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An Approach for the Disassembly of Permanent Magnet Synchronous Rotors to Recover Rare Earth Materials

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Abstract

The extensive electrification of the mobility sector is a crucial part for global decarbonization. To enable a successful transition, the availability of resources must be ensured. In particular, rare earth materials used in permanent magnets of permanent magnet synchronous machines (PMSM) are already considered as a critical resource. Therefore, high performance magnets of existing PMSM rotors must be recovered and remanufactured or recycled. A major challenge to recover the magnets is their fixation inside the rotor lamination stack. Hence, this paper presents an overview of remanufacturing and recycling methods for rare earth magnets. Based on this, a disassembly process for PMSM rotors is developed, technical challenges are pointed out and automation solution are proposed. As results of an experimental study conducted on different magnet configurations, four characteristic phases for the magnet disassembly process were identified and magnets with nickel coating showed significantly higher disassembly forces than magnets with epoxy coating. Moreover, analytical and empirical approaches for modeling the consecutive phases of the disassembly process are proposed.

Keywords: Electric traction motor; permanent magnet synchronous machine; rare earth magnets; disassembly; recycling; remanufacturing

1. Introduction

The electrification of the mobility sector takes a crucial role to fulfil the targets of the Paris climate agreement. To enable a successful transition, the future availability of essential resources must be ensured. In particular, rare earth elements like neodymium and dysprosium are basic elements for high performance permanent magnets used in electric traction motors. These elements have already been declared as critical resources by the White House and the EU [1,2]. Other sectors as the energy industry (generators) and the semiconductor industry (Hard Disk Drives HDD) also depend on the availability of rare earth elements. But due to the fast-growing market, electric vehicles have already become the largest contributor to worldwide rare earth demand [3]. In addition, China is dominating the global production of neodymium-iron-boron (NdFeB) magnets. Nowadays, up to 95 % of neodymium is mined in China [4,5] which results in an unstable supply chain. From an ecological point of view, the production of NdFeB magnets is highly CO2 intensive. Especially due to the low concentration of rare earths in the mined material the strip casting process has a high share in the total greenhouse emissions resulting from NdFeB magnet production [5]. Hence, the recovering and subsequent remanufacturing or recycling of rare earth magnets is a key factor for a reduction of CO2 emissions and a more resilient supply chain.

1.1. Design concepts of PMSM electric traction drives

Due to their high power density and efficiency PMSMs with buried magnets are often used as traction motors for all-electric

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vehicles. The basic mechanical design of rotors used in PMSMs, which is shown in Fig. 1, is very similar. A PMSM rotor consists of a lamination stack, a rotor shaft for torque transmission, two balancing discs and magnets attached to the lamination stack as well as two bearings. Depending on the mechanical design, additional elements for axial fixation of the lamination stack and the balancing discs are possible. Regarding the lamination stack, different magnet arrangements for buried magnets are known and applied in industry depending on the electromagnetic design. In most cases the magnets are fixated in the lamination stack by gluing or transfer molding, but also pure mechanical fixations can be used [6].

The permanent magnets are hard magnetic materials with a high remanence flux density (corresponding to the strength of the magnetic field) as well as a high coercive field strength against demagnetization. NdFeB magnets are characterized by a high level of performance and consist of neodymium, iron and boron. In addition to these elements, a variety of other elements is added to the alloy to improve various properties of the magnets. For example, small amounts of dysprosium are added on purpose to improve the resistance against thermal demagnetization [7]. Other materials for permanent magnets include aluminum-nickel-cobalt, iron (hard ferrite) or samarium-cobalt. Since neodymium-iron-boron magnets have a very high remanence flux density as well as a high coercive field strength, they are used in PMSMs for electric traction motors but also come with high specific costs [8]. To protect the magnet composition from oxidation, the magnets are protected with a surface coating, e.g. epoxy or nickel.

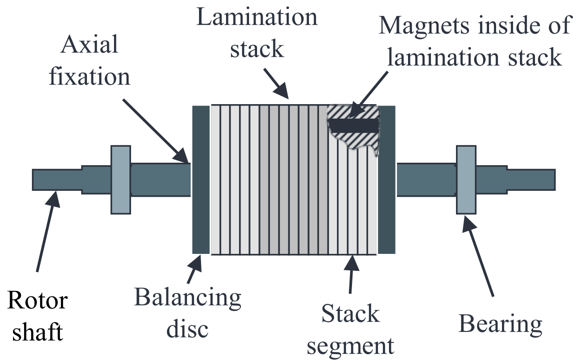

Fig. 1. Schematic presentation of the rotor of a PMSM.

1.2. Methodology and goals of research work

In this paper, a new disassembly approach for PMSM rotors is developed. By disassembling the components, the best degree of material separation can be achieved. Therefore, the loss of critical resources within the recycling process is minimized and the quality of the recycled material is maximized at a reduced energy consumption in comparison to destructive separation approaches. In addition, the direct reuse of undamaged components for remanufacturing purposes is enabled [9,10]. The goals of this research work are to gain process knowledge for the disassembly to enable a future industrialization of this process. Therefore, a literature review is conducted in section 2 and an own disassembly process for permanent magnets is derived in section 3. In section 4, an experimental study for different magnet configurations is conducted and approaches for the modeling of the disassembly process are discussed.

2. State of the art

The separation of the rare earth material and other components of the recycling volume is a fundamental part of the process chain for recycling of rare earth magnets. Therefore, various processes for separating the individual elements from the magnetic waste and the recycling possibilities are presented in this section. In addition to widely researched hydrometallurgical and pyrometallurgical recycling processes, there are other processes such as hydrogen decrepitation [11].

Most of the latest approaches for magnet recycling are focusing on the shredding of end-of-life products and the separation of the magnet material from other scrap [12–17]. This process enables the processing of different components like PMSMs and hard disc drives (HDDs) with rare earth magnets for large throughput and high profitability. However, there are also disadvantages of this process: The process is not fully developed and not industrialized. Also, due to the severe destruction of the components, not all of the material can be recovered and there is a limited purity of the recycled material. Depending on the process the purity of the recovered material is critical for the later application, since it can deteriorate the quality of the recycled magnets.

2.1. Magnet disassembly

The disassembly of PMSMs is rarely researched, especially for buried magnets. For the disassembly process the magnets can be demagnetized for better handling. For this purpose, a strong external magnetic field with opposing polarization can be applied to the magnets. Alternatively, permanent magnets lose their permanent magnetic field above their Curie temperature, which is a very energy intensive procedure due to the high coercive field strength required for PMSM magnets.

During the disassembly, it is especially important that the surface coating remains undamaged. If the coating is not in working order anymore, the magnet material starts to oxidize. The compressive strength of NdFeB magnets is 250 to 1000 MPa [18,19] and should not be exceeded as the magnets are brittle and can break apart. If the magnets were not demagnetized during disassembly, they may get in contact with the lamination stack and can cause damage to the machine, the worker or itself. If a high magnet quality is maintained after disassembly the magnets could be directly used for remanufacturing.

For the automated disassembly of magnets from PMSMs, a process chain for surface-mounted magnets was developed within the MORE project based on a blade to shear off the magnets [18].To simplify the disassembly process, the rotor was first demagnetized at 350°C, which also dissolved the resin. Afterwards, the magnets could be removed without large shear forces. Additionally, a concept for buried magnets was presented in which the rotor was not demagnetized. The separation of the magnets uses a punch which pushes all magnets out of the lamination stack at the same time. To exclude mutual interference between the individual magnetic parts the magnets were separated by a system of pipes. But due to the focus of the research work, within the MORE project no extensive process understanding was developed and the automated concept was not suitable for different rotors and the uncertainty of end-of-life products [18].

In summary, an extensive understanding of the disassembly process of buried permanent magnets is not known according to the state of the art and must be developed to enable an automated process dealing with different kinds of rotors as well as uncertainties of end-of-life products.

2.2. Hydrometallurgical processes

Hydrometallurgical processes have been widely researched and are used for the recycling of various metals. Different variants of processes are applied for this purpose, such as solvent extraction, leaching or ion exchange [20].

After the magnet-containing recycling volume has been demagnetized and crushed to a fine powder, the material is dissolved in a strong mineral acid. Relevant parameters related to the utilization rate are the particle size, the concentration of the acid and the process temperature. After that, the rare earths are precipitated from the solvent as various salts. These salts can be further separated depending on the containing materials; therefore, the final product is the respective oxide of these materials. From these metal oxides, the pure materials can then be extracted by endothermic reactions. Thus, the magnet components can be separated on a large scale – but it is a complex process using many chemicals [7,20,21].

2.3. Pyrometallurgical processes

As an alternative to hydrometallurgy, pyrometallurgical processes are equally used to recover rare earths from end-of-life products [21]. Depending on the process, the valuable recycling volume is either melted down (electroslag remelting) or melted in a liquid metal bath (liquid metal extraction). In case of electroslag remelting, the magnets are melted down and impurities are removed using a reactive melt. Challenging is that this method is only applicable to certain starting elements and that there is no optimal separation of the materials [22]. In summary, the pyrometallurgical processes are easy to implement but require a high amount of energy to continuously heat the melt [20,22,23].

2.4. Hydrogen depreciation process

The hydrogen depreciation process was developed in 2012 by the University of Birmingham on the use case of HDDs. This involves the infeed of hydrogen onto HDDs within a protective atmosphere to cause a chemical reaction of the magnetic materials. The special characteristic of this process is that the reaction demagnetizes the magnets and significantly increases the volume of the magnetic materials at the same time. As a result, the material breaks apart to a demagnetized hydrogenated powder. In the case of a nickel coating, small nickel particles occur in the powder as an impurity. Subsequently, the powder mixture can be directly reused to produce new magnets by sintering [7,24,25]. In future, this process may also be suitable for recycling magnets of PMSMs. However, studies by Jönsson et al. show that the adhesive residues and different coating types of buried magnets can contaminate the powder. Hence, further process steps to increase the purity grad of the powder before sintering will probably be required [26]. Furthermore, the reaction of the recycling volume and the fed hydrogen is slowed down by dysprosium, which inhibits the reaction – and there is a high share of dysprosium in magnets used for PMSMs compared to magnets of HDDs [26,27].

3. Own approach for the disassembly of PMSM Rotors

In the following, a new process chain for the disassembly for PMSMs is derived from their typical design. At first, the magnetic rotor must be demounted from the stator. The process chain for the disassembly is shown in Fig. 2 and derived from the design of the PMSM Rotor shown in chapter 1. An overall challenge, especially for the automation of the process steps, is the unknown state of end-of-life products and the resulting uncertainty regarding the mechanical and electromagnetic properties. Moreover, no extensive damaging is acceptable due to negative effects on the following process steps.

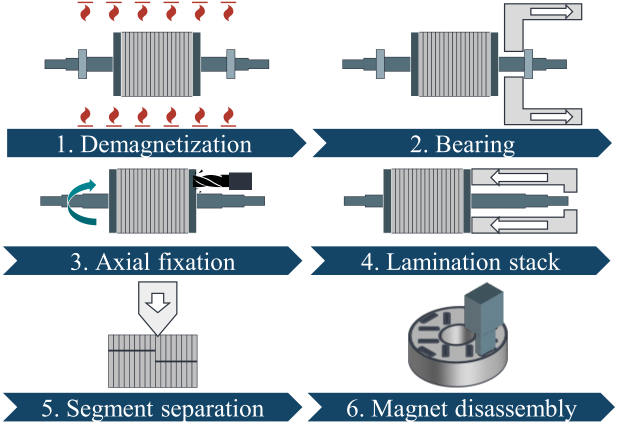

Fig. 2. Process chain for the rotor disassembly.

3.1. Demagnetization of the rotor

In a first step, the rotor can be demagnetized. This step is optional from a product-specific point of view and depends on the later usage of the magnets. Nevertheless, from a production-specific point of view, it is recommended, since the further process steps are substantially more difficult with a magnetized rotor. As introduced before, the demagnetization can be realized using two different methods: A strong external magnetic field with opposing polarization or a heating above the Curie temperature. The demagnetization using an external field is technically more challenging, but preferred due to its high efficiency. The necessary amount of energy is lower, the process time is shorter and there is no need for cooling afterwards. In contrast, the heat can be applied to the rotor using induction heating, thermal convection, electric current or several other methods.

3.2. Disassembly of bearings, axial fixation and rotor shaft

The following process step is the disassembly of the bearings. It can be considered as one of the less challenging process steps. The bearing can be dismounted using mechanical force which depends on the degree of the press fit.

The third step is the loosening of the axial fixation. This step strongly depends on the rotor design. Most relevant types of axial fixations are shaft shoulder, shaft nut, press fit (by an additional ring or a balancing disc) and tension rods. In case of a press fit, there is no need for this step because the lamination stack and the balancing disc can be dismounted without prior preparation in the following process step. The type of fixation defines the disassembly process as some of the connections can only be loosed by a damaging disassembly.

The subsequent step is the dismounting of the lamination stack and the balancing disc from the shaft. The direction of the process must be defined considering the characteristic design elements, as shaft shoulders. Due to the product requirements of high concentricity and torques the press force can be high.

3.3. Segmentation of the lamination stack

Afterwards, the dismounted lamination stack needs to be separated in segments. Depending on the rotor design, the segments of the lamination stack can be joined by the magnet fixation or not, which makes this process step optional. The segments are twisted to enhance the NVH behavior of the product. From a production-specific point of view, the axial length of all the rotor stacks to disassemble the magnets would require large press forces, potentially destroying the magnet.

3.4. Disassembly of the permanent magnets

The last step of the process chain is the actual dismounting of the permanent magnets from the lamination stack. As introduced before, the magnets are fixated in place usually using an adhesive. In this work, the promising mechanical disassembly process is chosen due to the short process time and the low energy consumption.

Since the process step needs to be repeated more than 100 times and therefore takes a high share on the total disassembly effort, this work focuses on this process step. To develop a highly automated process, the process requirements and characteristics need to be fully understood. In order to generate a basic knowledge, experimental test series were conducted.

4. Experimental investigation

To investigate the process of magnet disassembly, an experimental set-up was implemented as shown in Fig. 3. The central part of the setup was a uniaxial universal testing machine from ZwickRoell with a maximum compressive force of 10 kN. To carry out the process, a stamp was fixed in an adapter which is fixed to the force sensor at the top. In addition, there are two support elements on the bottom of the test stand to enable a downward disassembly of the magnet. During the experimental test series, the preforce was set to 30 N and the speed to 20 mm/min. Because the work of Wolff suggests that the disassembly speed has a minor influence on the disassembly forces, the speed is kept constant in this study [28].

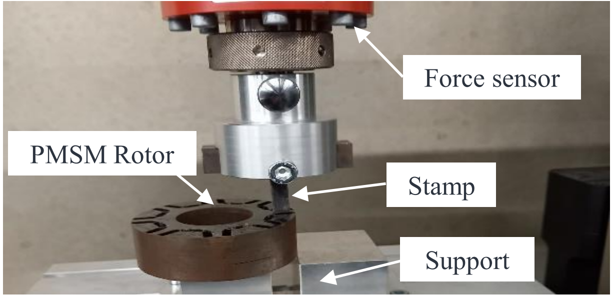

Fig. 3. Experimental setup for the magnet disassembly.

As specimen, lamination stacks of a PMSM rotor from a small electric traction motor developed by the Institute of Electrical Engineering (ETI) at Karlsruhe Institute of Technology is used [29]. The geometric properties of the rotor and the stamp are summarized in Table 1.

Table 1. Design parameters of the disassembled permanent magnet.

Parameter	Value	Parameter	Value
Magnet arrangement	U-Shape	Magnet slot length	9.38 mm
Outer Diameter	80 mm	Magnet slot width	3.98 mm
Inner Diameter	38 mm	Magnet slot height	25.9 mm
Magnet length	9.3 mm	Stamp length	8.8 mm
Magnet width	3.9 mm	Stamp width	3.6 mm
Magnet height	12.5 mm	Stamp height	30.9 mm
		Stamp phase	0.2 mm

The rotor electric sheets have a thickness of 0.35 mm and were bonded by bonding varnish. The rotor contains two magnets in the magnet slot, staked on top of each other. The magnets are manually fixated by gluing using Elantron EC 5000 / W 5690, a high thermal resistant two-component epoxy system from Elantas, often used in electric machines. In order to investigate the influence of the different parameters of the magnet fixation on the disassembly process, an experimental test series was conducted using four repetitions. The factors and the levels of the design of experiments are shown in Table 2. The size of the magnets as well as their tolerances for epoxy and nickel coating were identical.

Table 2. Factors for the experimental study of magnet disassembly.

Parameter	Low	High
Magnet coating	Epoxy	Nickel
Magnets per slot	1	2

4.1. Experimental results

As a result, a typical force-displacement diagram of the disassembly of two nickel coated magnets is shown in Fig. 4.

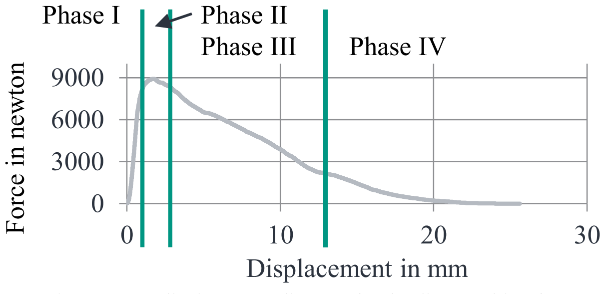

Fig. 4. Force-displacement diagram for the disassembly of two nickel coated magnets.

Based on the results of the experimental study, the disassembly process can be divided into four characteristic phases:

- I: Linear elastic deformation
- II: Adhesive separation
- III: Frictional behavior
- IV: Friction depreciation

<u>Phase I: Linear elastic deformation</u>

In the first phase, there is a linear correlation between the displacement and the force that can be classified by a gradient.

Phase II: Adhesive separation

The second phase is the damage of the adhesive. As typical for adhesive materials, there is a high spread in the maximum force. Because no surface treatment for the magnet or the magnet slot is established in industrial application, the spread is increased compared to other applications.

Phase III: Frictional behavior

In the third phase, there is a reduction in force with some uncertainty but with an overall linear behavior in approximation. After the first movement of the magnet the adhesive force of the glue is reduced which means that there is also another force holding the magnet still in place. Since the contact of the magnet and the slot is linearly reduced due to the constant process speed, it can be concluded that there is a linear correlation between the magnet length inside the slot of the lamination stack and the disassembly force.

Phase IV: Friction depreciation

The last phase is similar to the third phase from their work principles, but there a no linear characteristic anymore. The friction coefficient is declining, caused by the wear of the material, lowering the disassembly force continuously.

4.2. Experimental parameter study

The results of the experimental tests series with a total number of eight specimen are shown in Fig. 5. Across all test series, there is a large spread of the maximum disassembly forces. The required force for the disassembly of epoxy coated magnets is significantly lower than for nickel coated magnets. Furthermore, there is a large difference between the disassembly forces for one and two magnets with epoxy coating but only a small difference for nickel coated magnets.

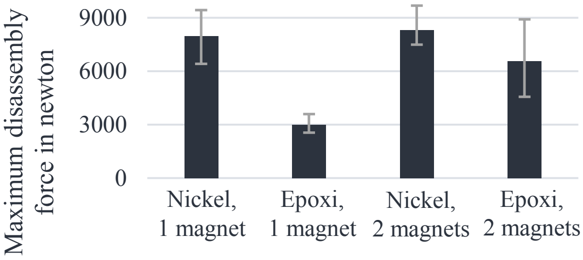

Fig. 5. Maximum disassembly forces.

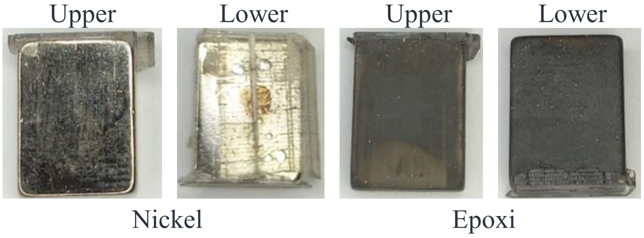

Fig. 6. Surface condition of magnets after disassembly.

The typical surface conditions of the disassembled magnets are pointed in Fig. 6, in which the upper and the lower magnet of a two magnet test series are shown. The nickel coated magnets have an excessive amount of magnet fixation attached to the magnet. The lower magnet with coating shows small vertical lines which are formed by the structure of the lamination stack during the gluing process. This structure can cause some effects of a form fit which could lead to a complex behavior. This could explain the small difference of the disassembly force of one magnet with nickel coating and two magnets with nickel coating.

In general, especially the lower magnets with nickel and epoxy coating have more magnet fixation attached. The condition of the magnets from the test series with one magnet is very similar to the condition of the lower magnets from the test series with two magnets. Hence, it can be concluded that the magnet fixation is peeled off when the magnet is pressed through the slot of the lamination stack as described in fourth phase of disassembly "Friction depreciation".

4.3. Modeling of magnet disassembly process

In this section, approaches for modeling the magnet disassembly process are discussed. The modeling can be used to increase the level of process understanding as well as to optimize the tool selection, to deal with uncertainty and for process monitoring. Because of the complex interrelationships of the slot with nickel coating, the modeling only applies to the epoxy coating within this work.

The first phase of disassembly "Linear elastic deformation" can be modeled using conventional analytic approaches. The main influence on the disassembly force is the contact surface of the magnet and the shear strength of the adhesive as shown in Fig. 7. The maximum disassembly force F_d can be modeled as the product of the surface area A and the shear strength τ:

$$F_d = A * \tau \tag{1}$$

Since the shear strength in the contact consisting of the adhesive and the magnet is unknown, it can be calculated using the magnet geometry and the experimental results acquired for magnets with epoxy coating. Resulting from this assumption, the shear strength can be set to 9.5 N/mm² for epoxy coating.

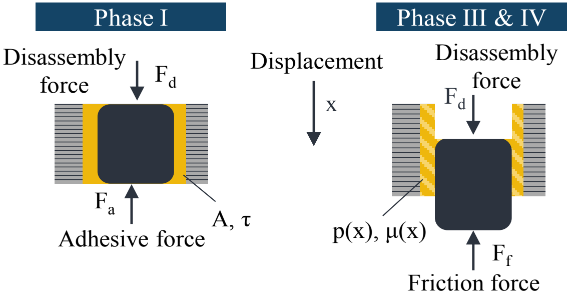

Fig. 7. Modeling of the magnet disassembly.

The second phase "Adhesive separation" cannot be modeled based on analytic and numerical approached due to uncertainty of adhesive joints. Hence, empirical studies are a more appropriate approach and therefore subject of this research work.

The third and fourth phase "Frictional behavior" and "Friction depreciation" can be modeled based on analytical correlations. After Phase II the adhesion force is significantly reduced. The remaining friction force results from the pressure p(x) and the friction coefficient μ(x). As pointed in the experimental results, the surface area of the magnet depends on its displacement which means that it corresponds to the friction coefficient in phase IV. Both the friction coefficient and the pressure are unknown. Either they can be determined by experimental studies or as a more simply approach they can be combined to a new variable V(x) = p(x) * μ(x).

4.4. Modeling of magnet damage

The average contact pressure of two nickel magnets resulting from the maximum press force and the surface area of the stamp can be calculated as follows:

$$p = \frac{F_d}{A} = 309\ N/mm^2 \qquad (2)$$

Considering the compressive strength of NdFeB magnets of 250 to 1000 N/mm² this parameter can be critical – especially if tools are used for different magnet sizes and are not fitted to every individual magnet.

4. Conclusion and Outlook

Within this paper, the disassembly of permanent magnets used in PMSMs to recover rare earth materials is focused. The disassembly enables new process chains for recycling, maximizes the recovery rate and minimizes the energy consumption. In order to generate basic process knowledge, an experimental study was conducted considering magnets with nickel and epoxy coating as well as either one or two magnets in the slot of the lamination stacks. The experimental study showed that the disassembly of permanent magnets is possible. However, high disassembly forces were observed that can potentially damage the magnet. Moreover, four typical phases of the disassembly process were identified and analyzed: Linear elastic deformation, adhesive separation, frictional behavior and friction depreciation. As typical for adhesive joints, there is high level of uncertainty and a large influence of the surface – the magnet coating – on the results. The condition of the disassembled magnets depends on both the magnet coating and the distance which need to be passed inside the magnet slot of the lamination stack during disassembly. Based on the experimental results, a basic analytical process model was developed for selected process phases. But the remaining challenges of a precise modeling are the uncertainty of the adhesive and unknown correlations of the pressure and the friction coefficient inside of the magnet slot. Hence, an end-to-end process model of the magnet disassembly process should be developed in future research work.

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