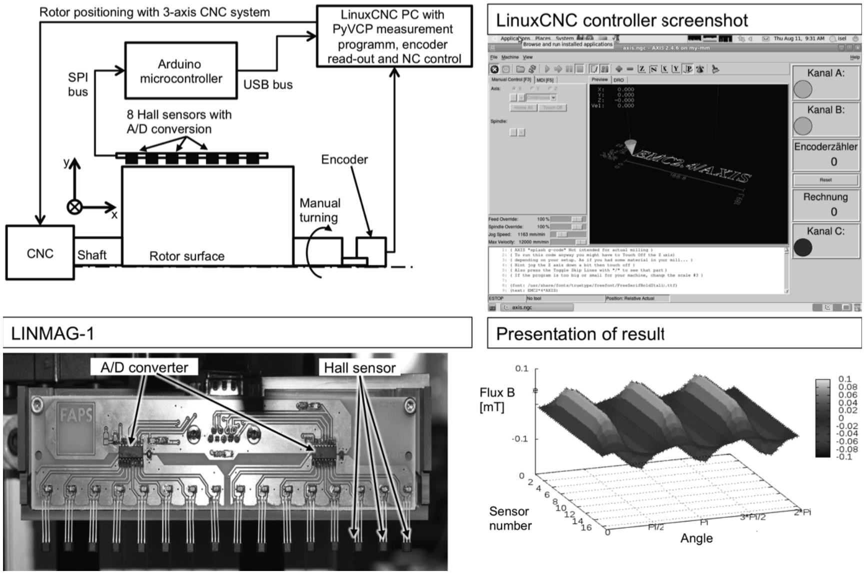


Fig. 84. The LINMAG-1 sensor system is based on 16 discrete hall sensors.

For better integration, the sensor must be easily adaptable to industrial equipment. A prototype system with a three-axis CNC to validate the principle has been build up. It consists of a XY- system for simplified loading of the rotor object and a Z-axis for the sensor position.

For proper loading of the rotor, a flexible fixture was designed. It consists of a chuck for sufficient holding with the adapted encoder feedback system. It delivers 6000 counts per revolution. The encoder steps for recording the next field value can be adjusted to fit the necessary wanted resolution over the rotor surface. Additionally the rotor is counter-parted with a height adjustable prism the shaft.

The CNC-program for the measurement process consists of the following actions:

- Inserting the rotor
- Closing the fixture
- Activate the loading motion program. The xy-table positions the rotor and the z-axis moves the sensor down for perpendicular measurement.
- Start of measurement. The rotor can be turned one revolution manually
- Automatically recall home position
- Open fixture
- Unloading of the fixture

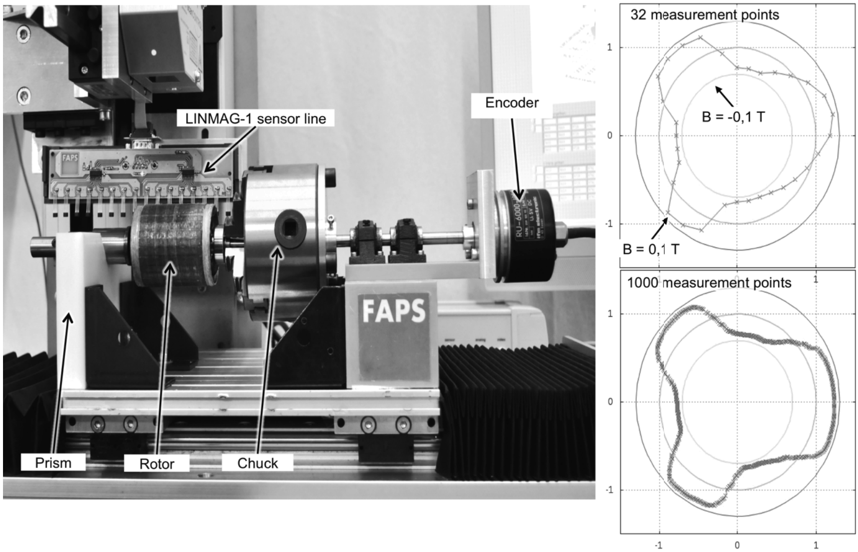


Fig. 85. The fixture for the prototype provides trigger and fixation elements.

First implementation tests showed a good response of the prototype hardware with the THD package devices. The minimum distance to the object has been determined as 2 mm. A closer distance leads to saturation of the integrated hall ICs, as the field strength increases. As the sensors have the same pin out, two versions have been built up. The presented measurements have been taken with the more sensitive A1301 hall sensor version (see also Tab. 10). Fig. 85 shows a synchronous rotor with three pole-pairs. Looking at the results, the number of measurement points clearly defines and structures the measured shapes.

Tab. 10. Maximum field intensity of the Allegro hall IC

Sensor name	Sensitivity per sensor	LINMAG-1 sensitivity (5 V supply)
Allegro A1301	2.5 mV/G	± 0,1 mT
Allegro A1302	1,3 mV/G	± 0,19 mT

For presentation of the measured values, a circle diagram represents the detected values for one sensor. The same rotor (see Fig. 85) has been measured with step lengths ranging from 1000 measurement points down to 32 measurement points. The magnetic flux profile gets more detailed with more points. The pictures do not start from exactly the same point, as the rotor has been rotated manually. The time for one measurement has been determined as 16,7 ms per line readout.

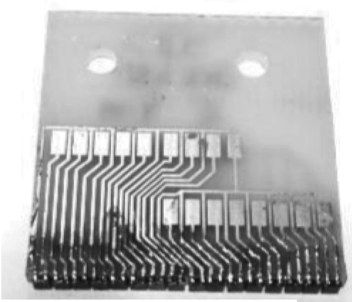
Tab. 11. Advantages and disadvantages of the LINMAG-1 system

Advantages	Disadvantages
Fast magnetic scan of rotors with different diameters possible	The THD-parts can easily bend and are not mechanically fixed.
Precise and adjustable angular correlation with measurement values	The measurement range is small. A “closer” look on the rotor surface is possible, until the sensor is saturated.
Seamless integration into CNC system enables manual and automatic movement of rotor	The axial distance (=resolution of line scanner) of the sensors
Immediate 3D representation of magnetic field values allow easy interpretation	The maximum number of sensors is limited 16 sensors by the sensor bus.

The characteristics of the prototype LINMAG-1 system (Tab. 11) offer a quick magnetic scan of a rotor specimen. Its handling has been designed for manual use, but can also be converted to an automated system. The system has drawbacks due to the mechanical design and the chosen integrated hall sensors with only a small field strength measurement capability, so it cannot be used for measurements very close to the surface.

8.6 The LINMAG-2 modular sensor

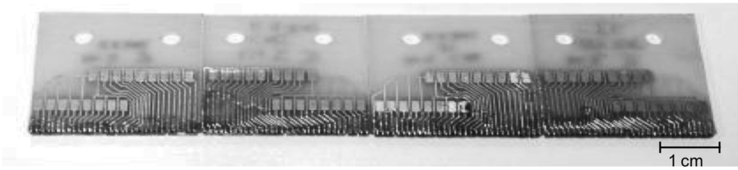
The drawbacks of the LINMAG-1 are the used THD hall sensor ICs, which limit the resolution and the possible minimal distance to the rotor surface. In the LINMAG-2, the hall ICs are replaced by hall elements with flexible adaption of measurement range. For the measurement system, additional hardware is required to read out the hall elements. The maximum number of sensors can also be increased and modularized with a change from THD to SMD technology. Due to the capability of measuring high field strengths, the sensors can be positioned as close as possible for highest radial field resolution. The measurement system is realized as stand-alone sensor for independent use.



One line module with 16 hall elements

- Single elements with 1,5 mm ± 0,1 mm x 2,5 mm (± 0,2 mm)
- One line module consists of 16 elements
- Four line modules form the LINMAG-2 (64 elements)

Parameter	Symbol	Value	Unit
Max. input current/ voltage	I_0, V_0	13 mA/ 10V	mA/V
Max. input Power	P_D	150	mW
Operating temperature range	T_A	-40 - 125	°C
Storage temperature range	T_S	-55 - 150	°C



Four line modules connected as line sensor

Fig. 86. The hall sensor line is extendable using further modules [133], [134].

The possible number of sensors has been expanded. For this aim an example for a programmable readout device was selected and eight modules of a flexible analog IO-module has been built up [135–142]. Each module is equipped with a multiplexer and a 16-bit AD converter [143], resulting in a 64 channel measurement device. If more channels (or Hallsensors respectively) are needed, further multiplexing of the eight channel modules or adding further devices is possible. The line resolution of the sensor pickup depends on the size of the discrete Hallelements. For a further improvement of the first LINMAG-1 demonstrator, SMD elements with an over all size of 1,5 x 1,5 mm have been chosen and placed on the layout with 1,875 mm distance in axial direction [133], [134].

Fig. 86 shows the modular PCB layout and the single sensor in custom 4-pin SMT package. It carries 16 Hallsensors and can be set perpendicular to reach the surface of the permanent magnet even for measurements on the inner diameter of outer rotor style motor designs. For the chosen 64 channel measurement device, 4 modules are set in one row resulting in 120 mm sensitive line length.

The complete standalone measurement system consists of three parts:

- The LINMAG-2 sensor head with four modules (4 x 16 Hallelements)
- The measurement rack for the sensor head
- PC with Labview control program

Fig. 87 presents the parts of the measurement system, consisting of the hardware sensor, the read-out with Labview and the 3D plot representation. The sensor can easily be mounted onto handling systems. Similar to the LINMAG-1 concept, external triggers can be fed via a digital I/O block to control the number of line read-outs.

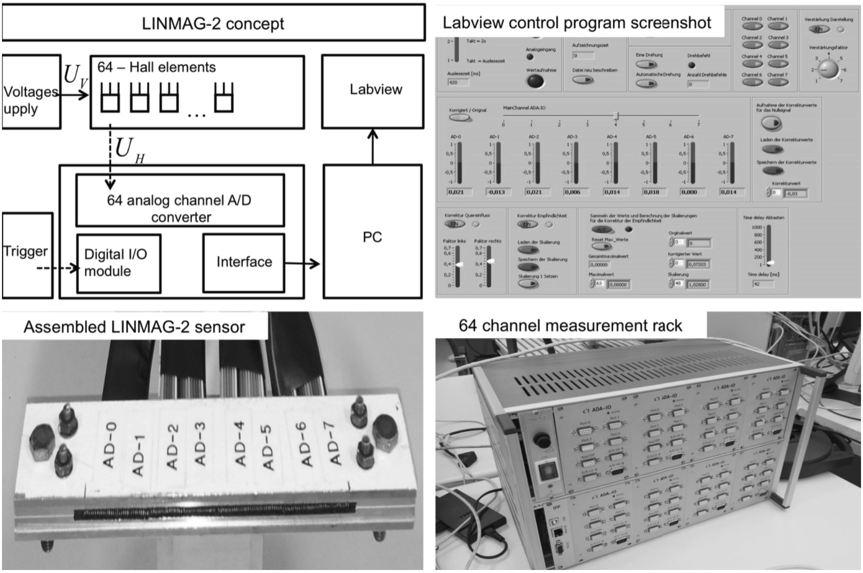


Fig. 87. The LINMAG-2 hardware can be used for flexible field measurements.

For live presentation of the measured fields, a qualitative 3D waterfall plot has been integrated. Additionally, the connectivity of the measurement rack is extended and provides common interfacing via Ethernet, serial USB and RS232. For larger systems with more sensors (128 and more) a second or more devices can be chained and synchronized.

Tab. 12. The calculated measurement cycle time of the LINMAG-2 system:

Data rate between measurement modules	38400 bit/s
Measurement result per module (= eight Hall elements)	4 ms
Additional A/D converter time	2-10 ms
Line read-out time (worst case)	**42 ms**

The sensor head can be referenced and calibrated for every sensor within the software. Therefore an offset calibration and peak value two-point calibration routine (with setting the maximum and minimum value with reference magnet source) with is integrated.

With the presented measurement system, permanent magnet excited rotors can be measured directly on the rotor surface with instant feedback. The readout speed of the LINMAG-2 is around 1,5 times faster than the LINMAG-1.

8.7 LINMAG-2 measurement for generator application

The LINMAG-2 sensor has been evaluated by measuring the outer runner rotor with permanent magnets as previously described. Therefore a simple change in the fixture system has been necessary removing the ELMAG gripper and substituting it with a simple gallows. The sensor is therefore attached to an aluminum bar and adjusted with a feeler gauge to ensure a distinct and repeatable distance to the surface of the permanent magnet.

Fig. 88 represents the measurement setup applied to the magnet placing workplace. For supplying the servo motor logic, an additional power supply has been added to avoid noise on the sensor. An extra encoder has been added to improve the rotational resolution up to 2500 counts per revolution, because the servomotor can only resolve 1024 counts. The encoder has been installed before the servomotor and enables a manual test. The encoder serves as position trigger, which is evaluated by an Arduino microcontroller computing the rotation direction and triggers impulses for the measurement AD-converter. The number for pulses can be programmed as gear-factor. For the tests, a maximum step rate has been used, so the gear-factor has been set to ‘1’.

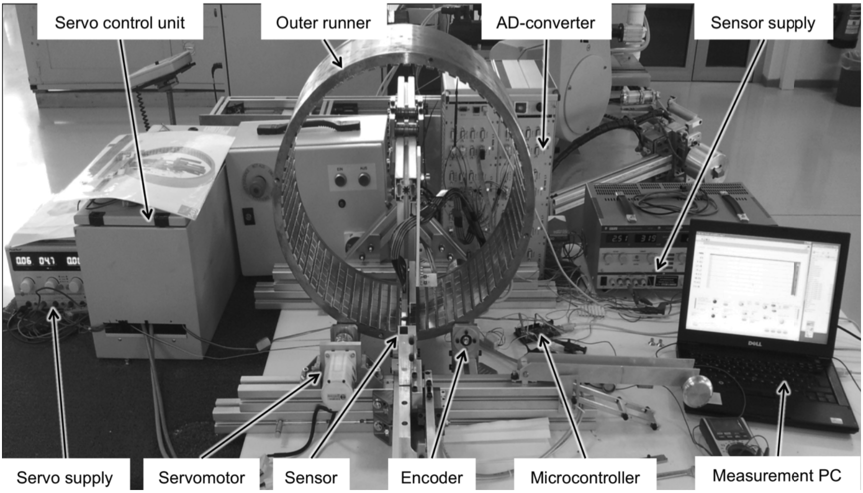


Fig. 88. The measurement setup for the LINMAG-2 line scanner

Manual tests without support of the servomotor showed, that a narrow point recording with high measurement frequency cannot be realized manually because of the large inertia of the rotor – it cannot be stopped and positioned accurately by hand. Therefore the measurement process has been switched to an automated rotor turning process with the servomotor as positioning device. Then two movement characteristics are possible:

- Distinct positioning and stopping for each measurement position
- Constant rotation of the rotor

The tested outer-runner diameter is about 500 mm, while the fixture rollers (one equipped with servo motor, the other one equipped with encoder) have a diameter of 40 mm. This results in a gear-factor of 12,5 between encoder and rotor. One turn of the rotor results in 31250 pulses that can be converted to 0,05 mm travel over the surface per pulse considering the perimeter of the rotor with 1570 mm. The active magnetic length of the rotor is larger than the sensor length. For that case the sensor has to be repositioned once in axial direction to detect the full field. This is done manually after measuring the first side of the ring. The sensor is reset to the second position and another measurement is taken. The resulting scan image of the rotor shows a complete representation of the real magnetic field created by the poles. For easy stitching of the single rows two reference values have been added to the values and are visualized as reference marks. Fig. 89 gives a complete overview of all 70 poles of the measurement. The reference marks are on top and on the bottom line, to be able to stitch the two measurement positions together. The magnet rows can be distinguished by the bright and dark representation of north and south pole.

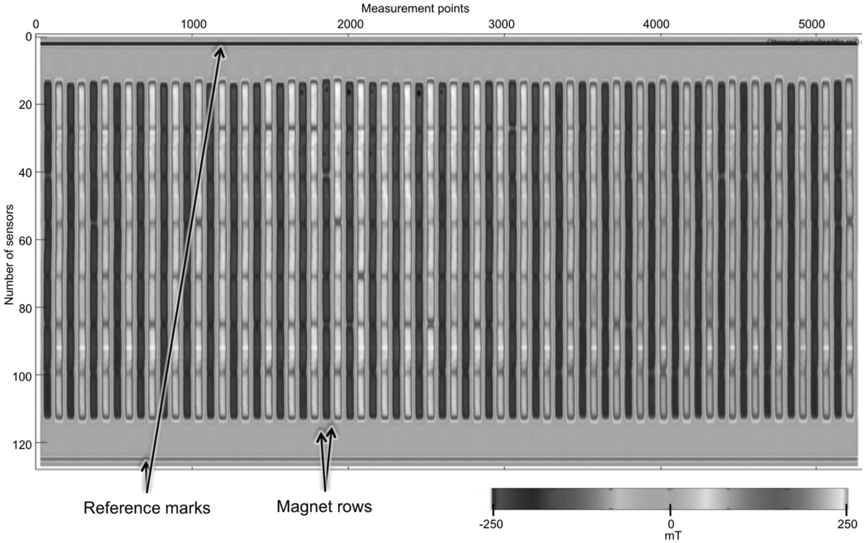


Fig. 89. Complete overview over resulting magnetic field of the rotor with 70 poles

The magnetic field is not perfectly sinusoidal as expected. The real field distribution consists of variations in the magnetic flux, causing magnetic misbalances of polarities and inhomogeneities in the magnet material. As described in previous chapters, the specified defect structures (see Fig. 23) are found on the rotor surface, too. The visual possibility of magnetic field recognition can lead to a better understanding of loss creation in the rotor stator combination. Displacements are found on this rotor, because it has been the lab demonstrator for realization of the first magnet assembly studies. Furthermore, differing magnet qualities have been used. Fig. 90 represents the part of the rotor with slight displacements of the rotor due to misalignment of the magnet. As presented, the consequence of mechanical misalignment during assembly leads to gaps in the magnetic field creation among the pole. If the permanent magnet is not exactly aligned, the magnetic field is also introduced with an angular displacement. For the given rotor, the assembly of several magnets should result in combined poles. A slight displacement leads to deep magnetic flux reductions in the flux image. Density gaps become clearly visible.

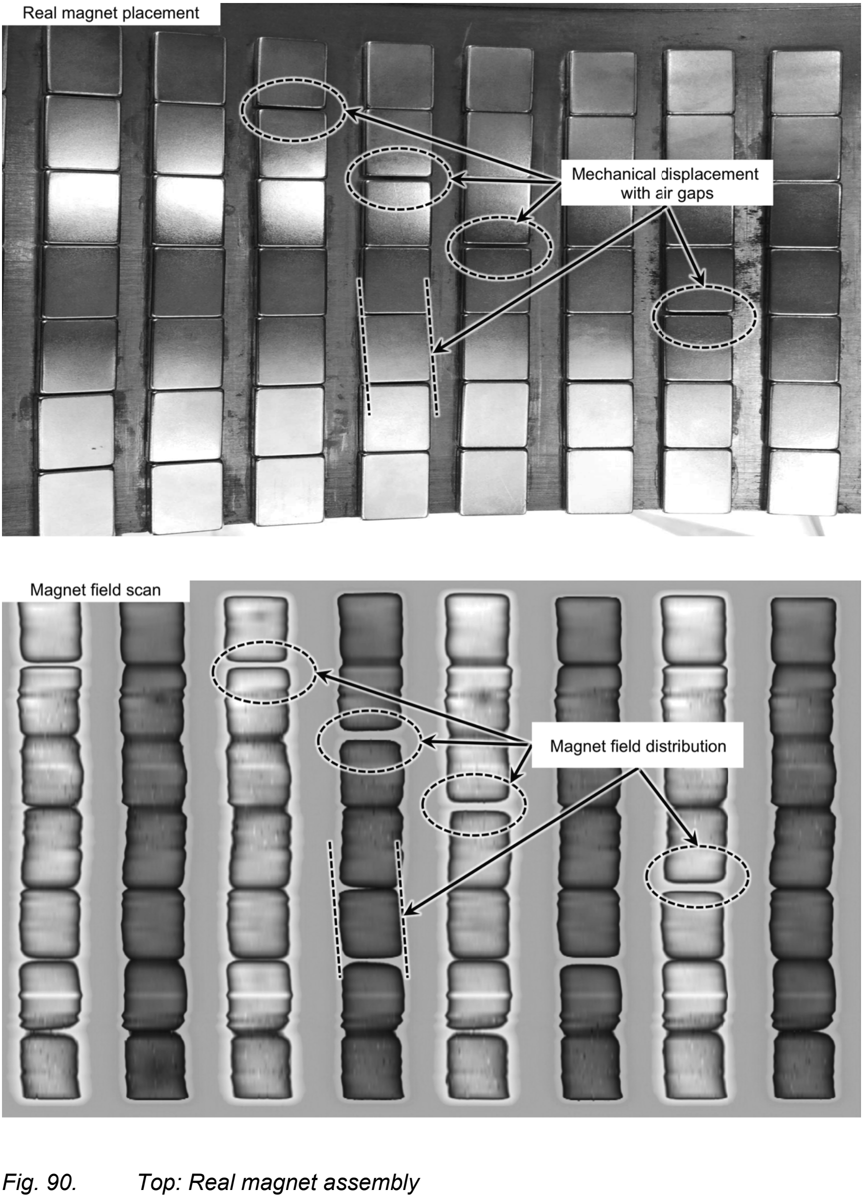


Fig. 90. *Top: Real magnet assembly*
Bottom: Resulting magnet field distribution measurement with the LINMAG-2

For well placed permanent magnet rows the magnetic field is not necessarly optimized as well. Fig. 91 gives an example of a standard assembly row. On the clean surface light scratches are visible, which can happen during manual separation (pull-off from a stack). The scratches are detected as variation in flux homogenization. Even for nearly gap free assembled magnets, the magnetic flux is clearly weaker at the junctions, because of the coating and the residual air gap, which are not contributing to the magnetic flux.

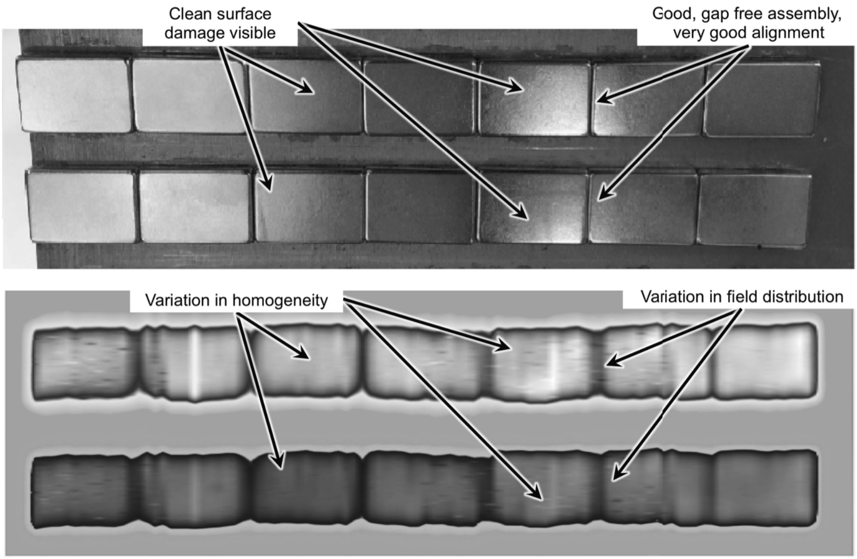


Fig. 91. For mechanically exactly placed rows, the magnetic field shows a differing picture of the real flux distribution.

The results enable insights into the resulting magnetic field. The size of the hall line sensor can be alternated with additional or less sensor modules. The readout interface can be optimized for rotor designs and magnetic materials.

Nevertheless the presented line sensor system also has drawbacks regarding the sensor resolution. The blurred representation of the poles can be caused by production differences between the single hall sensors and a slight displacement during the soldering. Furthermore the colored representation with an interpolation step in gnuplot can lead to increased distortions on the edges and corners of magnets and therefore to a reduction of the exactness of the measurements.

The sensor technology offers additional information compared to known industrial standards:

- Fast real time detection of polarity failures
- Measurement of magnetic field dependent on exact position
- Quality check of magnetic field homogeneity
- Recording of magnetic footprint: The individual magnetic field distribution can be mesaured and compared with later measurements (e.g. for maintenance comparison). Individual rotor ageing can then be evaluated.
- Real-time presentation of magnetic field
- Integration in workplace designs or fully automation process modules
- Real-time evaluation of exact field values for open circuit measurements
- Fast cycle times
- Magnetic imaging processes possible with further calculation incorporating visual imaging tools

As modern PM-motors include cost intensive magnet materials, maintenance cycles help to improve the lifetime of the motor. For larger drives, the rotor can be pulled out and the magnet material be checked for degradation. Furthermore, repair strategies can be developed with replacement of single magnet bodies as well as adjustments of frequency inverter control loops. The magnetic field measurement with a LINMAG offers a new process tool for the following scenarios:

- **Quality checks in mass production:** For mass and large batch size production of motors, the magnetic field check can be added in combination with traditional geometric and mechanical checks.
- **Changing supply chains:** If production lines are transferred to new sites and plants around the world, supply chains change. If the quality of suppliers varies, the inspection of the reached magnetic field ensures an early detection of failures.
- **Distributed manufacturing:** If the rotor and stator part is not produced at the same plant, a quality inspection of the magnetized rotor is possible to ensure constant quality level.
- **Improved design:** Customer specific motor designs demand high functional integrity of all calculated components. Modern FEM methods started to help designers to optimize motors for decent applications. With deeper insights into manufacturing, the calculation of the resulting field can be further improved.

8.8 Summary

In this chapter realizations for tracking the permanent magnet field of permanent magnet rotors have been presented. Available systems for measuring permanent magnets are given with the commercial MAGCAM and CMOS-MagView system. Initial measurements have been done and magnet characteristics are clearly worked out. With the ROBOTESLA, a six-axis robot has been combined with a traditional hall teslameter and is useful for flexible three-dimensional field evaluation. It adds

CAD/CAM path and spline planning features for online or offline programming. For transfer of the hall sensor measurements on a rotor, the LINMAG-1 sensor has been developed. It consists of a hall line sensor. Cylindrical rotor surfaces can therefore be probed and characterized after assembly of the rotor and provide new insights of field characteristics in mass production. Finally, the LINMAG-2 system is presented with a magnetic field characterization of the assembled outer runner, which has been assembled with the ELMAG system before.

9 Systems for Assembly and Measurement of Permanent Magnets

Permanent magnet excited electric motors are an important part of industrial applications and individual mobility concepts. The use of the permanent magnetic field enables optimal geometric integration of the motor, while highest power densities can be provided. In electric motor production systems, the handling and logistic of permanent magnets is focused by manufacturers. Research can support understanding and detection of magnetic properties and offer improvements of the processes.

Three concepts can be set up to explain necessary developments ranging from small prototyping, over medium batch to large scale mass production. From these scenarios, development of new process equipment for permanent magnet handling can be derived. This work focuses on two basic and urging manufacturing processes for permanent magnet excited motors: The handling and measurement of permanent magnets. All scenarios require solutions for further process development, cost reduction and equipment flexibility.

Handling processes differ in production due to numerous variants of motor designs, making it necessary to distinguish between SPM and IPM motor types. The size of the motor is an important factor for production sequences and alternative assembly strategies.

For the handling of magnets for SPM motors, the developments of gripper principles have been presented. It results in the mechatronic ELMAG-system and is ready for integration into workplace applications. Two semiautomatic workplaces have been realized for flexible production of small to medium batch sizes.

IPM technology arises as second design variant. It demands innovative automation methods for flexible mass production. The process forces for insertion of permanent magnets strongly demand automatic processes for small and larger motors. First, the handling device is able to detect the magnet slots in the lamination stack with an innovative cavity detection algorithm. It has been inserted twice into a workplace with a SCARA robot for smaller lamination stacks and into custom robot for loading magnetized magnets into a larger motor.

Magnetic measurements enable new possibilities for the manufacturers to establish additional quality controls. One goal is to understand the constant quality of magnetization characteristics of permanent magnets. A second goal for production is the integration of testing methods to ensure constant product quality. So the test method needs to be integrated out of the lab into the line.

New sensor concepts for measuring permanent magnets are shown, for single magnets and the assembled product. Basic implementations and evaluations are shown with a hall sensor array (MagCam) and a magneto-optical sensor (CMOS-MagView). An innovative method is presented with the developed hall line sensor system LINMAG, which enables exact field probing with adapted hardware in cycle time. Integration concepts and hardware realizations accompany the new measurement system. The given example of the outer runner produced during this work with the ELMAG gripper and measured with the LINMAG-system reveals that the manufacturing research topics discussed in this work are not finished yet, but issue new fascinating developments in the next years. Procedures will be developed for scanning rotors with maximum resolution during development and derived from these knowledge, adapted sensor arrangements for inline testing of previously specified spots will be realized and integrated.

Additional research topics arise and need to be addressed. A gap exists between simulation tools for magnetic fields and the real field generation in electric motors. In combination with magnetic measurements, correlations to simulation models can be improved. For evaluation of insertion forces during the assembly of IPM magnets, no simulation tool has been available for combined multi-physical determination of mechanical friction and magnetic field propagation. Simulation studies can therefore support development and process development for permanent magnet assembly.

The magnetization, the necessary tools and the simulation of the process are important steps for a better understanding of the production process. The gripper and handling solutions focus mainly on magnetized magnets. For IPM rotors with buried unmagnetized magnets innovative magnetization concepts will be necessary to reach full saturation of the magnetic material after assembly.

Regarding the magnetic fields, that have been measured with the LINMAG systems, the assembly of discrete permanent magnet bodies and the resulting air gaps lead to new requirements towards the generation of the permanent magnet field. Instead of the long process chain with production of the magnet body itself, its coating, the transport and the potential risks for damages during transport and handling in the assembly process, additive manufacturing methods with metal alloys offer innovative potentials for a substantial reduction of process steps. The magnetic field can then be “added” with the optimal amount and geometric form as initially designed by the motor developer.

10 Summary

Production methods for electric motors have been pushed due to increased demands for electric drives with optimized efficiency and flexible variant production in small, medium and large batch sizes tailored to suit industrial needs. Additional new markets arise from the technological shift from combustion based motors to electric drive systems.

The work presents the research work following the magnet supply chain from magnet supply to full assembly. Permanent magnet processing, the rotor designs and the transport handling are explained, including the logistics paths for magnets inside the factory to the assembly workplace. The process chains for three batch sizes and their effect on the design of workplaces for magnet assembly using SPM and IPM magnet technology are described and evaluated.

Derived from these process chains, gripper concepts for SPM-assembly have been evaluated, including the development of innovative gripper systems and the resulting electromagnetic gripper system. These grippers have been implemented in demonstrator workplaces for inner and outer runner rotors. Furthermore the results of flexible handling devices for IPM rotor assembly with the development of a vision tool for detecting the placing position in the lamination stack and its implementation in magnet insertion tools are presented.

The second part of the work presents new concepts for measuring the magnetic field of permanent magnets. Therefore available measurement equipment is presented. Measurement solutions for inline testing have been developed and realized within this work. These contain measurements with available devices and the development of an inline Hall sensor for scanning complete rotors.

11 Zusammenfassung

Produktionsprozesse für elektrische Maschinen haben in den vergangen Jahren einen zusätzlichen Schub durch eine verstärkte Nachfrage der Automobilindustrie erhalten. Insbesondere für Antriebsmotoren mit optimierter Leistung und flexibler Variantengeneration entstehen neue Märkte für Klein-, Mittel- und Großserie aus dem Technologieübergang vom Verbrennungs- zum elektrischen Motor. Die Verwendung permanentmagnetischer Werkstoffe im Rotorteil ermöglicht hierbei signifikante Verbesserungen der Leistungsentfaltung bei gleichzeitig verringertem Bauraum. Die Handhabung und der Test dieser Materialien im industriellen Umfeld sind Kern dieser Arbeit.

Die Arbeit umfasst die Betrachtung der Magnetzulieferkette von der Bereitstellung bis zur Montage. Hierzu werden die Magnetherstellverfahren, die verwendeten Rotorgeometrien und die Handhabung beim Transport magnetischer Materialien innerhalb der Fertigung bis zum Montageplatz erläutert. Die Prozessketten für drei unterschiedliche Losgrößenfertigungen und deren Auswirkung auf die jeweilige Arbeitsplatzgestaltung bei der Magnetmontage von oberflächen- (SPM) und innenverbauten (IPM) Magneten werden untersucht.

Von den Prozessketten werden Greifkonzepte für oberflächenbestückte Magnete abgeleitet. Diese werden nach Funktionsprinzipien unterteilt, wobei insbesondere das elektromagnetische Greifprinzip einen vielversprechenden Ansatz darstellt. Die realisierten Greifsysteme werden in Demonstrator Arbeitsplätzen für SPM und IPM montierte Magnete vorgestellt. Für IPM wurde hierzu ein kamerabasiertes Kavitätendetektionssystem aufgebaut, mit dem die Magnete automatisiert in das Blechpaket eingeführt werden können.

Der zweite Teil der Arbeit umfasst neue Konzepte zu Messung des Magnetfeldes von Magneten. Hierzu werden am Markt verfügbare Messprinzipien vorgestellt. Für die direkte Anwendung in der Montagelinie oder am Montageplatz werden Lösungen mit verfügbaren Sensorsystemen aufgezeigt. Für eine optimale Vermessung kompletter Rotoren ist ein inlinefähiges Hallsensorsystem aufgebaut worden. Dieses wird anhand eines aufgebauten Rotors vorgestellt.

12 Abbreviations

2D	2-dimensional
3D	3-dimensional
AMR	Anisotropic Magneto Resistance
AP	Axial Pressing
ASCII	American Standard Code for Information Interchange
ASTM	American Society for Testing and Materials
AWG	Average Wire Gauge
CAA	Computer Aided Assembling
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAI	Computer Aided Inspection
CAM	Computer Aided Manufacturing
CAP	Computer Aided Planning
CAPP	Computer Aided Process Planning
CAQ	Computer Aided Quality Assurance
CAR	Computer Aided Robotics
CIM	Computer Integrated Manufacturing
CNC	Computer Numerical Control
ELMAG	Electro Magnetic Gripper
EMC	Electromagnetic Compatibility
FAPS	Institute for Factory Automation and Production Systems
FEM	Finite Element Methode
FeCrCo	Iron Chromium Cobalt
GMR	Giant Magneto Resistance
HAST	Highly Accelerated Stress Test
HR	High-Remanent
ILI	In-line Inspection
IPM	Inner Permanent Magnet
MFL	Magnetic Flux Leakage

MnAlC	Manganese Aluminum Carbon
MO	Magneto-Optical
MTM	Methods-Time-Measurement
NC	Numerical Control
NdFeB	Neodymium-Iron-Boron
PCT	Pressure Cooker Test
PM	Permanent Magnet
PCB	Printed Circuit Board
PlP	Press-less Process
PtCo	Platinum Cobalt
PWM	Pulse Width Modulation
RH	Relative Humidity
SPM	Surface-Mounted Permanent Magnet
SPI	Serial Peripheral Interface
SST	Salt Spray Test
t_e	Executive Time
THB	Temperature Humidity Bias
t_r	Setup Time
TP	Transversal Pressing
UAS	Universal Analyzing System
UAT	Unbiased Autoclave Test
USPCT	Unsaturated Pressure Cooker Test

13 Literature

[1] BERNDL, J.: *Vorrichtung und Verfahren zum Bestücken eines Rotorblechpakets eines Rotors eines Elektromotors mit Magneten*. Bayerische Motoren Werke Aktiengesellschaft. December 2012. Publication nr. DE201110077215

[2] CASSING, W.: *Dauermagnete: Mess- und Magnetisiertechnik*. 1. ed., Expert Verlag. Renningen, 2007

[3] ANGERER, G.; ERDMANN, L.; MARSCHEIDER-WEIDEMANN, F.; SCHARP, M.; LUELLMANN, A.; HANDKE, V.; MARWEDE, M.: *Rohstoffe für Zukunftstechnologien Einfluss des branchenspezifischen Rohstoffbedarfs in rohstoffintensiven Zukunftstechnologien auf die zukünftige Rohstoffnachfrage*. Fraunhofer-IRB-Verl. Stuttgart, 2009

[4] LOHMANN, D.; PODBREGAR, N.: *Im Fokus: Bodenschätze: Auf der Suche nach Rohstoffen*. Springer. Heidelberg, 2012

[5] STEMME, O.: *Magnetismus: Grundlagen - Wirkungsweise - Anwendungen*. Maxon Acad. Sachseln, 2004

[6] TROUT, S.: *Understanding Permanent Magnet Materials; an Attempt at Universal Magnetic Literacy*. In: *Proceedings of EMCW*, Cincinnati, OH, USA, 2000

[7] MMPA STANDARD NO. 0100-00: *Standard Specifications for Permanent Magnet Materials*. Magnetic materials producers association (MMPA). URL www.smma.org/pdf/permanent-magnet-materials.pdf - last checked on 01/02/2013

[8] GOLDMAN, A.: *Handbook of Modern Ferromagnetic Materials*. Springer US. Boston, MA, 1999

[9] CULLITY, B.D.: *Introduction to Magnetic Materials*. 2. ed., IEEE/Wiley. Hoboken, N.J, 2009

[10] REPPEL, G. W.: *Duroplastgepresste Magnete–Werkstoffe, Verfahren und Eigenschaften*. In: *Kunststoffgebundene Dauermagnete, Springer-VDI-Verlag, Düsseldorf* (2004), p. 14–36

[11] TROUT, S.R.; WOOTEN, G.D.: *Selection and Specification of Permanent Magnet Materials*. In: *IEEE Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference*. *Cincinnati, USA* (2003), p. 59–63

[12] VUKOVICH, D.: *Magnet Tutorial*. URL http://www.allianceorg.com/pdfs/Magnet_Tutorial_v85_1.pdf - last checked on 21/11/2014

[13] Trémolet de Lacheisserie, E.; Gignoux, D.; Schlenker, M.: *Magnetism Materials and Applications*. Springer-Verlag New York. New York, NY, 2005

[14] Strnat, K.: *Permanent Magnet on the Basis of Cobalt-Rare Earth Alloys and Method for its Production*. December 1976. Publication nr. US3998669

[15] Greinacher, E.; Reinhardt, K.; Strnat, K.: *Method of Increasing the Coercive Force of Pulverized Rare Earth-Cobalt Alloys*. December 1977. Publication nr. US4063971

[16] Sagawa, M.; Fujimura, S.; Matsuura, Y.: *Magnetic Materials and Permanent Magnets*. December 1988. Publication nr. US4792368

[17] Croat, J.J.: *Boron, Praseodymium, Neodymium, and Iron*. July 1989. Publication nr. US4851058

[18] Rashidi, S.: *Use, Reduction and Probable Remedies of Heavy Rare Earth Metals in Neodymium Iron Boron Alloys*. In: *Magnetics 2012 Conference*, Olando, FL, USA, 13/03/2012

[19] Gutfleisch, O.; Woodcock, T.G.; Gueth, K.; Sawatzki, S.: *Magnetic Materials in Sustainable Energy*. In: *Prizztech Conference on Magnetic Materials in Electric Maschine Applications*, Pori, Finland, 06/2012

[20] Hono, K.; Sepehri-Amin, H.: *Strategy for High-Coercivity Nd–Fe–B Magnets*. In: *Scripta Materialia*, *vol. 67*, *no.* 6 (2012), p. 530–535

[21] Brown, D.; Ma, B.M.; Chen, Z.: *Developments in the Processing and Properties of NdFeB-Type Permanent Magnets*. In: *Journal of Magnetism and Magnetic Materials*, *vol. 248*, *no.* 3 (2002), p. 432–440

[22] Gutfleisch, O.; Khlopkov, K.; Teresiak, A.; Muller, K.-H.; Drazic, G.; Mishima, C.; Honkura, Y.: *Memory of Texture During HDDR Processing of NdFeB*. In: *IEEE Transactions on Magnetics*, *vol. 39*, *no.* 5 (2003), p. 2926–2931

[23] Molycorp: *Bonded Neo Powder History*. URL http://www.mqitechnology.com/bonded-neo-powder-history.jsp - last checked on 03/01/2013

[24] Nakayama, R.; Takeshita, T.; Itakura, M.; Kuwano, N.; Oki, K.: *Magnetic Properties and Microstructures of the Nd-Fe-B Magnet Powder Produced by Hydrogen Treatment-(II)*. In: *Journal of Applied Physics*, *vol. 67*, *no.* 9 (1990), p. 4665

[25] Livingston, J.D.: *A Review of Coercivity Mechanisms (invited)*. In: *Journal of Applied Physics*, *vol. 52*, *no.* 3 (1981), p. 2544–2548

[26] Schultz, L: *Hydrogenation Disproportionation Desorption and Recombination*

(HDDR). URL https://www.ifw-dresden.de/institutes/imw/research-departments/magnetism-and-superconductivity/functional-magnetic-materials-and-hydrides/permanent-magnet-materials/hddr/ - last checked on 02/01/2014

[27] SUGIMOTO, S.; BOOK, D.: *HDDR Process for the Production of High Performance Rare-Earth Magnets*. In: *Handbook of Advanced Magnetic Materials*. *Springer US*, *Boston, MA* (2006), p. 977–1007

[28] KANG, S.J.; KWON, H.W.: *Study on the Rigidity of the Solid - HDDR Treated Nd - Fe-B-type Materials*. In: *Journal of Magnetics*, *vol. 3* (1998), p. 9–14

[29] MCGUINESS, P.J.; DEVLIN, E.; HARRIS, I.R.; ROZENDAAL, E.; ORMEROD, J.: *A Study of Nd-Fe-B Magnets Produced Using a Combination of Hydrogen Decrepitation and Jet Milling*. In: *Journal of Materials Science*, *vol. 24*, *no.* 7 (1989), p. 2541–2548

[30] SAGAWA, M.: *NdFeB Magnets: Past, Present and Future*. In: *Prizztech Seminar on Advanced Magnetic Materials and their Applications*, Finland, 10/10/2007

[31] COEY, J. M. (ed.): *Rare-Earth Iron Permanent Magnets*. In: *Monographs on the physics and chemistry of materials*. Clarendon Press ; Oxford University Press. New York, 1996

[32] ELECTRONIC MATERIALS MANUFACTURERS ASSOCIATION OF JAPAN (EMAJ): *Magnet Story*. Jeita. Japan, 1998

[33] SCHATT, W.; WIETERS, K.P.; KIEBACK, B.: *Pulvermetallurgie Technologien und Werkstoffe*. 14. ed., Springer. Berlin, 2007

[34] TROUT, S.: *The End of Axial Pressing?* In: *Magnetics Magazine: Sponaneous thoughts*. URL http://www.magneticsmagazine.com/main/spontaneous-thoughts/the-end-of-axial-pressing/ - last checked on 09/10/2012

[35] HARRIS, I.R.; JEWELL, G.W.: *Rare-Earth Magnets: Properties, Processing and Applications*. In: *Functional Materials for Sustainable Energy Applications*. *Elsevier*, *Frankfurt* (2012), p. 600–639

[36] HILZINGER, R.: *Magnetic Materials: Fundamentals, Products, Properties, and Applications*. Publicis ; VAC, VACUUMSCHMELZE. Erlangen : Hanau, Germany, 2013

[37] GUTFLEISCH, O.: *Controlling the Properties of High Energy Density Permanent Magnetic Materials by Different Processing Routes*. In: *Journal of Physics D: Applied Physics*, *vol. 33*, *no.* 17 (2000), p. R157–R172

[38] GUTFLEISCH, O.; WILLARD, M.A.; BRÜCK, E.; CHEN, C.H.; SANKAR, S.G.; LIU, J.P.: *Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient*. In: *Advanced Materials*, *vol. 23*, *no.* 7 (2011), p. 821–842

[39] CONSTANTINIDES, S.: *The Important Role of Dysprosium in Modern Permanent Magnets*. URL http://www.arnoldmagnetics.com/WorkArea/DownloadAsset.aspx?id=5701 - last checked on 21/11/2014

[40] CHENG, C.W.: *Corrosion Protection of NdFeB Permanent Magnets*. The Hong Kong Polytechnic University, Hong Kong 1998

[41] MS SCHRAMBERG: *Beschichtungen*. Company brochure. URL http://www.magnete.de/uploads/media/beschichtungen_de.pdf, Schramberg, 04/11/2010

[42] MINOWA, T.; YOSHIKAWA, M.; HONSHIMA, M.: *Improvement of the Corrosion Resistance on Nd-Fe-B Magnet with Nickel Plating*. In: *IEEE Transactions on Magnetics*, *vol. 25*, *no.* 5 (1989), p. 3776–3778

[43] WALTON, A.; SPEIGHT, J.D.; WILLIAMS, A.J.; HARRIS, I.R.: *A Zinc Coating Method for Nd–Fe–B Magnets*. In: *Journal of Alloys and Compounds*, *vol. 306*, *no.* 1-2 (2000), p. 253–261

[44] DOBRZAŃSKI, L.A.; DRAK, M.; TRZASKA, J.: *Corrosion Resistance of the Polymer Matrix Hard Magnetic Composite Materials Nd–Fe–B*. In: *Journal of Materials Processing Technology*, *vol. 164–165* (2005), p. 795–804

[45] NINGBO MAGNETS: *Coating Instruction*. Acemade company datasheet, Ningbo, China 2013

[46] EL-MONEIM, A.A; GEBERT, A; UHLEMANN, M; GUTFLEISCH, O; SCHULTZ, L: *The Influence of Co and Ga Additions on the Corrosion Behavior of Nanocrystalline NdFeB Magnets*. In: *Corrosion Science*, *vol. 44*, *no.* 8 (2002), p. 1857–1874

[47] HUBERT, A.; SCHÄFER, R.: *Magnetic Domains: the Analysis of Magnetic Microstructures*. , 2009

[48] ASTM B117: *Practise for Operating Salt Spray (Fog) Apparatus*. ASTM International. URL http://www.astm.org/doiLink.cgi?B117 - last checked on 21/11/2014

[49] ISO: *Corrosion Tests in Artificial Atmospheres - Salt Spray Tests (ISO 9227:2012)*. International Organization for Standardization (ISO), Geneva, Switzerland 15/05/2012

[50] IEC: *IEC 60749-33 (Edition 1.0 2004-03) - Semiconductor Devices – Mechanical and Climatic Test Methods – Part 33: Accelerated Moisture Resistance – Unbiased Autoclave*. IEC international Standard, Geneva, Switzerland 15/07/2004

[51] YAMAMOTO, T.: *Humidity Measurement and Control in the HAST*. In: *Espec technology report No.5*. Espec, 1998

[52] JEDEC: *EIA JESD 22- A- 102-C - Accelerated Moisture Resistance - Unbiased Autoclave*. Joint Electronics Device Engineering Council (JEDEC), München 12/2000

[53] JEDEC: *EIA JESD 22- A-101-B - Steady State Temperature Humidity Bias Life Test*. Joint Electronics Device Engineering Council (JEDEC), München 03/2009

[54] DIN DEUTSCHES INSTITUT FÜR NORMUNG: *Paints and Varnishes: Determination of Resistance to Humidity : Part 2: Procedure for Exposing Test Specimens in Condensation-water Atmospheres (ISO 6270-2:2005) English Version of DIN EN ISO 6270-2*. In: *Deutsche Norm*. DIN Deutsches Institut für Normung. Berlin, 2005

[55] CONSTANTINIDES, S.; GULICK, D.: *NdFeB for High Temperature Motor Applications*. In: *SMMA Fall Technical Conference*, St. Louis, MO, USA, 03/11/2004

[56] VACUUMSCHMELZE: *PD 002 - VACODYM/VACOMAX · edition 2007*. Vacuumschmelze GmbH & Co. KG. Hanau, 2007

[57] TOLIYAT, H. A. ; KLIMAN, G. B. (eds.): *Handbook of Electric Motors*. 2nd ed., rev. and exp. ed., Marcel Dekker. New York, 2004

[58] JUNKER, S.: *Technologien und Systemlösungen für die flexibel automatisierte Bestückung permanenterregter Läufer mit oberflächenmontierten Dauermagneten*. 1. ed., Meisenbach publishing. Bamberg, 2007

[59] ABELE, M.G.: *Structures of Permanent Magnets: Generation of Uniform Fields*. John Wiley. New York, 1993

[60] STRNAT, K.: *Modern Permanent Magnets for Applications in Electro-Technology*. In: *Proceedings of the IEEE*, *vol. 78*, *no.* 6 (1990), p. 923–946

[61] PARKER, R.J.: *Permanent Magnet Guidelines*. Magnetic materials producers association (MMPA), Chicago, IL, USA 1998

[62] MICHALOWSKY, L.: *Magnettechnik: Grundlagen, Werkstoffe, Anwendungen*. Vulkan-Verl. Essen, 2006

[63] SCHROETER, K.-H.: *Dauermagnete - Werkstoffe und Systeme*. URL http://www.ibsmagnet.de/pdf/de/ibs_d.pdf - last checked on 22/11/2014

[64] NATIONAL IMPORTS LLC: *Permanent Magnet Design and Selection Handbook*. . Vienna/ USA, 2007

[65] STEINGROEVER, E.; ROSS, G.: *Magnetisieren, Entmagnetisieren und Kalibrieren von Permanent-Magnetsystemen*. Magnetphysik, Dr. Steingroever GmbH. Cologne, 2010

[66] N.N.: *Application note PE017: Messung von Magnetfeldern*. Projekt Elektronik GmbH, Berlin 27/07/2012

[67] N.N.: *Application note PE015: Messung zur Einhaltung der IATA 953 (früher 902)*. Projekt Elektronik GmbH, Berlin 03/05/2013

[68] TREMEL, J.; KREITLEIN, S.; FRANKE, J.: *Production Planning Scenarios for Manufacturing of Electric Drives*. In: *IEEE 2nd International Electric Drives Production Conference (EDPC)*. *Nürnberg* (2012), p. 1–9

[69] JUNKER, S.: *Gripper and Handling Device for Permanent Magnets Uses two Permanent Magnets which are Rotatable Between Accurate Pole Pieces to Attract or Repel Workpiece Magnets*. January 2006. Publication nr. DE202005017182U1

[70] MONKMAN, G. J. (ed.): *Robot Grippers*. Wiley-VCH. Weinheim, 2007

[71] TREMEL, J.; FRANKE, J.: *Handling and Assembly Methods for High Coercive Permanent Magnet Materials*. In: *Inductica: Coil Winding, Insulations & Electrical Manufacturing; International Conference and Exhibition*. *Berlin* (2010), p. 1–7

[72] TREMEL, J.: *Vorrichtung zum Greifen und Positionieren eines Permanentmagneten*. German Patent Office. February 2015. Publication nr. DE102013011513 B4

[73] FIORILLO, F.: *Measurement and Characterization of Magnetic Materials*. Elsevier Academic Press. Amsterdam, 2004

[74] MEEKER, D.: *FEMM: Finite Element Method Magnetics*. ver. FEMM 4.2, 2013

[75] KALLENBACH, E.: *Elektromagnete: Grundlagen, Berechnung, Entwurf und Anwendung*. Vieweg+Teubner Verlag. Wiesbaden, 2012

[76] FRANKE, J.; TREMEL, J.; KUEHL, A.: *Innovative Developments for Automated Magnet Handling and Bonding of Rare Earth Magnets*. In: *IEEE International Symposium on Assembly and Manufacturing (ISAM)*. *Tampere* (2011), p. 1–5

[77] KONOLD, P.; REGER, H.: *Praxis der Montagetechnik: Produktdesign, Planung, Systemgestaltung*. Vieweg. Wiesbaden, 2003

[78] STEGEMERTEN, G.J.; MAYNARD, H.B.; SCHWAB, J.L.: *Methods-Time Measurement*. Literary Licensing LLC. Secaucus, NJ, 2012

[79] WITTE, K.W.: *Neue Konzepte für wandlungsfähige Fabriken und Fabrikparks*. Shaker. Aachen, 2004

[80] VEREIN DEUTSCHER INGENIEURE ; LOTTER, B. ; WIENDAHL, H. P. (eds.): *Montage in der industriellen Produktion: ein Handbuch für die Praxis*. Springer. Berlin and New York, 2006

[81] MTM-ASSOCIATION: *MTM-Schulungsunterlagen*. German MTM Association e.V., Hamburg 2011

[82] BRITZKE, B.: *MTM in einer globalisierten Wirtschaft Arbeitsprozesse systematisch gestalten und optimieren*. mi-Wirtschaftsbuch. FinanzBuch-Verl. München, 2010

[83] BOKRANZ, R.; LANDAU, K.: *Produktivitätsmanagement von Arbeitssystemen: MTM-Handbuch*. Schäffer-Poeschel. Stuttgart, 2006

[84] CIF: *PRECITEC®-Hand Operated SMT Assembly Station*. URL http://www.cif.fr/en/manual-pick-place-stations/119-station-de-placement-manuel-professionnel-precitec.html - last checked on 21/11/2014

[85] LINUXCNC: *Linuxcnc - a Free and Powerful Machine Controller*. ver. LinuxCNC Live CD, 2013

[86] WILLIAMSON, M.; SOMMERKAMP, A.: *The Imaging and Vision Handbook*. Stemmer imaging GmbH. Puchheim, 2013

[87] JOSEPH, E.; TREMEL, J.; HOFMANN, B.; MEYER, A.; FRANKE, J.; ESCHRICH, S.: *Automated Magnet Assembly for Large PM Synchronous Machines with Integrated Permanent Magnets*. In: *IEEE 3rd International Electric Drives Production Conference (EDPC)*. *Nürnberg* (2013), p. 1–6

[88] NÜRNBERG, W.; HANITSCH, R.: *Die Prüfung elektrischer Maschinen*. Springer Berlin Heidelberg. Berlin, Heidelberg, 2001

[89] TUMANSKI, S.: *Handbook of Magnetic Measurements*. In: *Series in sensors*. Taylor & Fracis. Boca Raton, 2011

[90] LENZ, J.; EDELSTEIN, S.: *Magnetic Sensors and Their Applications*. In: *IEEE Sensors Journal*, *vol. 6*, *no.* 3 (2006), p. 631–649

[91] STEFANITA, C.: *Magnetism: Basics and Applications*. Springer. Berlin ; New York, 2012

[92] RAMSDEN, E.: *Hall-Effect Eensors: Theory and Applications*. 2nd. ed., Elsevier/Newnes. Amsterdam, 2006

[93] SIDES, C.: *AKM Hall-Effect Sensor Application*. URL http://www.akm.lfchosting.com/Brochures/HallSensorsTechnicalGuide.pdf - last checked on 21/11/2014

[94] RICHERT, H.; KOSCHNY, M.; HOLZEY, R.: *Far-Field Measurement: A New and Exciting Approach for Fast Magnet Characterization*. In: *Magnetics Technology International* (2012), p. 84–86

[95] LENZ, J.E.: *A Review of Magnetic Sensors*. In: *Proceedings of the IEEE*, *vol. 78*, *no.* 6 (1990), p. 973–989

[96] CARUSO, M.J.; BRATLAND, T.; SMITH, C.H.; SCHNEIDER, R.: *A New Perspective on Magnetic Field Sensing*. In: *Sensors Peterborough*, *vol. 15* (1998), p. 34–47

[97] HIROTA, E.; SAKAKIMA, H.; INOMATA, K.: *Giant Magneto-Resistance Devices*. Springer Berlin Heidelberg. Berlin, Heidelberg, 2002

[98] RIPKA, P. (ed.): *Magnetic Sensors and Magnetometers*. In: *Artech House remote sensing library*. Artech House. Boston, 2001

[99] MAGNETPHYSIK: *Sensor Foil 2174*. URL http://www.magnetphysik.de/fileadmin/Mediendatenbank/1_Produkte/2_Messtechnik/Datenblätter/Sensor_Foil_2174.pdf - last checked on 01/10/2011

[100] GIERAS, J.F.: *Axial Flux Permanent Magnet Brushless Machines*. 2. ed., Springer. New York, 2008

[101] BROCKHAUS MESSTECHNIK: *Gaussmeter 425*. URL http://www.brockhaus.com/en/measurements/measuring-technology-for-hard-magnetic-materials/gaussmeter/425/ - last checked on 21/11/2014

[102] MAGSYS: *Hand Gaussmeter HGM09s with Polarity Indicator*. URL http://www.magsys.de/index.php/en/products-and-services/hand-gaussmeter - last checked on 02/01/2013

[103] POPOVIĆ, R. S.: *Hall Effect Devices*. In: *Series in sensors*. 2. ed., CRC Press. Bristol; Philadelphia, 2004

[104] HONEYWELL: *Hall Effect Sensing and Application*. Honeywell Sensing and Control Sensing and Control Honeywell Inc., Freeport, Illinois, USA 2013

[105] VERVAEKE, K.: *Inline Magnet Inspection Using Fast High Resolution MagCam Magnetic Field Mapping and Analysis*. In: *IEEE 1st International Electric Drives Production Conference (EDPC)*. *Nürnberg* (2011), p. 172–180

[106] LAKESHORE CRYOTRONICS: *VSM 7400 - Vibrating Sample Vibrometer*. Lakeshore, Westerville, OH, USA 02/2013

[107] STEINGROEVER, E.; ROSS, G.: *Magnetische Messtechnik*. Magnetphysik, Dr. Steingroever GmbH. Cologne, 1997

[108] MAGNETPHYSIK: *PERMAGRAPH® L- for the Computer Controlled Measurement of Hysteresis Curves of Hard Magnetic Materials*. URL http://www.magnetphysik.de/fileadmin/Mediendatenbank/1_Produkte/2_Messtechnik/Datenbl%C3%A4tter/Permagraph_L_e_2094.pdf - last checked on 01/10/2013

[109] TUMANSKI, S.: *Induction Coil Sensors—A Review*. In: *Measurement Science and Technology*, *vol. 18*, *no.* 3 (2007), p. R31

[110] BROCKHAUS MESSTECHNIK: *XYZ Field Scanner*. URL http://www.brockhaus.com/en/measurements/measuring-technology-for-hard-magnetic-materials/xyz-field-scanner/ - last checked on 21/11/2014

[111] ORTH, T.; KAACK, M.; FISCHER, G.; WEINGARTEN, W.; KOKA, A.; NITSCHE, S.; ARZT, N.: *Neue Rohrendenprüfung für nahtlose Stahlrohre*. In: *DACH Jahrestagung*, St. Gallen, Switzerland, 2008

[112] KREUTZBRUCK, M.; NEUBAUER, A.; PELKNER, M.; REIMUND, V.: *Adapted GMR Array Used in Magnetic Flux Leakage Inspection*. In: *18th Wold Conference on Nondestructive Testing*. *Durban, South Africa* (2012), p. 1–8

[113] HETTERICH, M.; FLOCKE, H.: *Hochauflösende magnetische Zeilenkamera für die 2D- und 3D-Messung von Magnetfeldern*. iC-Haus GmbH. URL http://dx.doi.org/10.2314/GBV:723701962 - last checked on 21/11/2014

[114] ALBANESE, R; LEE, J.; LEE, H.; SHOJI, T.; MINKOV, D.: *Application of Magneto-Optical Method for Inspection of the Internal Surface of a Tube*. In: *Electromagnetic nondestructive evaluation (II)*, *NDT*, *vol. 2* (1998), p. 49

[115] WECKENMANN, A.; WERNER, T.: *Produktion: Messen und Prüfen*. In: *Masing Handbuch Qualitätsmanagement*. *Carl Hanser Verlag GmbH & Co. KG*, *München* (2014), p. 623–664

[116] VERVAEKE, K.: *MAGCAM Base Measurement Platform - User Manual*. MagCam. Leuven, 2012

[117] KOSCHNY, M.; LINDNER, M.: *Magische Momente beim Visualisieren von Magnetfeldern.* In: *Werkstoffe in der Fertigung, Fachzeitschrift für technische Führungskräfte*. URL http://werkstoffzeitschrift.de/blogwerkstoffe/magische-momente-beim-visualisieren-von-magnetfeldern/ - last checked on 26/02/2012

[118] VERVAEKE, K.: *Large Area Magnetic Field Camera for Inline Motor Magnet Inspection*. In: *IEEE 2nd International Electric Drives Production Conference (EDPC)*. *Nürnberg* (2012), p. 1–9

[119] FRANKE, J.; DOBROSCHKE, A.; TREMEL, J.; KUEHL, A.: *Innovative Processes and Systems for the Automated Manufacture, Assembly and Test of Magnetic Components for Electric Motors*. In: *IEEE 1st International Electric Drives Production Conference (EDPC)*. *Nürnberg* (2011), p. 228–234

[120] MS SCHRAMBERG: *NdFeB_342_135*. URL http://www.magnete.de/uploads/tx_fbmagneticfieldcalc/NdFeB_342_135_Version_04-2010.pdf - last checked on 22/11/2014

[121] SÜPTITZ, R.: *Einfluss homogener und inhomogener Magnetfelder auf die Korrosion ferromagnetischer Elektroden*. Leibniz Institut für Festkörper- und Werkstoffforschung Dresden, Institut für metallische Materialien. PhD thesis.

2011

[122] WEICKHMANN, M.: *Nd-Fe-B Magnets, Properties and Applications*. Vacuumschmelze GmbH & Co. KG. Hanau, Germany, 2009

[123] BOERGERMANN, F. J.; MARKS, S.: *Hot/cold-Side Characterization of Asymmetric Undulator Magnets*. In: *Proceedings of the 2nd International Particle and Accelerator Conference (IPAC)* (2011), p. 3257–3259

[124] LINDNER, M.; KOSCHNY, M.: *Magneto-Optical Sensors Accurately Analyze Magnetic Field Distribution of Magnetic Materials*. In: *Advanced Materials & Processes (AMP) ASM International* (2012), p. 13–16

[125] LINDNER, M.; KOSCHNY, M.: *Magnetooptische Analyse und Visualisierung der Verteilung magnetischer Felder*. In: *Photonik*, *no.* 1 (2012), p. 34–37

[126] CARAT: *Famos Robotics Offline Programming Tool*. ver. V8, Carat Robotic Innovation GmbH. Dortmund, 2012

[127] BROCKHAUS MESSTECHNIK: *Rotor Tester*. URL http://www.brockhaus.com/en/measurements/measuring-technology-for-hard-magnetic-materials/rotor-tester/ - last checked on 21/11/2014

[128] TREMEL, J.; FRANKE, J.: *Hall Sensor Line Array for Magnetic Field Inline Measurements of PM-Excited Rotors*. In: *IEEE 2nd International Electric Drives Production Conference (EDPC)*. *Nürnberg* (2012), p. 1–4

[129] HAUENSTEIN, R.; TREMEL, J.: *Method for Determining Operability of Magnetic Valve in Gear Box in Production Line, Involves Comparing Detected Field Distribution of Magnetic Valve with Reference Values of Field Distribution of Field of Functional Valve Without Air Gap*. January 2014. Publication nr. DE201210211272

[130] BURZALOW, C.: *A1301 and A1302: Continuous-Time Ratiometric Linear Hall Effect Sensor ICs*. Allegromicro, Worcester, Massachusetts, USA 2013

[131] KLOSTER, A.: *Aufbau einer Entwicklungsplattform für niederfrequente magnetische Prüfverfahren*. Naturwissenschaftlich-Technische Fakultät III Chemie, Pharmazie, Bio- und Werkstoffwissenschaften der Universität des Saarlandes. PhD thesis. 2008

[132] TUMANSKI, S.; BARANOWSKI, S.: *Magnetic Sensor Array for Investigations of Magnetic Field Distribution*. In: *Journal of Electrical Engineering*, *vol. 57* (2006), p. 185–188

[133] LIU, J.: *CYSJ106A GaAs Hall-Effect Elements*. URL http://www.hallsensors.de/CYSJ106A.pdf - last checked on 21/11/2012

[134] LIU, J.: *CYSJ166A GaAs Hall-Effect Elements*. URL

http://www.hallsensors.de/CYSJ166A.pdf - last checked on 21/11/2012

[135] MEYER, C.: *Fernwirkung*. In: *c't Magazin für Computer Technik*, *Praxis - Messen, Steuern, Regeln: Projekt: Bausteine zum Messen, Steuern und Regeln mit dem PC*, *no.* 10 (2007), p. 124–129

[136] MEYER, C.: *Leitungsschau*. In: *c't Magazin für Computer Technik*, *Praxis - Messen, Steuern, Regeln: c't-Lab: PC-Interface und Stromversorgung*, *no.* 10 (2007), p. 130–135

[137] MEYER, C.: *Modulbaukasten*. In: *c't Magazin für Computer Technik*, *Praxis - Messen, Steuern, Regeln:Projekt c't-Lab: A/D-, D/A- und Port-Motherboard ADA-IO*, *no.* 11 (2007), p. 212–217

[138] MEYER, C.: *Komplementäres Paar*. In: *c't Magazin für Computer Technik*, *Praxis - Messen, Steuern, Regeln: Projekt c't-Lab: A/D- und D/A-Wandler für Port-Modul ADA-IO*, *no.* 13 (2007), p. 202–207

[139] MEYER, C.: *Schwingungsformer*. In: *c't Magazin für Computer Technik*, *Praxis - Messen, Steuern, Regeln: Projekt c't-Lab: DDS-Funktionsgenerator-Modul*, *no.* 15 (2007), p. 188–195

[140] MEYER, C.: *Schalt- und Waltstelle*. In: *c't Magazin für Computer Technik*, *Praxis - Messen, Steuern, Regeln:Projekt c't-Lab: Bedienpanel und Stromversorgung*, *no.* 16 (2007), p. 176–179

[141] MEYER, C.: *Blick ins Labor*. In: *c't Magazin für Computer Technik*, *Praxis - Messen, Steuern, Regeln: c't-Lab: Grafische Programmierumgebung LabVIEW richtig einsetzen*, *no.* 18 (2007), p. 186–197

[142] MEYER, C.: *Kleinkraftwerk*. In: *c't Magazin für Computer Technik*, *Praxis - Messen, Steuern, Regeln: c't-lab: Programmierbares Netzteil-Modul DCG*, *no.* 19 (2007), p. 212–219

[143] LINEAR TECHNOLOGY CORPORATION: *LTC1865 - µPower, 16-Bit, 250ksps 1- and 2-Channel ADCs in MSOP*. URL http://www.linear.com/product/LTC1865 - last checked on 01/03/2013

Reihe Fertigungstechnik - Erlangen

www.mb.uni-erlangen.de/diss

Band 1 - 52
Carl Hanser Verlag, München

ab Band 53
Meisenbach Verlag, Bamberg
45,-- Euro

Band 1: Andreas Hemberger
Innovationspotentiale in der rechnerintegrierten Produktion durch wissensbasierte Systeme
208 Seiten, 107 Bilder. 1988.

Band 2: Detlef Classe
Beitrag zur Steigerung der Flexibilität automatisierter Montagesysteme durch Sensorintegration und erweiterte Steuerungskonzepte
194 Seiten, 70 Bilder. 1988.

Band 3: Friedrich–Wilhelm Nolting
Projektierung von Montagesystemen
201 Seiten, 107 Bilder, 1 Tabelle. 1989.

Band 4: Karsten Schlüter
Nutzungsgradsteigerung von Montagesystemen durch den Einsatz der Simulationstechnik
177 Seiten, 97 Bilder. 1989.

Band 5: Shir–Kuan Lin
Aufbau von Modellen zur Lageregelung von Industrierobotern
168 Seiten, 46 Bilder. 1989.

Band 6: Rudolf Nuss
Untersuchungen zur Bearbeitungsqualität im Fertigungssystem Laserstrahlschneiden
206 Seiten, 115 Bilder, 6 Tabellen. 1989.

Band 7: Wolfgang Scholz
Modell zur datenbankgestützten Planung automatisierter Montageanlagen
194 Seiten, 89 Bilder. 1989.

Band 8: Hans–Jürgen Wißmeier
Beitrag zur Beurteilung des Bruchverhaltens von Hartmetall–Fließpreßmatrizen
179 Seiten, 99 Bilder, 9 Tabellen. 1989.

Band 9: Rainer Eisele
Konzeption und Wirtschaftlichkeit von Planungssystemen in der Produktion
183 Seiten, 86 Bilder. 1990.

Band 10: Rolf Pfeiffer
Technologisch orientierte Montageplanung am Beispiel der Schraubtechnik
216 Seiten, 102 Bilder, 16 Tabellen. 1990.

Band 11: Herbert Fischer
Verteilte Planungssysteme zur Flexibilitätssteigerung der rechnerintegrierten Teilefertigung
201 Seiten, 82 Bilder. 1990.

Band 12: Gerhard Kleineidam
CAD/CAP: Rechnergestützte Montagefeinplanung
203 Seiten, 107 Bilder. 1990.

Band 13: Frank Vollertsen
Pulvermetallurgische Verarbeitung eines übereutektoiden verschleißfesten Stahls
XIII u. 217 Seiten, 67 Bilder, 34 Tabellen. 1990.

Band 14: Stephan Biermann
Untersuchungen zur Anlagen– und Prozeßdiagnostik für das Schneiden mit CO_2–Hochleistungslasern
VIII u. 170 Seiten, 93 Bilder, 4 Tabellen. 1991.

Band 15: Uwe Geißler
Material– und Datenfluß in einer flexiblen Blechbearbeitungszelle
124 Seiten, 41 Bilder, 7 Tabellen. 1991.

Band 16: Frank Oswald Hake
Entwicklung eines rechnergestützten Diagnosesystems für automatisierte Montagezellen
XIV u. 166 Seiten, 77 Bilder. 1991.

Band 17: Herbert Reichel
Optimierung der Werkzeugbereitstellung durch rechnergestützte Arbeitsfolgenbestimmung
198 Seiten, 73 Bilder, 2 Tabellen. 1991.

Band 18: Josef Scheller
Modellierung und Einsatz von Softwaresystemen für rechnergeführte Montagezellen
198 Seiten, 65 Bilder. 1991.

Band 19: Arnold vom Ende
Untersuchungen zum Biegeumformen mit elastischer Matrize
166 Seiten, 55 Bilder, 13 Tabellen. 1991.

Band 20: Joachim Schmid
Beitrag zum automatisierten Bearbeiten von Keramikguß mit Industrierobotern
XIV u. 176 Seiten, 111 Bilder, 6 Tabellen. 1991.

Band 21: Egon Sommer
Multiprozessorsteuerung für kooperierende Industrieroboter in Montagezellen
188 Seiten, 102 Bilder. 1991.

Band 22: Georg Geyer
Entwicklung problemspezifischer Verfahrensketten in der Montage
192 Seiten, 112 Bilder. 1991.

Band 23: Rainer Flohr
Beitrag zur optimalen Verbindungstechnik in der Oberflächenmontage (SMT)
186 Seiten, 79 Bilder. 1991.

Band 24: Alfons Rief
Untersuchungen zur Verfahrensfolge Laserstrahlschneiden und –schweißen in der Rohkarosseriefertigung
VI u. 145 Seiten, 58 Bilder, 5 Tabellen. 1991.

Band 25: Christoph Thim
Rechnerunterstützte Optimierung von Materialflußstrukturen in der Elektronikmontage durch Simulation
188 Seiten, 74 Bilder. 1992.

Band 26: Roland Müller
CO_2 -Laserstrahlschneiden von kurzglasverstärkten Verbundwerkstoffen
141 Seiten, 107 Bilder, 4 Tabellen. 1992.

Band 27: Günther Schäfer
Integrierte Informationsverarbeitung bei der Montageplanung
195 Seiten, 76 Bilder. 1992.

Band 28: Martin Hoffmann
Entwicklung einer CAD/CAM–Prozeßkette für die Herstellung von Blechbiegeteilen
149 Seiten, 89 Bilder. 1992.

Band 29: Peter Hoffmann
Verfahrensfolge Laserstrahlschneiden und –schweißen : Prozeßführung und Systemtechnik in der 3D–Laserstrahlbearbeitung von Blechformteilen
186 Seiten, 92 Bilder, 10 Tabellen. 1992.

Band 30: Olaf Schrödel
Flexible Werkstattsteuerung mit objektorientierten Softwarestrukturen
180 Seiten, 84 Bilder. 1992.

Band 31: Hubert Reinisch
Planungs– und Steuerungswerkzeuge zur impliziten Geräteprogrammierung in Roboterzellen
XI u. 212 Seiten, 112 Bilder. 1992.

Band 32: Brigitte Bärnreuther
Ein Beitrag zur Bewertung des Kommunikationsverhaltens von Automatisierungsgeräten in flexiblen Produktionszellen
XI u. 179 Seiten, 71 Bilder. 1992.

Band 33: Joachim Hutfless
Laserstrahlregelung und Optikdiagnostik in der Strahlführung einer CO_2-Hochleistungslaseranlage
175 Seiten, 70 Bilder, 17 Tabellen. 1993.

Band 34: Uwe Günzel
Entwicklung und Einsatz eines Simulationsverfahrens für operative und strategische Probleme der Produktionsplanung und –steuerung
XIV u. 170 Seiten, 66 Bilder, 5 Tabellen. 1993.

Band 35: Bertram Ehmann
Operatives Fertigungscontrolling durch Optimierung auftragsbezogener Bearbeitungsabläufe in der Elektronikfertigung
XV u. 167 Seiten, 114 Bilder. 1993.

Band 36: Harald Kolléra
Entwicklung eines benutzerorientierten Werkstattprogrammiersystems für das Laserstrahlschneiden
129 Seiten, 66 Bilder, 1 Tabelle. 1993.

Band 37: Stephanie Abels
Modellierung und Optimierung von Montageanlagen in einem integrierten Simulationssystem
188 Seiten, 88 Bilder. 1993.

Band 38: Robert Schmidt–Hebbel
Laserstrahlbohren durchflußbestimmender Durchgangslöcher
145 Seiten, 63 Bilder, 11 Tabellen. 1993.

Band 39: Norbert Lutz
Oberflächenfeinbearbeitung keramischer Werkstoffe mit XeCl–Excimerlaserstrahlung
187 Seiten, 98 Bilder, 29 Tabellen. 1994.

Band 40: Konrad Grampp
Rechnerunterstützung bei Test und Schulung an Steuerungssoftware von SMD–Bestücklinien
178 Seiten, 88 Bilder. 1995.

Band 41: Martin Koch
Wissensbasierte Unterstützung der Angebotsbearbeitung in der Investitionsgüterindustrie
169 Seiten, 68 Bilder. 1995.

Band 42: Armin Gropp
Anlagen– und Prozeßdiagnostik beim Schneiden mit einem gepulsten Nd:YAG–Laser
160 Seiten, 88 Bilder, 7 Tabellen. 1995.

Band 43: Werner Heckel
Optische 3D–Konturerfassung und on–line Biegewinkelmessung mit dem Lichtschnittverfahren
149 Seiten, 43 Bilder, 11 Tabellen. 1995.

Band 44: Armin Rothhaupt
Modulares Planungssystem zur Optimierung der Elektronikfertigung
180 Seiten, 101 Bilder. 1995.

Band 45: Bernd Zöllner
Adaptive Diagnose in der Elektronikproduktion
195 Seiten, 74 Bilder, 3 Tabellen. 1995.

Band 46: Bodo Vormann
Beitrag zur automatisierten Handhabungsplanung komplexer Blechbiegeteile
126 Seiten, 89 Bilder, 3 Tabellen. 1995.

Band 47: Peter Schnepf
Zielkostenorientierte Montageplanung
144 Seiten, 75 Bilder. 1995.

Band 48: Rainer Klotzbücher
Konzept zur rechnerintegrierten Materialversorgung in flexiblen Fertigungssystemen
156 Seiten, 62 Bilder. 1995.

Band 49: Wolfgang Greska
Wissensbasierte Analyse und Klassifizierung von Blechteilen
144 Seiten, 96 Bilder. 1995.

Band 50: Jörg Franke
Integrierte Entwicklung neuer Produkt– und Produktionstechnologien für räumliche spritzgegossene Schaltungsträger (3-D MID)
196 Seiten, 86 Bilder, 4 Tabellen. 1995.

Band 51: Franz–Josef Zeller
Sensorplanung und schnelle Sensorregelung für Industrieroboter
190 Seiten, 102 Bilder, 9 Tabellen. 1995.

Band 52: Michael Solvie
Zeitbehandlung und Multimedia–Unterstützung in Feldkommunikationssystemen
200 Seiten, 87 Bilder, 35 Tabellen. 1996.

Band 53: Robert Hopperdietzel
Reengineering in der Elektro- und Elektronikindustrie
180 Seiten, 109 Bilder, 1 Tabelle. 1996.
ISBN 3-87525-070-2

Band 54: Thomas Rebhan
Beitrag zur Mikromaterialbearbeitung mit Excimerlasern – Systemkomponenten und Verfahrensoptimierungen
148 Seiten, 61 Bilder, 10 Tabellen. 1996.
ISBN 3-87525-075-3

Band 55: Henning Hanebuth
Laserstrahlhartlöten mit Zweistrahltechnik
157 Seiten, 58 Bilder, 11 Tabellen. 1996.
ISBN 3-87525-074-5

Band 56: Uwe Schönherr
Steuerung und Sensordatenintegration für flexible Fertigungszellen mit kooperierenden Robotern
188 Seiten, 116 Bilder, 3 Tabellen. 1996.
ISBN 3-87525-076-1

Band 57: Stefan Holzer
Berührungslose Formgebung mit Laserstrahlung
162 Seiten, 69 Bilder, 11 Tabellen. 1996.
ISBN 3-87525-079-6

Band 58: Markus Schultz
Fertigungsqualität beim 3D–Laserstrahlschweißen von Blechformteilen
165 Seiten, 88 Bilder, 9 Tabellen. 1997.
ISBN 3-87525-080-X

Band 59: Thomas Krebs
Integration elektromechanischer CA–Anwendungen über einem STEP–Produktmodell
198 Seiten, 58 Bilder, 8 Tabellen. 1997.
ISBN 3-87525-081-8

Band 60: Jürgen Sturm
Prozeßintegrierte Qualitätssicherung in der Elektronikproduktion
167 Seiten, 112 Bilder, 5 Tabellen. 1997.
ISBN 3-87525-082-6

Band 61: Andreas Brand
Prozesse und Systeme zur Bestückung räumlicher elektronischer Baugruppen (3D-MID)
182 Seiten, 100 Bilder. 1997.
ISBN 3-87525-087-7

Band 62: Michael Kauf
Regelung der Laserstrahlleistung und der Fokusparameter einer CO_2-Hochleistungslaseranlage
140 Seiten, 70 Bilder, 5 Tabellen. 1997.
ISBN 3-87525-083-4

Band 63: Peter Steinwasser
Modulares Informationsmanagement in der integrierten Produkt– und Prozeßplanung
190 Seiten, 87 Bilder. 1997.
ISBN 3-87525-084-2

Band 64: Georg Liedl
Integriertes Automatisierungskonzept für den flexiblen Materialfluß in der Elektronikproduktion
196 Seiten, 96 Bilder, 3 Tabellen. 1997.
ISBN 3-87525-086-9

Band 65: Andreas Otto
Transiente Prozesse beim Laserstrahlschweißen
132 Seiten, 62 Bilder, 1 Tabelle. 1997.
ISBN 3-87525-089-3

Band 66: Wolfgang Blöchl
Erweiterte Informationsbereitstellung an offenen CNC–Steuerungen zur Prozeß– und Programmoptimierung
168 Seiten, 96 Bilder. 1997.
ISBN 3-87525-091-5

Band 67: Klaus–Uwe Wolf
Verbesserte Prozeßführung und Prozeßplanung zur Leistungs– und Qualitätssteigerung beim Spulenwickeln
186 Seiten, 125 Bilder. 1997.
ISBN 3-87525-092-3

Band 68: Frank Backes
Technologieorientierte Bahnplanung für die 3D–Laserstrahlbearbeitung
138 Seiten, 71 Bilder, 2 Tabellen. 1997.
ISBN 3-87525-093-1

Band 69: Jürgen Kraus
Laserstrahlumformen von Profilen
137 Seiten, 72 Bilder, 8 Tabellen. 1997.
ISBN 3-87525-094-X

Band 70: Norbert Neubauer
Adaptive Strahlführungen für CO_2-Laseranlagen
120 Seiten, 50 Bilder, 3 Tabellen. 1997.
ISBN 3-87525-095-8

Band 71: Michael Steber
Prozeßoptimierter Betrieb flexibler Schraubstationen in der automatisierten Montage
168 Seiten, 78 Bilder, 3 Tabellen. 1997.
ISBN 3-87525-096-6

Band 72: Markus Pfestorf
Funktionale 3D–Oberflächenkenngrößen in der Umformtechnik
162 Seiten, 84 Bilder, 15 Tabellen. 1997.
ISBN 3-87525-097-4

Band 73: Volker Franke
Integrierte Planung und Konstruktion von Werkzeugen für die Biegebearbeitung
143 Seiten, 81 Bilder. 1998.
ISBN 3-87525-098-2

Band 74: Herbert Scheller
Automatisierte Demontagesysteme und recyclinggerechte Produktgestaltung elektronischer Baugruppen
184 Seiten, 104 Bilder, 17 Tabellen. 1998.
ISBN 3-87525-099-0

Band 75: Arthur Meßner
Kaltmassivumformung metallischer Kleinstteile – Werkstoffverhalten, Wirkflächenreibung, Prozeßauslegung
164 Seiten, 92 Bilder, 14 Tabellen. 1998.
ISBN 3-87525-100-8

Band 76: Mathias Glasmacher
Prozeß– und Systemtechnik zum Laserstrahl–Mikroschweißen
184 Seiten, 104 Bilder, 12 Tabellen. 1998.
ISBN 3-87525-101-6

Band 77: Michael Schwind
Zerstörungsfreie Ermittlung mechanischer Eigenschaften von Feinblechen mit dem Wirbelstromverfahren
124 Seiten, 68 Bilder, 8 Tabellen. 1998.
ISBN 3-87525-102-4

Band 78: Manfred Gerhard
Qualitätssteigerung in der Elektronikproduktion durch Optimierung der Prozeßführung beim Löten komplexer Baugruppen
179 Seiten, 113 Bilder, 7 Tabellen. 1998.
ISBN 3-87525-103-2

Band 79: Elke Rauh
Methodische Einbindung der Simulation in die betrieblichen Planungs– und Entscheidungsabläufe
192 Seiten, 114 Bilder, 4 Tabellen. 1998.
ISBN 3-87525-104-0

Band 80: Sorin Niederkorn
Meßeinrichtung zur Untersuchung der Wirkflächenreibung bei umformtechnischen Prozessen
99 Seiten, 46 Bilder, 6 Tabellen. 1998.
ISBN 3-87525-105-9

Band 81: Stefan Schuberth
Regelung der Fokuslage beim Schweißen mit CO_2–Hochleistungslasern unter Einsatz von adaptiven Optiken
140 Seiten, 64 Bilder, 3 Tabellen. 1998.
ISBN 3-87525-106-7

Band 82: Armando Walter Colombo
Development and Implementation of Hierarchical Control Structures of Flexible Production Systems Using High Level Petri Nets
216 Seiten, 86 Bilder. 1998.
ISBN 3-87525-109-1

Band 83: Otto Meedt
Effizienzsteigerung bei Demontage und Recycling durch flexible Demontagetechnologien und optimierte Produktgestaltung
186 Seiten, 103 Bilder. 1998.
ISBN 3-87525-108-3

Band 84: Knuth Götz
Modelle und effiziente Modellbildung zur Qualitätssicherung in der Elektronikproduktion
212 Seiten, 129 Bilder, 24 Tabellen. 1998.
ISBN 3-87525-112-1

Band 85: Ralf Luchs
Einsatzmöglichkeiten leitender Klebstoffe zur zuverlässigen Kontaktierung elektronischer Bauelemente in der SMT
176 Seiten, 126 Bilder, 30 Tabellen. 1998.
ISBN 3-87525-113-7

Band 86: Frank Pöhlau
Entscheidungsgrundlagen zur Einführung räumlicher spritzgegossener Schaltungsträger (3–D MID)
144 Seiten, 99 Bilder. 1999.
ISBN 3-87525-114-8

Band 87: Roland T. A. Kals
Fundamentals on the miniaturization of sheet metal working processes
128 Seiten, 58 Bilder, 11 Tabellen. 1999.
ISBN 3-87525-115-6

Band 88: Gerhard Luhn
Implizites Wissen und technisches Handeln am Beispiel der Elektronikproduktion
252 Seiten, 61 Bilder, 1 Tabelle. 1999.
ISBN 3-87525-116-4

Band 89: Axel Sprenger
Adaptives Streckbiegen von Aluminium–Strangpreßprofilen
114 Seiten, 63 Bilder, 4 Tabellen. 1999.
ISBN 3-87525-117-2

Band 90: Hans–Jörg Pucher
Untersuchungen zur Prozeßfolge Umformen, Bestücken und Laserstrahllöten von Mikrokontakten
158 Seiten, 69 Bilder, 9 Tabellen. 1999.
ISBN 3-87525-119-9

Band 91: Horst Arnet
Profilbiegen mit kinematischer Gestalterzeugung
128 Seiten, 67 Bilder, 7 Tabellen. 1999.
ISBN 3-87525-120-2

Band 92: Doris Schubart
Prozeßmodellierung und Technologieentwicklung beim Abtragen mit CO_2-Laserstrahlung
133 Seiten, 57 Bilder, 13 Tabellen. 1999.
ISBN 3-87525-122-9

Band 93: Adrianus L. P. Coremans
Laserstrahlsintern von Metallpulver – Prozeßmodellierung, Systemtechnik, Eigenschaften laserstrahlgesinterter Metallkörper
184 Seiten, 108 Bilder, 12 Tabellen. 1999.
ISBN 3-87525-124-5

Band 94: Hans-Martin Biehler
Optimierungskonzepte für Qualitätsdatenverarbeitung und Informationsbereitstellung in der Elektronikfertigung
194 Seiten, 105 Bilder. 1999.
ISBN 3-87525-126-1

Band 95: Wolfgang Becker
Oberflächenausbildung und tribologische Eigenschaften excimerlaserstrahlbearbeiteter Hochleistungskeramiken
175 Seiten, 71 Bilder, 3 Tabellen. 1999.
ISBN 3-87525-127-X

Band 96: Philipp Hein
Innenhochdruck-Umformen von Blechpaaren: Modellierung, Prozeßauslegung und Prozeßführung
129 Seiten, 57 Bilder, 7 Tabellen. 1999.
ISBN 3-87525-128-8

Band 97: Gunter Beitinger
Herstellungs- und Prüfverfahren
für thermoplastische Schaltungsträger
169 Seiten, 92 Bilder, 20 Tabellen. 1999.
ISBN 3-87525-129-6

Band 98: Jürgen Knoblach
Beitrag zur rechnerunterstützten verursachungsgerechten Angebotskalkulation von Blechteilen mit Hilfe wissensbasierter Methoden
155 Seiten, 53 Bilder, 26 Tabellen. 1999.
ISBN 3-87525-130-X

Band 99: Frank Breitenbach
Bildverarbeitungssystem zur Erfassung der Anschlußgeometrie
elektronischer SMT-Bauelemente
147 Seiten, 92 Bilder, 12 Tabellen. 2000.
ISBN 3-87525-131-8

Band 100: Bernd Falk
Simulationsbasierte Lebensdauervorhersage
für Werkzeuge der Kaltmassivumformung
134 Seiten, 44 Bilder, 15 Tabellen. 2000.
ISBN 3-87525-136-9

Band 101: Wolfgang Schlögl
Integriertes Simulationsdaten-Management
für Maschinenentwicklung und Anlagenplanung
169 Seiten, 101 Bilder, 20 Tabellen. 2000.
ISBN 3-87525-137-7

Band 102: Christian Hinsel
Ermüdungsbruchversagen hartstoffbeschichteter
Werkzeugstähle in der Kaltmassivumformung
130 Seiten, 80 Bilder, 14 Tabellen. 2000.
ISBN 3-87525-138-5

Band 103: Stefan Bobbert
Simulationsgestützte Prozessauslegung
für das Innenhochdruck-Umformen von Blechpaaren
123 Seiten, 77 Bilder. 2000.
ISBN 3-87525-145-8

Band 104: Harald Rottbauer
Modulares Planungswerkzeug
zum Produktionsmanagement in der Elektronikproduktion
166 Seiten, 106 Bilder. 2001.
ISBN 3-87525-139-3

Band 105: Thomas Hennige
Flexible Formgebung von Blechen durch Laserstrahlumformen
119 Seiten, 50 Bilder. 2001.
ISBN 3-87525-140-7

Band 106: Thomas Menzel
Wissensbasierte Methoden für die rechnergestützte Charakterisierung
und Bewertung innovativer Fertigungsprozesse
152 Seiten, 71 Bilder. 2001.
ISBN 3-87525-142-3

Band 107: Thomas Stöckel
Kommunikationstechnische Integration der Prozeßebene
in Produktionssysteme durch Middleware-Frameworks
147 Seiten, 65 Bilder, 5 Tabellen. 2001.
ISBN 3-87525-143-1

Band 108: Frank Pitter
Verfügbarkeitssteigerung von Werkzeugmaschinen
durch Einsatz mechatronischer Sensorlösungen
158 Seiten, 131 Bilder, 8 Tabellen. 2001.
ISBN 3-87525-144-X

Band 109: Markus Korneli
Integration lokaler CAP-Systeme
in einen globalen Fertigungsdatenverbund
121 Seiten, 53 Bilder, 11 Tabellen. 2001.
ISBN 3-87525-146-6

Band 110: Burkhard Müller
Laserstrahljustieren mit Excimer-Lasern – Prozeßparameter und Modelle zur Aktorkonstruktion
128 Seiten, 36 Bilder, 9 Tabellen. 2001
ISBN 3-87525-159-8

Band 111: Jürgen Göhringer
Integrierte Telediagnose via Internet zum effizienten Service von Produktionssystemen
178 Seiten, 98 Bilder, 5 Tabellen. 2001.
ISBN 3-87525-147-4

Band 112: Robert Feuerstein
Qualitäts- und kosteneffiziente Integration neuer Bauelementetechnologien in die Flachbaugruppenfertigung
161 Seiten, 99 Bilder, 10 Tabellen. 2001.
ISBN 3-87525-151-2

Band 113: Marcus Reichenberger
Eigenschaften und Einsatzmöglichkeiten alternativer Elektroniklote in der Oberflächenmontage (SMT)
165 Seiten, 97 Bilder, 18 Tabellen. 2001.
ISBN 3-87525-152-0

Band 114: Alexander Huber
Justieren vormontierter Systeme mit dem Nd:YAG-Laser unter Einsatz von Aktoren
122 Seiten, 58 Bilder, 5 Tabellen. 2001.
ISBN 3-87525-153-9

Band 115: Sami Krimi
Analyse und Optimierung von Montagesystemen in der Elektronikproduktion
155 Seiten, 88 Bilder, 3 Tabellen. 2001.
ISBN 3-87525-157-1

Band 116: Marion Merklein
Laserstrahlumformen von Aluminiumwerkstoffen - Beeinflussung der Mikrostruktur und der mechanischen Eigenschaften
122 Seiten, 65 Bilder, 15 Tabellen. 2001.
ISBN 3-87525-156-3

Band 117: Thomas Collisi
Ein informationslogistisches Architekturkonzept zur Akquisition simulationsrelevanter Daten
181 Seiten, 105 Bilder, 7 Tabellen. 2002.
ISBN 3-87525-164-4

Band 118: Markus Koch
Rationalisierung und ergonomische Optimierung im Innenausbau durch den Einsatz moderner Automatisierungstechnik
176 Seiten, 98 Bilder, 9 Tabellen. 2002.
ISBN 3-87525-165-2

Band 119: Michael Schmidt
Prozeßregelung für das Laserstrahl-Punktschweißen in der Elektronikproduktion
152 Seiten, 71 Bilder, 3 Tabellen. 2002.
ISBN 3-87525-166-0

Band 120: Nicolas Tiesler
Grundlegende Untersuchungen zum Fließpressen metallischer Kleinstteile
126 Seiten, 78 Bilder, 12 Tabellen. 2002.
ISBN 3-87525-175-X

Band 121: Lars Pursche
Methoden zur technologieorientierten Programmierung für die 3D-Lasermikrobearbeitung
111 Seiten, 39 Bilder, 0 Tabellen. 2002.
ISBN 3-87525-183-0

Band 122: Jan-Oliver Brassel
Prozeßkontrolle beim Laserstrahl-Mikroschweißen
148 Seiten, 72 Bilder, 12 Tabellen. 2002.
ISBN 3-87525-181-4

Band 123: Mark Geisel
Prozeßkontrolle und –steuerung beim Laserstrahlschweißen mit den Methoden der nichtlinearen Dynamik
135 Seiten, 46 Bilder, 2 Tabellen. 2002.
ISBN 3-87525-180-6

Band 124: Gerd Eßer
Laserstrahlunterstützte Erzeugung metallischer Leiterstrukturen auf Thermoplastsubstraten für die MID-Technik
148 Seiten, 60 Bilder, 6 Tabellen. 2002.
ISBN 3-87525-171-7

Band 125: Marc Fleckenstein
Qualität laserstrahl-gefügter Mikroverbindungen elektronischer Kontakte
159 Seiten, 77 Bilder, 7 Tabellen. 2002.
ISBN 3-87525-170-9

Band 126: Stefan Kaufmann
Grundlegende Untersuchungen zum Nd:YAG- Laserstrahlfügen von Silizium für Komponenten der Optoelektronik
159 Seiten, 100 Bilder, 6 Tabellen. 2002.
ISBN 3-87525-172-5

Band 127: Thomas Fröhlich
Simultanes Löten von Anschlußkontakten elektronischer Bauelemente mit Diodenlaserstrahlung
143 Seiten, 75 Bilder, 6 Tabellen. 2002.
ISBN 3-87525-186-5

Band 128: Achim Hofmann
Erweiterung der Formgebungsgrenzen beim Umformen von Aluminiumwerkstoffen durch den Einsatz prozessangepasster Platinen
113 Seiten, 58 Bilder, 4 Tabellen
ISBN 3-87525-182-2

Band 129: Ingo Kriebitzsch
3 - D MID Technologie in der Automobilelektronik
129 Seiten, 102 Bilder, 10 Tabellen. 2002.
ISBN 3-87525-169-5

Band 130: Thomas Pohl
Fertigungsqualität und Umformbarkeit laserstrahlgeschweißter Formplatinen aus Aluminiumlegierungen
133 Seiten, 93 Bilder, 12 Tabellen. 2002
ISBN 3-87525-173-3

Band 131: Matthias Wenk
Entwicklung eines konfigurierbaren Steuerungssystems für die flexible Sensorführung von Industrierobotern
167 Seiten, 85 Bilder, 1 Tabelle. 2002.
ISBN 3-87525-174-1

Band 132: Matthias Negendanck
Neue Sensorik und Aktorik für Bearbeitungsköpfe zum Laserstrahlschweißen
116 Seiten, 60 Bilder, 14 Tabellen
ISBN 3-87525-184-9

Band 133: Oliver Kreis
Integrierte Fertigung –
Verfahrensintegration durch Innenhochdruck-Umformen, Trennen und Laserstrahlschweißen in einem Werkzeug sowie ihre tele- und multimediale Präsentation
167 Seiten, 90 Bilder, 43 Tabellen
ISBN 3-87525-176-8

Band 134: Stefan Trautner
Technische Umsetzung produktbezogener Instrumente der Umweltpolitik bei Elektro- und Elektronikgeräten
179 Seiten, 92 Bilder, 11 Tabellen. 2002.
ISBN 3-87525-177-6

Band 135: Roland Meier
Strategien für einen produktorientierten Einsatz räumlicher spritzgegossener Schaltungsträger (3-D MID)
155 Seiten, 88 Bilder, 14 Tabellen. 2002.
ISBN 3-87525-178-4

Band 136: Jürgen Wunderlich
Kostensimulation – Simulationsbasierte Wirtschaftlichkeitsregelung komplexer Produktionssysteme
202 Seiten, 119 Bilder, 17 Tabellen. 2002.
ISBN 3-87525-179-2

Band 137: Stefan Novotny
Innenhochdruck-Umformen von Blechen aus Aluminium- und Magnesiumlegierungen bei erhöhter Temperatur
132 Seiten, 82 Bilder, 6 Tabellen. 2002.
ISBN 3-87525-185-7

Band 138: Andreas Licha
Flexible Montageautomatisierung zur Komplettmontage flächenhafter Produktstrukturen durch kooperierende Industrieroboter
158 Seiten, 87 Bilder, 8 Tabellen. 2003.
ISBN 3-87525-189-X

Band 139: Michael Eisenbarth
Beitrag zur Optimierung der Aufbau- und Verbindungstechnik für mechatronische Baugruppen
207 Seiten, 141 Bilder, 9 Tabellen. 2003.
ISBN 3-87525-190-3

Band 140: Frank Christoph
Durchgängige simulationsgestützte Planung von Fertigungseinrichtungen der Elektronikproduktion
187 Seiten, 107 Bilder, 9 Tabellen. 2003.
ISBN 3-87525-191-1

Band 141: Hinnerk Hagenah
Simulationsbasierte Bestimmung der zu erwartenden Maßhaltigkeit für das Blechbiegen
131 Seiten, 36 Bilder, 26 Tabellen. 2003.
ISBN 3-87525-192-X

Band 142: Ralf Eckstein
Scherschneiden und Biegen metallischer Kleinstteile – Materialeinfluss und Materialverhalten
148 Seiten, 71 Bilder, 19 Tabellen. 2003.
ISBN 3-87525-193-8

Band 143: Frank H. Meyer-Pittroff
Excimerlaserstrahlbiegen dünner metallischer Folien mit homogener Lichtlinie
138 Seiten, 60 Bilder, 16 Tabellen. 2003.
ISBN 3-87525-196-2

Band 144: Andreas Kach
Rechnergestützte Anpassung von Laserstrahlschneidbahnen an Bauteilabweichungen
139 Seiten, 69 Bilder, 11 Tabellen. 2004.
ISBN 3-87525-197-0

Band 145: Stefan Hierl
System- und Prozeßtechnik für das simultane Löten mit Diodenlaserstrahlung von elektronischen Bauelementen
124 Seiten, 66 Bilder, 4 Tabellen. 2004.
ISBN 3-87525-198-9

Band 146: Thomas Neudecker
Tribologische Eigenschaften keramischer Blechumformwerkzeuge- Einfluss einer Oberflächenendbearbeitung mittels Excimerlaserstrahlung
166 Seiten, 75 Bilder, 26 Tabellen. 2004.
ISBN 3-87525-200-4

Band 147: Ulrich Wenger
Prozessoptimierung in der Wickeltechnik durch innovative maschinenbauliche und regelungstechnische Ansätze
132 Seiten, 88 Bilder, 0 Tabellen. 2004.
ISBN 3-87525-203-9

Band 148: Stefan Slama
Effizienzsteigerung in der Montage durch marktorientierte Montagestrukturen und erweiterte Mitarbeiterkompetenz
188 Seiten, 125 Bilder, 0 Tabellen. 2004.
ISBN 3-87525-204-7

Band 149: Thomas Wurm
Laserstrahljustieren mittels Aktoren – Entwicklung von Konzepten und Methoden für die rechnerunterstützte Modellierung und Optimierung von komplexen Aktorsystemen in der Mikrotechnik
122 Seiten, 51 Bilder, 9 Tabellen. 2004.
ISBN 3-87525-206-3

Band 150: Martino Celeghini
Wirkmedienbasierte Blechumformung: Grundlagenuntersuchungen zum Einfluss von Werkstoff und Bauteilgeometrie
146 Seiten, 77 Bilder, 6 Tabellen. 2004.
ISBN 3-87525-207-1

Band 151: Ralph Hohenstein
Entwurf hochdynamischer Sensor- und Regelsysteme für die adaptive Laserbearbeitung
282 Seiten, 63 Bilder, 16 Tabellen. 2004.
ISBN 3-87525-210-1

Band 152: Angelika Hutterer
Entwicklung prozessüberwachender Regelkreise für flexible Formgebungsprozesse
149 Seiten, 57 Bilder, 2 Tabellen. 2005.
ISBN 3-87525-212-8

Band 153: Emil Egerer
Massivumformen metallischer Kleinstteile bei erhöhter Prozesstemperatur
158 Seiten, 87 Bilder, 10 Tabellen. 2005.
ISBN 3-87525-213-6

Band 154: Rüdiger Holzmann
Strategien zur nachhaltigen Optimierung von Qualität und Zuverlässigkeit in der Fertigung hochintegrierter Flachbaugruppen
186 Seiten, 99 Bilder, 19 Tabellen. 2005.
ISBN 3-87525-217-9

Band 155: Marco Nock
Biegeumformen mit Elastomerwerkzeugen
Modellierung, Prozessauslegung und Abgrenzung des Verfahrens am Beispiel des Rohrbiegens
164 Seiten, 85 Bilder, 13 Tabellen. 2005.
ISBN 3-87525-218-7

Band 156: Frank Niebling
Qualifizierung einer Prozesskette zum Laserstrahlsintern metallischer Bauteile
148 Seiten, 89 Bilder, 3 Tabellen. 2005.
ISBN 3-87525-219-5

Band 157: Markus Meiler
Großserientauglichkeit trockenschmierstoffbeschichteter Aluminiumbleche im Presswerk
Grundlegende Untersuchungen zur Tribologie, zum Umformverhalten und Bauteilversuche
104 Seiten, 57 Bilder, 21 Tabellen. 2005.
ISBN 3-87525-221-7

Band 158: Agus Sutanto
Solution Approaches for Planning of Assembly Systems in Three-Dimensional Virtual Environments
169 Seiten, 98 Bilder, 3 Tabellen. 2005.
ISBN 3-87525-220-9

Band 159: Matthias Boiger
Hochleistungssysteme für die Fertigung elektronischer Baugruppen auf der Basis flexibler Schaltungsträger
175 Seiten, 111 Bilder, 8 Tabellen. 2005.
ISBN 3-87525-222-5

Band 160: Matthias Pitz
Laserunterstütztes Biegen höchstfester Mehrphasenstähle
120 Seiten, 73 Bilder, 11 Tabellen. 2005.
ISBN 3-87525-223-3

Band 161: Meik Vahl
Beitrag zur gezielten Beeinflussung des Werkstoffflusses beim Innenhochdruck-Umformen von Blechen
165 Seiten, 94 Bilder, 15 Tabellen. 2005.
ISBN 3-87525-224-1

Band 162: Peter K. Kraus
Plattformstrategien – Realisierung einer varianz- und kostenoptimierten Wertschöpfung
181 Seiten, 95 Bilder, 0 Tabellen. 2005.
ISBN 3-87525-226-8

Band 163: Adrienn Cser
Laserstrahlschmelzabtrag – Prozessanalyse und -modellierung
146 Seiten, 79 Bilder, 3 Tabellen. 2005.
ISBN 3-87525-227-6

Band 164: Markus C. Hahn
Grundlegende Untersuchungen zur Herstellung von Leichtbauverbundstrukturen mit Aluminiumschaumkern
143 Seiten, 60 Bilder, 16 Tabellen. 2005.
ISBN 3-87525-228-4

Band 165: Gordana Michos
Mechatronische Ansätze zur Optimierung von Vorschubachsen
146 Seiten, 87 Bilder, 17 Tabellen. 2005.
ISBN 3-87525-230-6

Band 166: Markus Stark
Auslegung und Fertigung hochpräziser Faser-Kollimator-Arrays
158 Seiten, 115 Bilder, 11 Tabellen. 2005.
ISBN 3-87525-231-4

Band 167: Yurong Zhou
Kollaboratives Engineering Management in der integrierten virtuellen Entwicklung der Anlagen für die Elektronikproduktion
156 Seiten, 84 Bilder, 6 Tabellen. 2005.
ISBN 3-87525-232-2

Band 168: Werner Enser
Neue Formen permanenter und lösbarer elektrischer Kontaktierungen für mechatronische Baugruppen
190 Seiten, 112 Bilder, 5 Tabellen. 2005.
ISBN 3-87525-233-0

Band 169: Katrin Melzer
Integrierte Produktpolitik bei elektrischen und elektronischen Geräten zur Optimierung des Product-Life-Cycle
155 Seiten, 91 Bilder, 17 Tabellen. 2005.
ISBN 3-87525-234-9

Band 170: Alexander Putz
Grundlegende Untersuchungen zur Erfassung der realen Vorspannung von armierten Kaltfließpresswerkzeugen mittels Ultraschall
137 Seiten, 71 Bilder, 15 Tabellen. 2006.
ISBN 3-87525-237-3

Band 171: Martin Prechtl
Automatisiertes Schichtverfahren für metallische Folien – System- und Prozesstechnik
154 Seiten, 45 Bilder, 7 Tabellen. 2006.
ISBN 3-87525-238-1

Band 172: Markus Meidert
Beitrag zur deterministischen Lebensdauerabschätzung von Werkzeugen der Kaltmassivumformung
131 Seiten, 78 Bilder, 9 Tabellen. 2006.
ISBN 3-87525-239-X

Band 173: Bernd Müller
Robuste, automatisierte Montagesysteme durch adaptive Prozessführung und montageübergreifende Fehlerprävention am Beispiel flächiger Leichtbauteile
147 Seiten, 77 Bilder, 0 Tabellen. 2006.
ISBN 3-87525-240-3

Band 174: Alexander Hofmann
Hybrides Laserdurchstrahlschweißen von Kunststoffen
136 Seiten, 72 Bilder, 4 Tabellen. 2006.
ISBN 978-3-87525-243-9
ISBN 3-87525-243-8

Band 175: Peter Wölflick
Innovative Substrate und Prozesse mit feinsten Strukturen für bleifreie Mechatronik-Anwendungen
177 Seiten, 148 Bilder, 24 Tabellen. 2006.
ISBN 978-3-87525-246-0
ISBN 3-87525-246-2

Band 176: Attila Komlódi
Detection and Prevention of Hot Cracks during Laser Welding of Aluminium Alloys Using Advanced Simulation Methods
155 Seiten, 89 Bilder, 14 Tabellen. 2006.
ISBN 978-3-87525-248-4
ISBN 3-87525-248-9

Band 177: Uwe Popp
Grundlegende Untersuchungen zum Laserstrahlstrukturieren von Kaltmassivumformwerkzeugen
140 Seiten, 67 Bilder, 16 Tabellen. 2006.
ISBN 978-3-87525-249-1
ISBN 3-87525-249-7

Band 178: Veit Rückel
Rechnergestützte Ablaufplanung und Bahngenerierung Für kooperierende Industrieroboter
148 Seiten, 75 Bilder, 7 Tabellen. 2006.
ISBN 978-3-87525-250-7
ISBN 3-87525-250-0

Band 179: Manfred Dirscherl
Nicht-thermische Mikrojustiertechnik mittels ultrakurzer Laserpulse
154 Seiten, 69 Bilder, 10 Tabellen. 2007.
ISBN 978-3-87525-251-4
ISBN 3-87525-251-9

Band 180: Yong Zhuo
Entwurf eines rechnergestützten integrierten Systems für Konstruktion und Fertigungsplanung räumlicher spritzgegossener Schaltungsträger (3D-MID)
181 Seiten, 95 Bilder, 5 Tabellen. 2007.
ISBN 978-3-87525-253-8

Band 181: Stefan Lang
Durchgängige Mitarbeiterinformation zur Steigerung von Effizienz und Prozesssicherheit in der Produktion
172 Seiten, 93 Bilder. 2007.
ISBN 978-3-87525-257-6

Band 182: Hans-Joachim Krauß
Laserstrahlinduzierte Pyrolyse präkeramischer Polymere
171 Seiten, 100 Bilder. 2007.
ISBN 978-3-87525-258-3

Band 183: Stefan Junker
Technologien und Systemlösungen für die flexibel automatisierte Bestückung permanent erregter Läufer mit oberflächenmontierten Dauermagneten
173 Seiten, 75 Bilder. 2007.
ISBN 978-3-87525-259-0

Band 184: Rainer Kohlbauer
Wissensbasierte Methoden für die simulationsgestützte Auslegung wirkmedienbasierter Blechumformprozesse
135 Seiten, 50 Bilder. 2007.
ISBN 978-3-87525-260-6

Band 185: Klaus Lamprecht
Wirkmedienbasierte Umformung tiefgezogener Vorformen unter besonderer Berücksichtigung maßgeschneiderter Halbzeuge
137 Seiten, 81 Bilder. 2007.
ISBN 978-3-87525-265-1

Band 186: Bernd Zolleiß
Optimierte Prozesse und Systeme für die Bestückung mechatronischer Baugruppen
180 Seiten, 117 Bilder. 2007.
ISBN 978-3-87525-266-8

Band 187: Michael Kerausch
Simulationsgestützte Prozessauslegung für das Umformen lokal wärmebehandelter Aluminiumplatinen
146 Seiten, 76 Bilder, 7 Tabellen 2007.
ISBN 978-3-87525-267-5

Band 188: Matthias Weber
Unterstützung der Wandlungsfähigkeit von Produktionsanlagen durch innovative Softwaresysteme
183 Seiten, 122 Bilder, 3 Tabellen 2007.
ISBN 978-3-87525-269-9

Band 189: Thomas Frick
Untersuchung der prozessbestimmenden Strahl-Stoff-Wechselwirkungen beim Laserstrahlschweißen von Kunststoffen
104 Seiten, 62 Bilder, 8 Tabellen 2007.
ISBN 978-3-87525-268-2

Band 190: Joachim Hecht
Werkstoffcharakterisierung und Prozessauslegung für die wirkmedienbasierte Doppelblech-Umformung von Magnesiumlegierungen
107 Seiten, 91 Bilder, 2 Tabellen 2007.
ISBN 978-3-87525-270-5

Band 191: Ralf Völkl
Stochastische Simulation zur Werkzeuglebensdaueroptimierung und Präzisionsfertigung in der Kaltmassivumformung
178 Seiten, 75 Bilder, 12 Tabellen 2008.
ISBN 978-3-87525-272-9

Band 192: Massimo Tolazzi
Innenhochdruck-Umformen verstärkter Blech-Rahmenstrukturen
164 Seiten, 85 Bilder, 7 Tabellen 2008.
ISBN 978-3-87525-273-6

Band 193: Cornelia Hoff
Untersuchung der Prozesseinflussgrößen beim Presshärten des höchstfesten Vergütungsstahls 22MnB5
133 Seiten, 92 Bilder, 5 Tabellen 2008.
ISBN 978-3-87525-275-0

Band 194: Christian Alvarez
Simulationsgestützte Methoden zur effizienten Gestaltung von Lötprozessen in der Elektronikproduktion
149 Seiten, 86 Bilder, 8 Tabellen 2008.
ISBN 978-3-87525-277-4

Band 195: Andreas Kunze
Automatisierte Montage von makromechatronischen Modulen zur flexiblen Integration in hybride Pkw-Bordnetzsysteme
160 Seiten, 90 Bilder, 14 Tabellen 2008.
ISBN 978-3-87525-278-1

Band 196: Wolfgang Hußnätter
Grundlegende Untersuchungen zur experimentellen Ermittlung und zur Modellierung von Fließortkurven bei erhöhten Temperaturen
152 Seiten, 73 Bilder, 21 Tabellen 2008.
ISBN 978-3-87525-279-8

Band 197: Thomas Bigl
Entwicklung, angepasste Herstellungsverfahren und erweiterte Qualitätssicherung von einsatzgerechten elektronischen Baugruppen
175 Seiten, 107 Bilder, 14 Tabellen 2008.
ISBN 978-3-87525-280-4

Band 198: Stephan Roth
Grundlegende Untersuchungen zum Excimerlaserstrahl-Abtragen unter Flüssigkeitsfilmen
113 Seiten, 47 Bilder, 14 Tabellen 2008.
ISBN 978-3-87525-281-1

Band 199: Artur Giera
Prozesstechnische Untersuchungen zum Rührreibschweißen metallischer Werkstoffe
179 Seiten, 104 Bilder, 36 Tabellen 2008.
ISBN 978-3-87525-282-8

Band 200: Jürgen Lechler
Beschreibung und Modellierung des Werkstoffverhaltens von presshärtbaren Bor-Manganstählen
154 Seiten, 75 Bilder, 12 Tabellen 2009.
ISBN 978-3-87525-286-6

Band 201: Andreas Blankl
Untersuchungen zur Erhöhung der Prozessrobustheit bei der Innenhochdruck-Umformung von flächigen Halbzeugen mit vor- bzw. nachgeschalteten Laserstrahlfügeoperationen
120 Seiten, 68 Bilder, 9 Tabellen 2009.
ISBN 978-3-87525-287-3

Band 202: Andreas Schaller
Modellierung eines nachfrageorientierten Produktionskonzeptes für mobile Telekommunikationsgeräte
120 Seiten, 79 Bilder, 0 Tabellen 2009.
ISBN 978-3-87525-289-7

Band 203: Claudius Schimpf
Optimierung von Zuverlässigkeitsuntersuchungen, Prüfabläufen und Nacharbeitsprozessen in der Elektronikproduktion
162 Seiten, 90 Bilder, 14 Tabellen 2009.
ISBN 978-3-87525-290-3

Band 204: Simon Dietrich
Sensoriken zur Schwerpunktslagebestimmung der optischen Prozessemissionen beim Laserstrahltiefschweißen
138 Seiten, 70 Bilder, 5 Tabellen 2009.
ISBN 978-3-87525-292-7

Band 205: Wolfgang Wolf
Entwicklung eines agentenbasierten Steuerungssystems zur Materialflussorganisation im wandelbaren Produktionsumfeld
167 Seiten, 98 Bilder, 2009.
ISBN 978-3-87525-293-4

Band 206: Steffen Polster
Laserdurchstrahlschweißen transparenter Polymerbauteile
160 Seiten, 92 Bilder, 13 Tabellen 2009.
ISBN 978-3-87525-294-1

Band 207: Stephan Manuel Dörfler
Rührreibschweißen von walzplattiertem Halbzeug und Aluminiumblech zur Herstellung flächiger Aluminiumschaum-Sandwich-Verbundstrukturen
190 Seiten, 98 Bilder, 5 Tabellen 2009.
ISBN 978-3-87525-295-8

Band 208: Uwe Vogt
Seriennahe Auslegung von Aluminium Tailored Heat Treated Blanks
151 Seiten, 68 Bilder, 26 Tabellen 2009.
ISBN 978-3-87525-296-5

Band 209: Till Laumann
Qualitative und quantitative Bewertung der Crashtauglichkeit von höchstfesten Stählen
117 Seiten, 69 Bilder, 7 Tabellen 2009.
ISBN 978-3-87525-299-6

Band 210: Alexander Diehl
Größeneffekte bei Biegeprozessen- Entwicklung einer Methodik zur Identifikation und Quantifizierung
180 Seiten, 92 Bilder, 12 Tabellen 2010.
ISBN 978-3-87525-302-3

Band 211: Detlev Staud
Effiziente Prozesskettenauslegung für das Umformen lokal wärmebehandelter und geschweißter Aluminiumbleche
164 Seiten, 72 Bilder, 12 Tabellen 2010.
ISBN 978-3-87525-303-0

Band 212: Jens Ackermann
Prozesssicherung beim Laserdurchstrahlschweißen thermoplastischer Kunststoffe
129 Seiten, 74 Bilder, 13 Tabellen 2010.
ISBN 978-3-87525-305-4

Band 213: Stephan Weidel
Grundlegende Untersuchungen zum Kontaktzustand zwischen Werkstück und Werkzeug bei umformtechnischen Prozessen unter tribologischen Gesichtspunkten
144 Seiten, 67 Bilder, 11 Tabellen 2010.
ISBN 978-3-87525-307-8

Band 214: Stefan Geißdörfer
Entwicklung eines mesoskopischen Modells zur Abbildung von Größeneffekten in der Kaltmassivumformung mit Methoden der FE-Simulation
133 Seiten, 83 Bilder, 11 Tabellen 2010.
ISBN 978-3-87525-308-5

Band 215: Christian Matzner
Konzeption produktspezifischer Lösungen zur Robustheitssteigerung elektronischer Systeme gegen die Einwirkung von Betauung im Automobil
165 Seiten, 93 Bilder, 14 Tabellen 2010.
ISBN 978-3-87525-309-2

Band 216: Florian Schüßler
Verbindungs- und Systemtechnik für thermisch hochbeanspruchte und miniaturisierte elektronische Baugruppen
184 Seiten, 93 Bilder, 18 Tabellen 2010.
ISBN 978-3-87525-310-8

Band 217: Massimo Cojutti
Strategien zur Erweiterung der Prozessgrenzen bei der Innhochdruck-Umformung von Rohren und Blechpaaren
125 Seiten, 56 Bilder, 9 Tabellen 2010.
ISBN 978-3-87525-312-2

Band 218: Raoul Plettke
Mehrkriterielle Optimierung komplexer Aktorsysteme für das Laserstrahljustieren
152 Seiten, 25 Bilder, 3 Tabellen 2010.
ISBN 978-3-87525-315-3

Band 219: Andreas Dobroschke
Flexible Automatisierungslösungen für die Fertigung wickeltechnischer Produkte
184 Seiten, 109 Bilder, 18 Tabellen 2011.
ISBN 978-3-87525-317-7

Band 220: Azhar Zam
Optical Tissue Differentiation for Sensor-Controlled Tissue-Specific Laser Surgery
99 Seiten, 45 Bilder, 8 Tabellen 2011.
ISBN 978-3-87525-318-4

Band 221: Michael Rösch
Potenziale und Strategien zur Optimierung des Schablonendruckprozesses in der Elektronikproduktion
192 Seiten, 127 Bilder, 19 Tabellen 2011.
ISBN 978-3-87525-319-1

Band 222: Thomas Rechtenwald
Quasi-isothermes Laserstrahlsintern von Hochtemperatur-Thermoplasten - Eine Betrachtung werkstoff- prozessspezifischer Aspekte am Beispiel PEEK
150 Seiten, 62 Bilder, 8 Tabellen 2011.
ISBN 978-3-87525-320-7

Band 223: Daniel Craiovan
Prozesse und Systemlösungen für die SMT-Montage optischer Bauelemente auf Substrate mit integrierten Lichtwellenleitern
165 Seiten, 85 Bilder, 8 Tabellen 2011.
ISBN 978-3-87525-324-5

Band 224: Kay Wagner
Beanspruchungsangepasste Kaltmassivumformwerkzeuge durch lokal optimierte Werkzeugoberflächen
147 Seiten, 103 Bilder, 17 Tabellen 2011.
ISBN 978-3-87525-325-2

Band 225: Martin Brandhuber
Verbesserung der Prognosegüte des Versagens von Punktschweißverbindungen bei höchstfesten Stahlgüten
155 Seiten, 91 Bilder, 19 Tabellen 2011.
ISBN 978-3-87525-327-6

Band 226: Peter Sebastian Feuser
Ein Ansatz zur Herstellung von pressgehärteten Karosseriekomponenten mit maßgeschneiderten mechanischen Eigenschaften: Temperierte Umformwerkzeuge. Prozessfenster, Prozesssimulation und funktionale Untersuchung
195 Seiten, 97 Bilder, 60 Tabellen 2012.
ISBN 978-3-87525-328-3

Band 227: Murat Arbak
Material Adapted Design of Cold Forging Tools Exemplified by Powder Metallurgical Tool Steels and Ceramics
109 Seiten, 56 Bilder, 8 Tabellen 2012.
ISBN 978-3-87525-330-6

Band 228: Indra Pitz
Beschleunigte Simulation des Laserstrahlumformens von Aluminiumblechen
137 Seiten, 45 Bilder, 27 Tabellen 2012.
ISBN 978-3-87525-333-7

Band 229: Alexander Grimm
Prozessanalyse und -überwachung des Laserstrahlhartlötens mittels optischer Sensorik
125 Seiten, 61 Bilder, 5 Tabellen 2012.
ISBN 978-3-87525-334-4

Band 230: Markus Kaupper
Biegen von höhenfesten Stahlblechwerkstoffen - Umformverhalten und Grenzen der Biegbarkeit
160 Seiten, 57 Bilder, 10 Tabellen 2012.
ISBN 978-3-87525-339-9

Band 231: Thomas Kroiß
Modellbasierte Prozessauslegung für die Kaltmassivumformung unter Brücksichtigung der Werkzeug- und Pressenauffederung
169 Seiten, 50 Bilder, 19 Tabellen 2012.
ISBN 978-3-87525-341-2

Band 232: Christian Goth
Analyse und Optimierung der Entwicklung und Zuverlässigkeit räumlicher Schaltungsträger (3D-MID)
176 Seiten, 102 Bilder, 22 Tabellen 2012.
ISBN 978-3-87525-340-5

Band 233: Christian Ziegler
Ganzheitliche Automatisierung mechatronischer Systeme in der Medizin am Beispiel Strahlentherapie
170 Seiten, 71 Bilder, 19 Tabellen 2012.
ISBN 978-3-87525-342-9

Band 234: Florian Albert
Automatisiertes Laserstrahllöten und -reparaturlöten elektronischer Baugruppen
127 Seiten, 78 Bilder, 11 Tabellen 2012.
ISBN 978-3-87525-344-3

Band 235: Thomas Stöhr
Analyse und Beschreibung des mechanischen Werkstoffverhaltens von presshärtbaren Bor-Manganstählen
118 Seiten, 74 Bilder, 18 Tabellen 2013.
ISBN 978-3-87525-346-7

Band 236: Christian Kägeler
Prozessdynamik beim Laserstrahlschweißen verzinkter Stahlbleche im Überlappstoß
145 Seiten, 80 Bilder, 3 Tabellen 2013.
ISBN 978-3-87525-347-4

Band 237: Andreas Sulzberger
Seriennahe Auslegung der Prozesskette zur wärmeunterstützten Umformung von Aluminiumblechwerkstoffen
153 Seiten, 87 Bilder, 17 Tabellen 2013.
ISBN 978-3-87525-349-8

Band 238: Simon Opel
Herstellung prozessangepasster Halbzeuge mit variabler Blechdicke durch die Anwendung von Verfahren der Blechmassivumformung
165 Seiten, 108 Bilder, 27 Tabellen 2013.
ISBN 978-3-87525-350-4

Band 239: Rajesh Kanawade
In-vivo Monitoring of Epithelium Vessel and Capillary Density for the Application of Detection of Clinical Shock and Early Signs of Cancer Development
124 Seiten, 58 Bilder, 15 Tabellen 2013.
ISBN 978-3-87525-351-1

Band 240: Stephan Busse
Entwicklung und Qualifizierung eines Schneidclinchverfahrens
119 Seiten, 86 Bilder, 20 Tabellen 2013.
ISBN 978-3-87525-352-8

Band 241: Karl-Heinz Leitz
Mikro- und Nanostrukturierung mit kurz und ultrakurz gepulster Laserstrahlung
154 Seiten, 71 Bilder, 9 Tabellen 2013.
ISBN 978-3-87525-355-9

Band 242: Markus Michl
Webbasierte Ansätze zur ganzheitlichen technischen Diagnose
182 Seiten, 62 Bilder, 20 Tabellen 2013.
ISBN 978-3-87525-356-6

Band 243: Vera Sturm
Einfluss von Chargenschwankungen auf die Verarbeitungsgrenzen von Stahlwerkstoffen
113 Seiten, 58 Bilder, 9 Tabellen.
ISBN 978-3-87525-357-3

Band 244: Christian Neudel
Mikrostrukturelle und mechanisch-technologische Eigenschaften widerstandspunktgeschweißter Aluminium-Stahl-Verbindungen für den Fahrzeugbau
178 Seiten, 171 Bilder, 31 Tabellen.
ISBN 978-3-87525-358-0

Band 245: Anja Neumann
Konzept zur Beherrschung der Prozessschwankungen im Presswerk
162 Seiten, 68 Bilder, 15 Tabellen.
ISBN 978-3-87525-360-3

Band 246: Ulf-Hermann Quentin
Laserbasierte Nanostrukturierung mit optisch positionierten Mikrolinsen
137 Seiten, 89 Bilder, 6 Tabellen.
ISBN 978-3-87525-361-0

Band 247: Erik Lamprecht
Der Einfluss der Fertigungsverfahren auf die Wirbelstromverluste von Stator-Einzelzahnblechpaketen für den Einsatz in Hybrid- und Elektrofahrzeugen
148 Seiten, 138 Bilder, 4 Tabellen.
ISBN 978-3-87525-362-7

Band 248: Sebastian Rösel
Wirkmedienbasierte Umformung von Blechhalbzeugen unter Anwendung magnetorheologischer Flüssigkeiten als kombiniertes Wirk- und Dichtmedium
148 Seiten, 61 Bilder, 12 Tabellen.
ISBN 978-3-87525-363-4

Band 249: Paul Hippchen
Simulative Prognose der Geometrie indirekt pressgehärteter Karosseriebauteile für die industrielle Anwendung
163 Seiten, 89 Bilder, 12 Tabellen.
ISBN 978-3-87525-364-1

Band 250: Martin Zubeil
Versagensprognose bei der Prozesssimulation von Biegeumform- und Falzverfahren
171 Seiten, 90 Bilder, 5 Tabellen.
ISBN 978-3-87525-365-8

Band 251: Alexander Kühl
Flexible Automatisierung der Statorenmontage mit Hilfe einer universellen ambidexteren Kinematik
142 Seiten, 60 Bilder, 26 Tabellen 2014.
ISBN 978-3-87525-367-2

Band 252: Thomas Albrecht
Optimierte Fertigungstechnologien für Rotoren getriebeintegrierter PM-Synchronmotoren von Hybridfahrzeugen
198 Seiten, 130 Bilder, 38 Tabellen 2014.
ISBN 978-3-87525-368-9

Band 253: Florian Risch
Planning and Production Concepts for Contactless Power Transfer Systems for Electric Vehicles
185 Seiten, 125 Bilder, 13 Tabellen 2014.
ISBN 978-3-87525-369-6

Band 254: Markus Weigl
Laserstrahlschweißen von Mischverbindungen aus austenitischen und ferritischen korrosionsbeständigen Stahlwerkstoffen
184 Seiten, 110 Bilder, 6 Tabellen 2014.
ISBN 978-3-87525-370-2

Band 255: Johannes Noneder
Beanspruchungserfassung für die Validierung von FE-Modellen zur Auslegung von Massivumformwerkzeugen
161 Seiten, 65 Bilder, 14 Tabellen 2014.
ISBN 978-3-87525-371-9

Band 256: Andreas Reinhardt
Ressourceneffiziente Prozess- und Produktionstechnologie für flexible Schaltungsträger
123 Seiten, 69 Bilder, 19 Tabellen 2014.
ISBN 978-3-87525-373-3

Band 257: Tobias Schmuck
Ein Beitrag zur effizienten Gestaltung globaler Produktions- und Logistiknetzwerke mittels Simulation
151 Seiten, 74 Bilder 2014.
ISBN 978-3-87525-374-0

Band 258: Bernd Eichenhüller
Untersuchungen der Effekte und Wechselwirkungen charakteristischer Einflussgrößen auf das Umformverhalten bei Mikroumformprozessen
127 Seiten, 29 Bilder, 9 Tabellen 2014.
ISBN 978-3-87525-375-7

Band 259: Felix Lütteke
Vielseitiges autonomes Transportsystem basierend auf Weltmodellerstellung mittels Datenfusion von Deckenkameras und Fahrzeugsensoren
152 Seiten, 54 Bilder, 20 Tabellen 2014.
ISBN 978-3-87525-376-4

Band 260: Martin Grüner
Hochdruck-Blechumformung mit formlos festen Stoffen als Wirkmedium
144 Seiten, 66 Bilder, 29 Tabellen.
ISBN 978-3-87525-379-5

Band 261: Christian Brock
Analyse und Regelung des Laserstrahltiefschweißprozesses durch Detektion der Metalldampffackelposition
126 Seiten, 65 Bilder, 3 Tabellen.
ISBN 978-3-87525-380-1

Band 262: Peter Vatter
Sensitivitätsanalyse des 3-Rollen-Schubbiegens auf Basis der Finite Elemente Methode
145 Seiten, 57 Bilder, 26 Tabellen.
ISBN 978-3-87525-381-8

Band 263: Florian Klämpfl
Planung von Laserbestrahlungen durch simulationsbasierte Optimierung
169 Seiten, 78 Bilder, 32 Tabellen.
ISBN 978-3-87525-384-9

Band 264: Matthias Domke
Transiente physikalische Mechanismen bei der Laserablation von dünnen Metallschichten
133 Seiten, 43 Bilder, 3 Tabellen.
ISBN 978-3-87525-385-6

Band 265: Johannes Götz
Community-basierte Optimierung des Anlagenengineerings
177 Seiten, 80 Bilder, 30 Tabellen 2015.
ISBN 978-3-87525-386-3

Band 266: Hung Nguyen
Qualifizierung des Potentials von Verfestigungseffekten zur Erweiterung des Umformvermögens aushärtbarer Aluminiumlegierungen
137 Seiten, 57 Bilder, 16 Tabellen 2015.
ISBN 978-3-87525-387-0

Band 267: Andreas Kuppert
Erweiterung und Verbesserung von Versuchs- und Auswertetechniken für die Bestimmung von Grenzformänderungskurven
138 Seiten, 82 Bilder, 2 Tabellen 2015.
ISBN 978-3-87525-388-7

Band 268: Kathleen Klaus
Erstellung eines Werkstofforientierten Fertigungsprozessfensters zur Steigerung des Formgebungsvermögens von Aluminiumlegierungen unter Anwendung einer zwischengeschalteten Wärmebehandlung
154 Seiten, 70 Bilder, 8 Tabellen 2015.
ISBN 978-3-87525-391-7

Band 269: Thomas Svec
Untersuchungen zur Herstellung von funktionsoptimierten Bauteilen im partiellen Presshärtprozess mittels lokal unterschiedlich temperierter Werkzeuge
166 Seiten, 87 Bilder, 15 Tabellen 2015.
ISBN 978-3-87525-392-4

Band 270: Tobias Schrader
Grundlegende Untersuchungen zur Verschleißcharakterisierung beschichteter Kaltmassivumformwerkzeuge
164 Seiten, 55 Bilder, 11 Tabellen 2015.
ISBN 978-3-87525-393-1

Band 271: Matthäus Brela
Untersuchung von Magnetfeld-Messmethoden zur ganzheitlichen Wertschöpfungsoptimierung und Fehlerdetektion an magnetischen Aktoren
170 Seiten, 97 Bilder, 4 Tabellen 2015.
ISBN 978-3-87525-394-8

Band 272: Michael Wieland
Entwicklung einer Methode zur Prognose adhäsiven Verschleißes an Werkzeugen für das direkte Presshärten
156 Seiten, 84 Bilder, 9 Tabellen 2015.
ISBN 978-3-87525-395-5

Band 273: René Schramm
Strukturierte additive Metallisierung durch kaltaktives Atmosphärendruckplasma
136 Seiten, 62 Bilder, 15 Tabellen 2015.
ISBN 978-3-87525-396-2

Band 274: Michael Lechner
Herstellung beanspruchungsangepasster Aluminiumblechhalbzeuge durch eine maßgeschneiderte Variation der Abkühlgeschwindigkeit nach Lösungsglühen
136 Seiten, 62 Bilder, 15 Tabellen 2015.
ISBN 978-3-87525-397-9

Band 275: Kolja Andreas
Einfluss der Oberflächenbeschaffenheit auf das Werkzeugeinsatzverhalten beim Kaltfließpressen
169 Seiten, 76 Bilder, 4 Tabellen 2015.
ISBN 978-3-87525-398-6

Band 276: Marcus Baum
Laser Consolidation of ITO Nanoparticles for the Generation of Thin Conductive Layers on Transparent Substrates
158 Seiten, 75 Bilder, 3 Tabellen 2015.
ISBN 978-3-87525-399-3

Band 277: Thomas Schneider
Umformtechnische Herstellung dünnwandiger Funktionsbauteile aus Feinblech durch Verfahren der Blechmassivumformung
188 Seiten, 95 Bilder, 7 Tabellen 2015.
ISBN 978-3-87525-401-3

Band 278: Jochen Merhof
Sematische Modellierung automatisierter Produktionssysteme zur Verbesserung der IT-Integration zwischen Anlagen-Engineering und Steuerungsebene
157 Seiten, 88 Bilder, 8 Tabellen 2015.
ISBN 978-3-87525-402-0

Band 279: Fabian Zöller
Erarbeitung von Grundlagen zur Abbildung des tribologischen Systems in der Umformsimulation
126 Seiten, 51 Bilder, 3 Tabellen 2016.
ISBN 978-3-87525-403-7

Band 280: Christian Hezler
Einsatz technologischer Versuche zur Erweiterung der Versagensvorhersage bei Karosseriebauteilen aus höchstfesten Stählen
147 Seiten, 63 Bilder, 44 Tabellen 2016.
ISBN 978-3-87525-404-4

Band 281: Jochen Bönig
Integration des Systemverhaltens von Automobil-Hochvoltleitungen in die virtuelle Absicherung durch strukturmechanische Simulation
177 Seiten, 107 Bilder, 17 Tabellen 2016.
ISBN 978-3-87525-405-1

Band 282: Johannes Kohl
Automatisierte Datenerfassung für diskret ereignisorientierte Simulationen in der energieflexibelen Fabrik
160 Seiten, 80 Bilder, 27 Tabellen 2016.
ISBN 978-3-87525-406-8

Band 283: Peter Bechtold
Mikroschockwellenumformung mittels ultrakurzer Laserpulse
155 Seiten, 59 Bilder, 10 Tabellen 2016.
ISBN 978-3-87525-407-5

Band 284: Stefan Berger
Laserstrahlschweißen thermoplastischer Kohlenstofffaserverbundwerkstoffe mit spezifischem Zusatzdraht
118 Seiten, 68 Bilder, 9 Tabellen 2016.
ISBN 978-3-87525-408-2

Band 285: Martin Bornschlegl
Methods-Energy Measurement - Eine Methode zur Energieplanung für Fügeverfahren im Karosseriebau
136 Seiten, 72 Bilder, 46 Tabellen 2016.
ISBN 978-3-87525-409-9

Band 286: Tobias Rackow
Erweiterung des Unternehmenscontrollings um die Dimension Energie
164 Seiten, 82 Bilder, 29 Tabellen 2016.
ISBN 978-3-87525-410-5

Band 287: Johannes Koch
Grundlegende Untersuchungen zur Herstellung zyklisch-symmetrischer Bauteile mit Nebenformelementen durch Blechmassivumformung
125 Seiten, 49 Bilder, 17 Tabellen 2016.
ISBN 978-3-87525-411-2

Band 288: Hans Ulrich Vierzigmann
Beitrag zur Untersuchung der tribologischen Bedingungen in der Blechmassivumformung - Bereitsellung von tribologischen Modellversuchen und Realisierung von Tailored Surfaces
174 Seiten, 102 Bilder, 34 Tabellen 2016.
ISBN 978-3-87525-412-9

Band 289: Thomas Senner
Methodik zur virtuellen Absicherung der formgebenden Operation des Nasspressprozesses von Gelege-Mehrschichtverbunden
156 Seiten, 96 Bilder, 21 Tabellen 2016.
ISBN 978-3-87525-414-3

Band 290: Sven Kreitlein
Der grundoperationsspezifische Mindestenergiebedarf als Referenzwert zur Bewertung der Energieeffizienz in der Produktion
185 Seiten, 64 Bilder, 30 Tabellen 2016.
ISBN 978-3-87525-415-0

Band 291: Christian Roos
Remote-Laserstrahlschweißen verzinkter Stahlbleche in Kehlnahtgeometrie
123 Seiten, 52 Bilder, 0 Tabellen 2016.
ISBN 978-3-87525-416-7

Band 292: Alexander Kahrimanidis
Thermisch unterstützte Umformung von Aluminiumblechen
165 Seiten, 103 Bilder, 18 Tabellen 2016.
ISBN 978-3-87525-417-4

Band 293: Jan Tremel
Flexible Systems for Permanent Magnet Assembly and Magnetic Rotor Measurement / Flexible Systeme zur Montage von Permanentmagneten und zur Messung magnetischer Rotoren
152 Seiten, 91 Bilder, 12 Tabellen 2016.
ISBN 978-3-87525-419-8