The Adaptability of Production Systems as the Key to Diversified Development of Rotor Shafts for Battery Electric Vehicles

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Abstract. In 2025, a total of 14.5 million battery electric vehicles (BEV) were produced worldwide [1]. Manufacturers of BEVs use various technologies for their electric motors. These technologies can be divided into permanent magnet synchronous machines (PMSM), electrically excited synchronous machines (EESM), and induction machines, also known as asynchronous machines, (ASM). All these technologies have their respective advantages and disadvantages. In terms of the high efficiency curve, PMSMs offer a broad torque range at low to medium speeds. ASMs provide about half the torque range, mainly at medium to high speeds. EESMs are positioned between PMSM and ASM technologies. To achieve efficient driving both in urban traffic and on highways, manufacturers of battery electric vehicles use and combine different technologies on the front and rear axles. For all these technologies, the rotor shaft is an essential component of the electric motor. In a PMSM, the rotor shaft accommodates the laminated core and the permanent magnets. In an EESM, two star-shaped disks are attached to the two outer ends of the rotor shaft, which hold the coil windings along the shaft. Depending on the integrated components and the technical requirements, the rotor shafts are designed and manufactured individually according to customer-specific needs and requirements. Production must adapt to a volatile market and short product lifecycles. This publication presents an adaptable and flexible production system for manufacturing rotor shafts for BEVs. The relevant processes, methods, and resources are described. The focus lies on production planning in development, based on the worldwide development concept of the original equipment manufacturers (OEM) and Tier 1 suppliers for rotor shafts.

Keywords: Battery Electric Vehicles, E-Motor, E-Drive, Rotor Shaft

1 The Global Electric Automotive Market

1.1 Worldwide Production of Battery Electric Vehicles

In 2025, a total number of 14.5 million battery electric vehicles (BEV) were produced worldwide. That is an increase of 26 percent for the total BEV market in comparison to 2024. In general, the global BEV market can be divided into the following regions: the USA, the European Union, and Asia (**Fig. 1**). [1]

In the USA, including Mexico and Canada, about 1.17 million BEVs were produced in 2025. The termination of electric vehicle tax credits in the USA at the end of September 2025 slowed down sales volumes at the end of that year. Despite this volatility, the BEV market share in the USA for 2025 stagnated in comparison to 2024. The top three original equipment manufacturers (OEM) were Tesla with 0.60 million, GM with 0.22 million, and Hyundai with 0.10 million produced cars in 2025. [1]

In the European Union, comprising the 27 member states, the United Kingdom, and the states of the European Free Trade Association, about 2.2 million BEVs were produced in 2025. The European BEV market saw an increase of 24.4 % in 2025 in comparison to 2024. The top three OEMs were VW with 0.76 million, Stellantis with 0.39 million, and BMW with 0.26 million produced cars in 2025. [1]

In the Asian market, which includes China, India, Korea, Japan, the Middle East, and Africa, about 11.0 million BEVs were produced in 2025. The BEV market in Asia saw an increase of 29.5 % in 2025 in comparison to 2024. The top three OEMs were BYD with 2.19 million, Geely with 1.31 million, and Tesla with 0.84 million produced cars in 2025. [1]

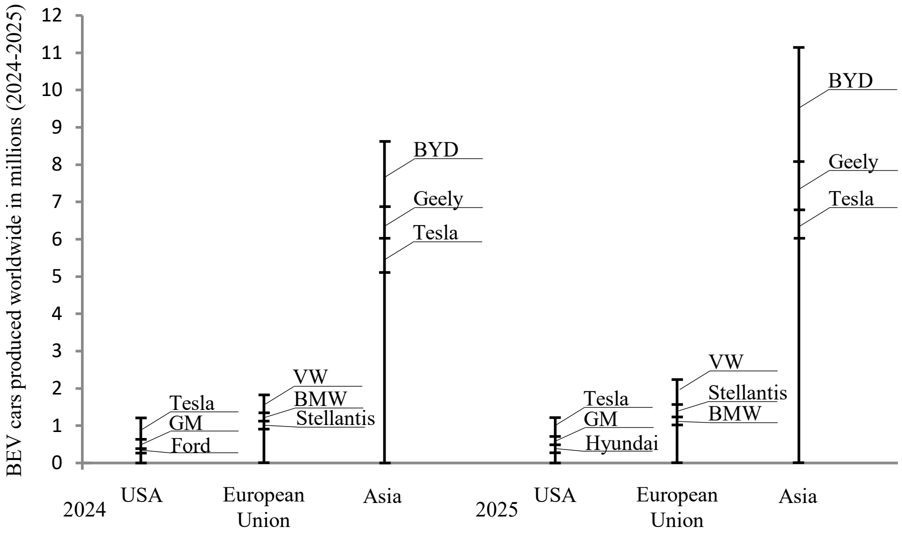

Fig. 1. BEV cars produced worldwide with a focus on the top three OEMs for each region for the years 2024 and 2025 [1].

1.2 Motor Technologies in Electric Vehicles

OEMs of BEVs use various technologies for their electric motors. The technologies for radial-flow machines can generally be divided into permanent magnet synchronous machines (PMSM), electrically/externally excited synchronous machines (EESM), and induction machines, also known as asynchronous machines (ASM). Furthermore, there are additional technologies, such as axial-flow machines, reluctance machines, and transverse-flow machines. However, these are currently only suitable for niche applications and will not be discussed in detail in this paper. In terms of the high efficiency curve, PMSMs offer a broad torque range at low to medium speeds (**Fig. 2**). ASMs provide about half the torque range, mainly at medium to high speeds. EESMs are positioned between PMSM and ASM technologies. To achieve efficient driving both in urban traffic and on highways, OEMs of BEVs use and combine different technologies on the front and rear axles. [2]

The PMSM is the dominant technology in the automotive industry due to its high torque, power density, and performance. These motors also offer the highest level of efficiency based on energy recovery through regenerative braking phases. Thanks to good cooling performance, these motors can be used for high torque phases in short cycles without any overheating issues. In general, the magnets continuously create a magnetic field, meaning that this field cannot be turned off. That leads to some disadvantages for this technology. The design itself is more complex in assembly if the magnets are already magnetized. Permanent magnets contain rare earth materials like neodymium (Nd) and praseodymium (Pr). Rare earth materials are traded worldwide and are also subject to massive price fluctuations on the global markets. [2,3,4]

The EESM provides a high level of efficiency and performance. While it has the advantage of not requiring permanent magnets, there is some additional complexity involved due to the rotor shaft assembly. The magnetic field is generated by an applied voltage with the help of copper coil. These motors can therefore be turned off during the non-torque phase almost instantly and without any magnetic drag losses. The applied voltage can either be transmitted by conduction via brush contacts and slip rings, which can lead to mechanical wear, or in a contactless way via induction, which tends to cause power losses. The high torque at high speeds can be achieved because it is possible to reduce the rotor field to adjust the back electromotive force (Back-EMF) across the field windings. [2,3,4]

The ASM provides robustness and manufacturing simplicity without magnets. The omission of magnets means that these motors can be turned off during the non-torque phase without any drag losses. In the full load phase, ASMs demonstrate a high efficiency curve. The main drawbacks are the lower power, torque density, and efficiency at the lower torque range. The latter results from the asynchronous operation of the magnetic fields in the rotor and stator, rendering the ASM less efficient at lower torque demand. For the full operation phase, the ASM needs electricity to create the magnetic field for the rotor. [2,3,4]

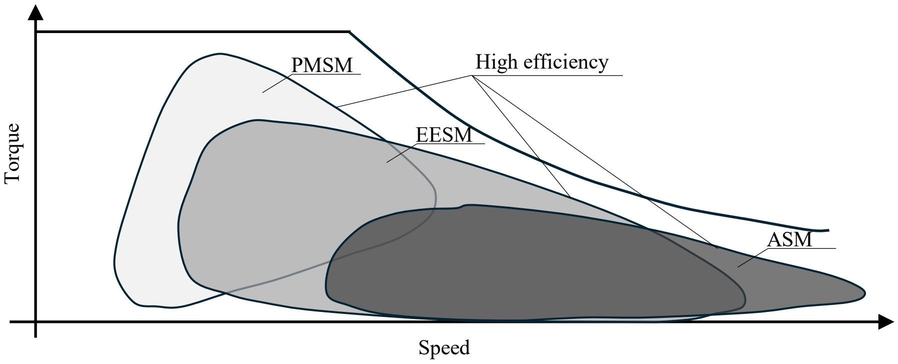

Fig. 2. Efficiency diagram for PMSMs, EESMs, and ASMs [2].

1.3 Main Components of Electric Vehicle Motors

There are various types of electric vehicle motors on the market, which differ in terms of their technology and, consequently, the components used in their design and construction. All electric vehicle motors consist mainly of a housing, a stator, and a rotor (**Fig. 3**) [5]. This paper will focus on the rotor.

The PMSM rotor consists of two bearings, a large number of sheet metal stacks, a significant number of permanent magnets, two balancing disks, and one rotor shaft. A current development in PMSM technology involves the reduction in the wall thickness of the sheet metal stacks for increasing efficiency. This development significantly reduces the remagnetization losses caused by time-varying magnetic fields in the sheet metals [6]. Another development focuses on optimizing the configuration of the permanent magnets, with the aim of reducing the number of magnets needed to generate the same magnetic field [7]. This optimization can be achieved by means of a carbon sleeve placed around the sheet metal stacks [7]. The bridge thickness between the permanent magnets can thus be reduced and the magnet flux improved. At high speeds it is important to protect the permanent magnets against centrifugal forces in order to increase mechanical resistance [7].

The EESM rotor consists of two bearings, a large number of sheet metal stacks, two star disks for the copper windings, two balancing disks, one slip ring module or one induction transmission module, and one rotor shaft. For the conductive transmission of the voltage via brush contacts and slip rings, the wear caused by the brush affects the durability of the transmission system and is thus a critical factor to consider here [4]. With EESMs, the material combination, the contact pressure, and other parameters must be optimally aligned with each other [4]. A power transmission system based on induction includes a rotating transformer and a rotating rectifier to supply the field windings with direct current [4]. The components of the inductive power transmission systems must be designed for maximum centrifugal forces at maximum speed [4]. The rotors suffer rotor and field losses and usually require additional cooling. The cooling concept can be based on active oil cooling of the rotor. For this reason, specific requirements regarding cleanliness and the inner geometry design of the rotor shafts are essential.

The ASM rotor consists of two bearings, a large number of steel cores, a copper or aluminum cage or rods, two balancing disks, and one rotor shaft. An ASM is often used as a second motor in all-wheel drive vehicles or as a booster with a focus on compact design [8]. In addition, the rotor must be capable of reaching speeds of more than 20,000 rpm. For this purpose, two gearboxes have been especially developed with a countershaft designed for high speeds on the rotor shaft [8]. Despite a further reduction in rotor losses, additional optimization of the motor cooling concept is necessary [8]. One option is to fully immerse the stator windings in a circulating oil flow [8]. This is also known as immersion cooling of the stator [8].

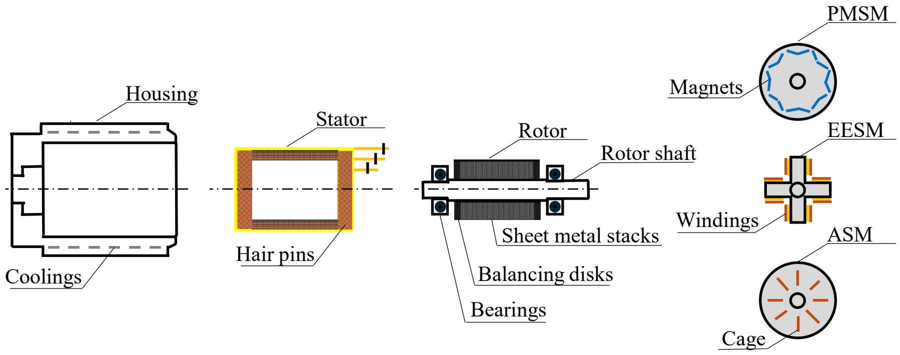

Fig. 3. Main electric vehicle motor components for PMSMs, EESMs, and ASMs [5].

2 Rotor Shafts for Electric Vehicle Motors

2.1 Main Attributes of Rotor Shafts

The rotor shaft lies at the heart of all electric vehicle motor technologies (PMSMs, EESMs, and ASMs). The rotor shaft converts the electrical energy of the magnetic fields into kinetic energy and transmits this kinetic energy to the transmission and drivetrain. The design of the rotor shaft determines the torque and speed at which an electric motor technology can operate. For these reasons, the attributes of rotor shafts will be described in more detail in this paper (**Fig. 4**). All data is based on professional experience from 2016 to 2026.

The material used for the rotor shaft is similar to that used for common drive or transmission shafts. Key properties include the tensile strength, yield point, and the core hardness of the rotor shaft. To meet these requirements, alloy steels or case-hardening steels are used. For alloy steels, steels with a carbon content of between 0.35% (C35) and 0.50% (C50) are generally used. For case-hardening steels, with a hard surface for reducing wear and a tough core for shock absorption, steels containing chromium (Cr) and molybdenum (Mo), such as 42CrMo4, or chromium and manganese (Mn), such as 20MnCr5, are generally used.

In the case of the splines, a distinction can be made between inner splines and outer splines, depending on the connection between the rotor shaft and the gearbox. The design of the adjacent component to the rotor shaft, in this case the input shaft of the transmission, is important. For the inner and outer splines, the hardness of the splines must be taken into account. Furthermore, the effective spline length for transmission of the torque is crucial. The spline module is usually between 0.8 and 1.2 and the number of teeth lies between 25 and 35.

In addition to the inner and outer splines, helical gears are also used for rotor shafts. The use of a helical gear depends on the transmission design. Some transmissions do not have any input shaft. In this case, the rotor shaft takes over the function of the input shaft, and the helical gear of the rotor shaft works directly into the transmission. Although this eliminates the need for an input shaft, it is crucial that the entire rotor shaft is case-hardened in order to achieve the required hardness of the helical gear. This means that more material needs to be case-hardened.

Two bearing sections are necessary for mounting the shaft at a maximum speed of 20,000 to 30,000 rpm. The outer diameter tolerances are normally between seven to twelve micromillimeters for the entire bearing length. The cylindricity of the bearings is normally between five to eight micromillimeters.

The shaft for a PMSM is designed to hold the sheet metal stacks, the permanent magnets, and two balancing disks. Taking into account the assembly of the metal stacks, the permanent magnets, and the two balancing disks, the shaft needs to fulfill the required hardness. Experiments have highlighted the ejection of material when assembling the shaft with the sheet metal stacks. If there are some issues during the assembly process, a thermal assembly must be used. The current state of the art and experience show that assembly is possible even without cooling down the shaft (thermal treatment). The shaft for the EESM is designed to hold the sheet metal stacks, two star disks for the copper windings, and two balancing disks. If the sheet metal stacks and the two star disks with the copper windings form a one-part design after pre-assembly and in the context of the assembly, the hardness of the shaft can be reduced to the core hardness of the rotor shaft. The shaft for the ASM is designed to hold the steel cores, the copper or aluminum rods or cage, and two balancing disks. It is therefore crucial to achieve the required shaft hardness for the assembly of the package. The outer diameter of all the shafts for PMSMs, EESMs, and ASMs in the case of motors in electric passenger vehicles generally lies between 40 and 70 millimeters, with tolerances of approximately 14 to 20 micromillimeters. However, recent global developments indicate a shift towards outer diameters that are smaller than 70 millimeters.

The inner cooling system is designed with a view to achieving weight savings, cooling down the rotor, and transporting the oil to the gearbox. If an inner cooling design is needed, the demanding cleanliness requirements must be met. In this case, the gravimetric weight and the grain size have to be fulfilled.

The wall thickness of the rotor shaft is designed for transmitting the torque from the magnetic fields to the gearbox. Additionally, the wall thickness supports weight savings and cooling. The state-of-the-art wall thickness is between four and six millimeters.

The length of the rotor shaft depends on the required length for the sheet metal stacks in PMSMs, EESMs, and ASMs based on the magnetic field strength. The length of the rotor shafts generally lies between 200 and 350 mm.

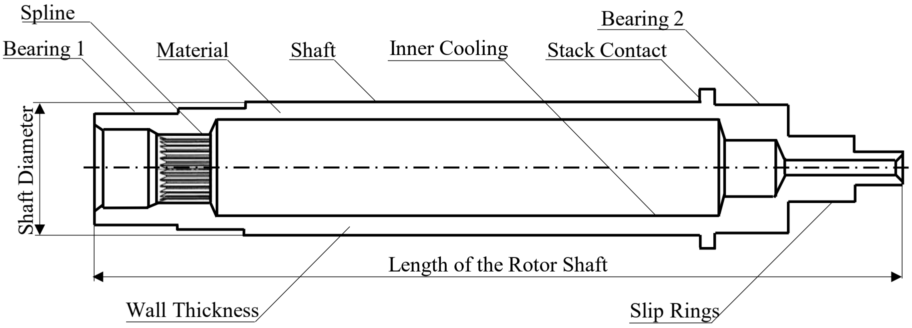

Fig. 4. Main attributes of a rotor shaft based on an EESM (sectional view).

2.2 Main Manufacturing Processes for Rotor Shafts

In the industrialized manufacturing of rotor shafts, the shaft component is further processed by means of mechanical machining. The shaft component for rotor shafts can be produced from bar or tube material or from a forging. An internal global study shows that only five percent of rotor shafts are produced from bar and tube material and then subsequently machined. The remaining 95 % are produced in the first stage from a forging. Taking into account material usage and costs, different forging processes for rotor shafts are described in more detail in this paper.

Forging Processes for Rotor Shafts

In general, and particularly with respect to rotor shafts, forging is a method of forming billets with a cylindrical cross section into a shape that meets the near net shape of the machined component, here the rotor shaft (**Fig. 5**). Forging encompasses a variety of processes that are carried out hot (>= 1,200 °C), warm (700 to 950 °C), cold (20 to 40 °C), or by means of rotary swaging (a combination of cold and warm). Forging is a suitable process for all rotor shafts made of metal. In combination with heat treatment processes, the material may be adapted to optimally meet the requirements of rotor shafts. To achieve this, the material, the rotor shaft design, and the forging temperatures need to be optimally aligned. Particularly in the case of rotors shafts, different forging temperatures can also be combined with each other. In this way, optimum rotor shaft properties and cost-efficient production can be guaranteed. The strength of the rotor shafts is dependent on suitable fiber flow. Rolled steel is directionally aligned during forging to produce the desired component. In the worst case, the fibers then protrude perpendicularly from the surface, which may render the material more liable to fatigue and pitting. Furthermore, machined parts produced without prior forging demonstrate poor material utilization due to the high chip volume involved. [9]

Fig. 5. Cold forged rotor shaft (left) and warm forged rotor shaft (right) produced by Hirschvogel for PMSMs.

Machining Processes for Rotor Shafts

Depending on the technical requirements, forged parts may be provided with ready-for-assembly contours. Current developments in the area of forging are focusing on the forged surface for the inner geometry and the shaft, as in the case of rotor shafts.

In all instances, forging is followed by machining processes. These start with turning and drilling operations for the outer and inner diameters. As such operations are standardized processes, they are not explained in detail in this paper. Subsequent heat treatment is used to provide the final material properties in terms of hardness, especially for the splines or gears and, in some cases, for the bearings and the shaft. The following section lists the main attributes of rotor shafts, as described in 2.1, and outlines the associated machining processes.

The manufacturing of the splines has been divided into the manufacturing of the inner and outer splines. To produce the inner splines, machining processes such as broaching or axial forming are state-of-the-art. Axial forming of the spline is used if there is not enough space within the inner geometry of the rotor shaft for the broaching tool. In addition, for axial forming of the inner splines, two to three millimeters of space must be provided at the end of the spline for the run-out of the forming tool. With axial forming, spline tolerances of seven to eight based on ISO 1328 can be achieved. For the production of the outer splines, machining processes such as spline rolling or spline milling are used. With spline rolling, tolerances of eight to nine can be achieved based on the ISO 1328.

To attain the required spline hardness, induction hardening is state-of-the-art. For induction hardening, a near-shape inductor is increasingly being used in the market instead of a feed-forward controlled induction hardening process.

For the production of the helical gears, additional processes are necessary. When the rotor shaft is in the unhardened condition, gear milling is used. After gear milling, the rotor shafts are case hardened. Following this, the final shape of the helical gear is produced by gear grinding or gear honing. To increase efficiency, gear honing reduces the tooth friction losses between the rotor shaft and the transmission [6]. It should be noted that gear honing as the final machining process is only possible if the rotor shaft does not bend significantly after case hardening.

The bearings and the shaft are manufactured by cylindrical grinding. Cylindrical grinding is often carried out between centers. The grinding wheel can be dressed individually and is aligned to the shape of the bearings and the shaft.

Fig. 6. Machined rotor shaft with inner splines (left) and rotor shaft with helical gear (right) produced by Hirschvogel.

3 Adaptability and Flexibility of Production Systems in Machining Rotor Shafts

The global electric automotive industry for passenger cars is served by a wide variety of OEMs, as mentioned in Chapter 1, and is highly volatile. Against this backdrop, it is crucial to secure the future of production and manufacturing technology in Germany and Europe by maintaining the leading edge with innovative products and processes. In addition to the demand for high productivity and machining accuracy, modern production systems must also be capable of being rapidly and cost-effectively adapted in terms of their capacity and functional scope as well as the technologies made available. Ultimately, such adaptable technologies and systems form the basis for the energy-efficient, resource-conserving, low-emission, and cyber-physical manufacturing currently required in production. [10]

Based on short cycle times and short set-up times in forging, this paper focuses on the adaptability and flexibility of production systems in machining rotor shafts.

3.1 Adaptive and Flexible Production Systems in Machining

The need for adaptive production systems is derived from current development activities and the wide range of rotor shaft variants. These have a direct impact on the requirements placed on machining production systems in terms of quantity, quality, and technologies (**Fig. 7**). Over the past years, when producing components for internal combustion engines (ICE), high production volumes, a limited range of variance, and long production runs formed the ideal conditions for the use of product-oriented and highly productive manufacturing lines. All of this requires a lower flexibility corridor, as shown in **Fig. 7**. In the case of rotor shafts, shorter product life cycles and consequently shorter production runs are now leading to constant changes in the requirements placed on machining production systems. In addition, inaccurate sales volume forecasts for rotor shafts on the part of OEMs as well as volatile sales volumes over the production lifecycle lead to discrepancies between the required production capacity and production processes. In this context, excess production capacity that is provided but not utilized leads to increased costs, a shortage of production capacity, waiting times for OEMs, and project losses due to orders that cannot be fulfilled in the given timeframe.

To increase the flexibility corridor (see **Fig. 7)**, adaptive production systems for machining make it possible to minimize both excess capacity and capacity shortage by adapting to changing capacity requirements at any time and with less effort. This adaptability and flexibility can be achieved to a certain extent using flexible manufacturing systems in machining or by interlinking individual machines. When machining rotor shafts, these optimizations are directly connected to adaptive drivers such as compatibility, modularity, mobility, universality, and scalability of machines, including their clamping and tooling devices (**Fig. 7**). However, the combination of increased capacity adaptability and decreased productivity leads to higher production costs and extended production times. In the quest for high productivity and high flexibility, adaptive and flexible production systems in machining offer a solution thanks to the interchangeability and retrofitting of mechanical and software modules as well as adaptable manufacturing strategies.

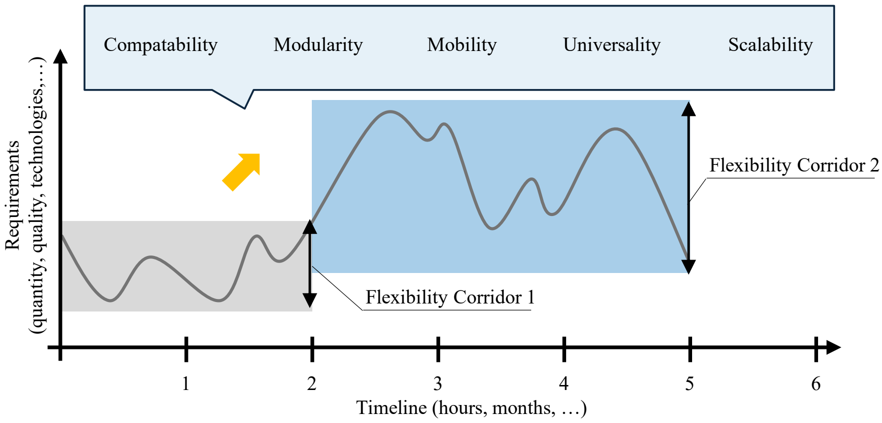

Fig. 7. Increasing the flexibility corridor by implementing adaptive drivers in machining for the manufacturing of rotor shafts [11, 12].

3.2 Adaptive and Flexible Production Line Implemented for Rotor Shaft Machining

To fulfil global requirements in terms of quantity, quality, and technologies based on development activities in the area of electric vehicle motors for passenger cars, a sample manufacturing process flow and value stream for machining rotor shafts has been developed and successfully implemented. The illustrated process flow includes the main manufacturing processes for rotor shafts as mentioned in Chapter 2.2 (**Fig. 8**). Firstly, the rotor shaft is cold forged before undergoing a turning operation on the right and left. After this, the surface is milled for the data matrix code and additional oil cooling holes are drilled for cooling down the sheet metal stacks. This is followed by axial forming of the inner splines and then induction hardening of the shaft, the bearings, and inner splines. Next come a hard turning operation and grinding of the shaft and bearings. Lastly, the marking, demagnetization, and inspection of the component takes place.

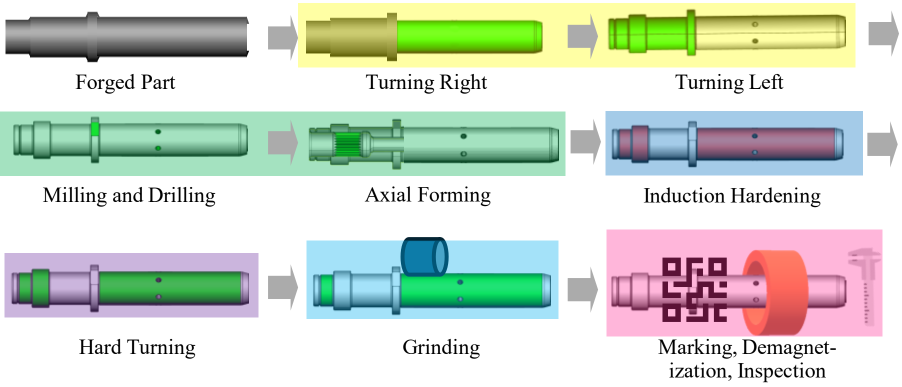

Fig. 8. Sample manufacturing process flow for a rotor shaft.

To implement the manufacturing process flow for machining rotor shafts, a detailed value stream analysis and planning approach was developed and successfully employed (**Fig. 9**). This involved the retrofitting and relocation of machinery. For this purpose, one machine hall was divided into six sections. The first section (yellow) includes the turning machines and operations. The second section (green) includes all milling, drilling, and axial forming machines and operations. The third section (dark blue) includes all induction hardening machines with different inductors. The fourth section (purple) includes all hard turning machines and operations. The fifth section (light blue) includes all grinding machines and grinding wheels. The sixth section (magenta) includes all marking, demagnetization, and inspection machines and processes.

Fig. 9. Sample value stream for machining rotor shafts.

4 Summary and Outlook

In summary, the global electric automotive market is growing. This growth is primarily taking place in the European Union and Asian markets. To fulfil customer needs around the world, OEMs of passenger vehicles use various electric vehicle motor technologies for radial-flow machines such as PMSM, EESM, and ASM, for the front and rear axles and for different vehicle segments. At the heart of all electric vehicle motor technologies lies the rotor shaft. This converts the electrical energy of the magnetic fields into kinetic energy and transmits this kinetic energy to the transmission and the drivetrain. The main components of rotor shafts include the spline or helical gear, the two bearings, the shaft itself, and the inner cooling system. Important considerations are the material used as well as the wall thickness and length of the rotor shaft. Production involves a combination of forging and machining processes. The main machining operations are turning, drilling, spline or helical gear forming or milling, induction hardening, and grinding. The growing and volatile market for electric vehicles leads to short product life cycles and consequently shorter production runs. To address the need for cost-effective and highly flexible solutions in the context of manufacturing rotor shafts, a highly adaptable and flexible production line for machining rotor shafts was developed and successfully implemented. The planned process flow and production costs for rotor shafts manufactured on the adaptive and flexible machining line needs to be verified in practice.

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