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Process Management and Technological Challenges in the Aspect of Permanent Magnets Recovery - the Second Life of Neodymium Magnets

Katarzyna Kapustka[1], Gerhard Ziegmann[1], Dorota Klimecka-Tatar[2], Sara Nakonczy[1]
[1]University of Technology, Clausthal Centre of Material Technology, Agricolastraße 2, 38678 Clausthal-Zellerfeld, Germany. E-mail: katarzyna.kapustka@tu-clausthal.de, ziegmann@puk.tu-clausthal.de, swn18@tu-clausthal.de
[2]Czestochowa University of Technology, Department of Production Engineering and Safety, ul. Armii Krajowej 19B, 42-200 Czestochowa, Poland. E-mail: d.klimecka-tatar@pcz.pl

Very dynamic development in the field of computerization and industry robotization, as well as an implementation of the Industry 4.0 assumptions are the main reason for the increased demand for magnetic materials. The limited rare earths availability and the sustainable development in the field of material engineering indicate that the methods of recycling magnetic materials from Waste of Electrical and Electronic Equipment are necessary. This paper presents the impovement stages of magnets recovery process - extrusion process of magnetic scraps/particles with polymer (magnetic scraps and particles obtained from WEEE). The process is developed based on the Process Failure Mode and Effects Analysis. The reserch pointed the irregularities, that pose the greatest risk of failure in the process. The paper presents changes in the process based on the values of the indicators: severity (*S*), probability of occurrence (*O*), probability of detection (*D*) and the Risk Performance Number (*RPN*). Based on the PFMEA, 5 operations were added to the process. Due to changes in the process course, it is possible to minimize the effects of the irregularities occurrence.

Keywords: NdFeB, neodymium magnets, recycling, magnets recycling, magnets recovery, FMEA

1 Introduction

Rare earths, at present, have the highest strategic value in the modern technology industry. Computerization, robotization and implementation of the Industry 4.0 assumptions increase the demand for magnetic materials with the best performance parameters. According to the principles of industry 4.0, production processes should be carried out using fully automated technological lines, supervised and monitored by digital (intelligent) operating systems [1-8].

According to the state of technology, rare-earth magnets are currently difficult or impossible to replace. Increasing demand, as well as existing technological difficulties in obtaining materials based on rare earths intensifies the risk of supply bottlenecks. Consequently, limitations or a slowdown in supply continuity may have a very large impact on the development of advanced industrial technologies, e.g. the production of smartphones, flat screens and energy-saving lamps, also in audio devices, hard drives, the production of hybrid cars, electric motorcycles, wind turbines, and advanced medical devices etc.. Most devices driven automatically using stepper motors, processors, etc. use the properties of hard (permanent) magnets. Because, the permanent magnets produce a constant magnetic field in the space around and have a tendency to remain magnetized. Unlike soft magnetic materials, which do not have this property. There are many kinds of permanent magnets, but the most popular are: sintered Sm-Co magnets, ceramic magnets (sintered ferrite), bonded magnets (based on Sm-Co or Nd-Fe-B powders) [9, 10].

Magnets manufactured from a combination of neodymium, iron and boron with $Nd_2Fe_{14}B$ ferromagnetic phase are commonly named as neodymium magnets. And neodymium magnets, next to samarium magnets, are the strongest type of permanent magnet available commercially [11]. It is assumed that, the inventor of Nd-Fe-B magnets is Sumitomo Special Metals Company in Japan (1984), but it is worth noting that at the same time Gerenal Motors had published independently an equivalent composition [12]. Studies on the magnetic properties of this type of alloys have resulted in the formation of $Nd_2Fe_{14}B$ phase with a tetragonal structure, strong uniaxial anisotropy and high Curie temperature. Generaly, the $RE_2M_{14}B$ (RE-rare earth, M- transition metal) phase is characterized with unique magnetic properties, high resistant to change of magnetization direction, which in turn results in high resistance to demagnetization [13, 14]. Additionally, it is worth noting that the stoichiometric $Nd_2Fe_{14}B$ phase composition contains only about 12% of rare earth elements, which makes it cheap and accessible for mass production [13].

Due to its deposits and having the world's largest amount of rare earths mines, China has become a global exporter supplying more than 100,000 metric tons of rare earth oxide equivalent per year – Fig 1 [13]. It is obvious, the extraction of this raw material also takes place in other countries, for example in India, the USA, Russia or Australia, but to a much lesser extent [15]. Despite their name, rare earth elements are found in many other places, but construction and maintenance of mines very often is uneconomic. Because of the important role of magnets in modern technologies and at the same time political uncertainty and growing trade tensions, the recycling methods of magnets already put into circulation are sought in many countries [16].

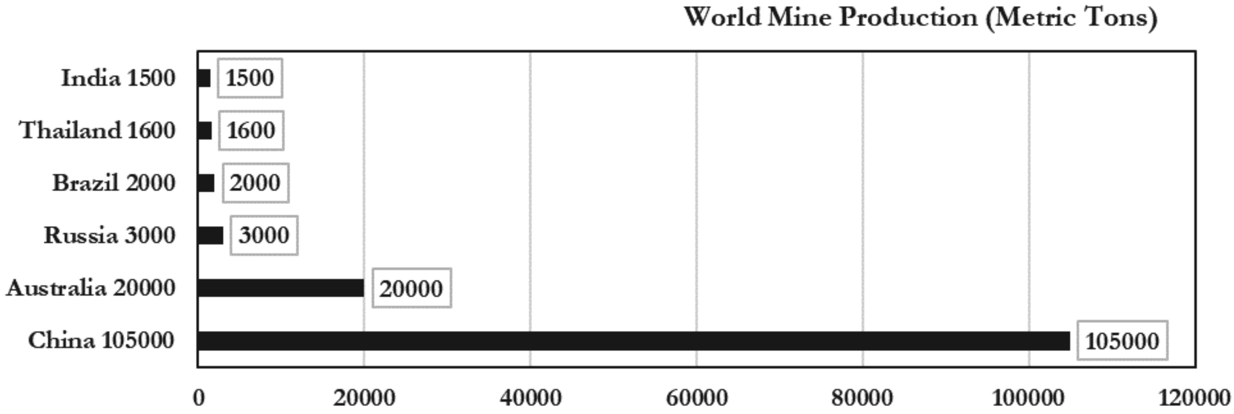

Fig. 1 *Estimates of 2012 World Rare Earth Element Production [based on 12]*

The more recent rare earth crisis in 2011 (Fig. 2) had been seen in huge increases in the price of rare earth metal stemming from market in China, which by then had become the dominant source of supply. Neodymium prices reached as high as 250 thousand USD dollars per metric ton, respectively in current terms. That crisis jeopardized the credibility of future supplies of the heavy rare earth metals (Dy and Tb), which constituted 5% by weight of the high-temperature grades of Nd-Fe-B used for electric vehicles at that time. From 2018 onwards, the situation has stabilized, also through the effective reaction of scientists and the rapid identification of other possibilities for extracting magnets [17].

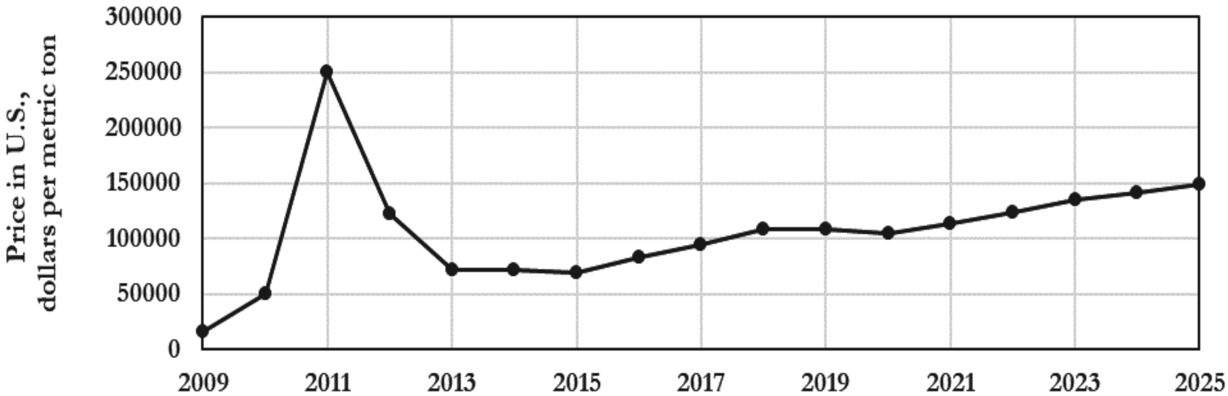

Fig. 2 *Neodymium oxide price in U.S. dollars per metric ton, worldwide from 2009 to 2025 [based on 17]*

The statistics present the price, and price forecast, of rare earth oxide and neodymium oxide in the years 2009-2025. Until 2025, the price is expected to increase over 148 thousand dollars per metric ton.

The unstable market of magnetic materials is the most important reason for the launch of numerous studies on [18-24]: minimalization of rare earth metals consumption, magnets protection (e.g. protective coatings), and developement of magnets recovery processes. Therefore, the main aim of this paper is to present the planning and stages development of the magnets recovery process.

2 Experiment

The main object of research is the permanent magnets recovery process – the indirect material recovery from permanent Nd-Fe-B magnets. Based on a literature review and numerous studies, it was assumed that the effectiveness of such a process largely depends on the successive technological operations. Fig. 3 presents a graphical presentation of the course of the magnets recovery process carried out on a prototype production line (in laboratory conditions) – process preliminary designed. For the purpose of further research and evaluation, the process was divided into 10 stages - (1) and (10) are transport and storage operations, which in this case do not affect the efficiency of the process.

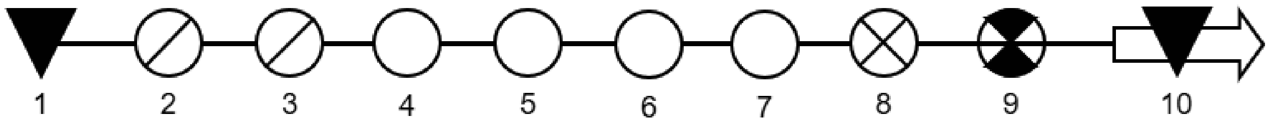

Fig. 3 *Technological approach of magnets recovery process - extrusion process of magnetic scraps/particles with polymer (magnetic scraps and particles obtained from WEEE): (1) Storage of electronic waste WEEE; (2) Dismantling of multi-material systems (dismantling of magnets from motors in WEEE); (3) Thermal demagnetization (temperature above the Curie temperature); (4) Mechanical grinding in a protective atmosphere; (5) Homogenization of the composition - aggregate from magnetic materials and polymer (at the temperature of plasticization of the binder); (6) Composite blend extrusion and granulation; (7) Injection molding; (8) Magnetization, (9) Packaging - protection against the atmosphere; (10) Storage and transport.*

The experiment consisted in carrying out a test production on a proptotype laboratory line for magnets recovery. The aim of this study was to identify possible errors/failures in production at the process design stage. For this purpose, with the prototype technological line use, the test samples of recovery magnets (composites) were made - 200 samples were made (100 samples according to the process scheme presented in Fig. 3 and 100 samples according to the scheme after introducing the necessary changes in the process, Fig. 4). The ssessment and inspection of samples quality was based on a surface visual inspection as well as the measurements with the use of the calipers and a measuring templates. In visual inspection, attention was paid to particles distribution in the composite and the consistency of the material - only samples with significant changes and chipping on the surface were considered as defective. In the measurement control, attention was paid to geometry and symmetry - only samples with significant deformation or breakage were considered as defective.

With regard to the principles of process management and process improvement, the FMEA of the process, i.e. PFMEA (*Process Failure Mode and Effects Analysis*) was carried out. As it is known, FMEA method is the most common method of process testing at the initial stage of designing, before starting serial production. The presented FMEA (PFMEA) method is widely known among manufacturing technology designer, process engineers and project managers. Due to its versatility and ease of use, FMEA is adapted under the quality assurance and ISO 9000 standards, in particular in the standards used in the automotive industry (ISO/TS 16949, QS 9000, VDA 6.1, AVSQ and EAQF). The PFMEA analysis consists in identifying the components and functions of the designed process in the technological order (Fig 3), and allows to indicate the possible errors/irregularities, their effects and errors/irregularities causes.

In accordance with the procedure of the PFMEA method, process errors/irregularities were assigned with the following indicators values (Table 1):

- severity (*S*),
- probability of occurrence (*O*),
- probability of detection (*D*).

Based on the values of *S*, *O*, *D* indicators the Risk Performance Number (*RPN*) was determined (1) [28-30]:

$$RPN = S \cdot O \cdot D \tag{1}$$

Where:
S – severity;
O – probability of occurrence;
D – probability of detection..

Tab. 1 *The value scale of indicators used in the PFMEA analysis of magnets recovery process - magnetic scraps/particles with polymer extrusion process (magnetic scraps and particles obtained from WEEE)*

Rating	Severity	Probability of occurrence	Probability of detection
10	Extremely hazardous	Extremely high (>1 in 2)	Absolute uncertainty
9	Hazardous	Very high (1 in 3)	Very remote
8	Very high	Repeated failures (1 in 8)	Remote
7	High	High (1 in 20)	Very low
6	Moderate	Moderately high (1 in 80)	Low
5	Low	Moderate (1 in 400)	Moderate
4	Very low	Quite low (1 in 2k)	Moderately high
3	Minor	Low (1 in 15k)	High
2	Very minor	Remote (1 in 150k)	Very high
1	None	Nearly impossible	Almost certain

Parameters as severity (*S*), probability of occurrence (*O*), and probability of detection (*D*) were determined in accordance with the requirements of PN-EN IEC 60812: 2018 [31], on the basis of observations and tests carried out on one production batch. Simplified evaluation data are presented in the Table 1

As is known, if *RPN* > 120, the corrective actions need to be taken. For the purposes of this paper, the three most important errors have been presented and analyzed [32].

3 Results and disussion

The performed PFMEA and others analysis enables the identification of problems and irregularities at an early stage of the process design [32, 33]. At the prototype stage, it is possible to make changes to the technology and eliminate critical stages. And most importantly, it is possible to determine the suitability of the process, identify weaknesses and introduce preventive measures [34-36].

The direct recycling method involves the reprocessing of material into new magnets. Before the magnets could be used as an input material for an indirect recycling process, magnets need to be extracted from the WEEE and demagnetized. The first step, the separation of the magnets from WEEE, has been identified as one of the key barriers to Nd-Fe-B magnets recycling [25-27]. However, an automated process for the extraction of the magnets from hard disc drive and motors has already been developed. Table 2 presents the characteristics and assessment of the three most dangerous irregularities that arise during the magnets recovery process (process according to Fig 3).

Tab. 2 *The PFMEA analysis of magnets recovery process - magnetic scraps/particles with polymer extrusion process (magnetic scraps and particles obtained from WEEE) according to preliminary designed process (Fig. 3)*

Process description / functions: The success and efficiency of the magnets recovery process							
1	2	3	4	5	6	7	8
Process	Potential irregularities	Potential effects of irregularities	Severity S	Potential causes	Probability of occurrence O	Probability of detection D	Risk Performance Number RPN
Magnet recovery process	Uneven distribution of magnetic particles in the composite	Isotropy of magnetic properties - classification as incompatible product	10	Insufficient homogenization of ingredients (uneven distribution of scraps / powder particles and polymer binder)	9	8	**720**
	Material is inconsistent	Non-permanent magnetic properties - waste	10	Cracks, holes, voids, chipping, delamination	9	6	**540**
	Inappropriate shape of the finished product	Failure to meet dimensional requirements	5	Lack of proper adhesion between the powder particles and the polymer binder	5	8	**200**

As it is easy to see, in the three indicated errors / irregularities are characterized with *RPN* significantly exceeded the value of 120. This means that it is absolutely necessary to introduce corrective actions that will allow to prevent these errors / irregularities occurance. The proposed corrective actions are:

- After the operation (3) Thermal demagnetization, an additional special control was introduced – preliminary control of the chemical composition of magnetic materials (3A) and segregation in terms of the content of rare earth elements (3B).
- After the operation (4) Mechanical milling in a protective atmosphere, a sieve selection (4A) was introduced, the aim of which was to extract the fraction of powder particles in certain sizes. For further processing, it is suggested to use fractions with a sieve diameter 50 < d < 200 μm, while the powder particles with d ~ 50μm would be finally used in a 3D printer, and the powder particles with d > 200

μm should be sent for regrinding.

- After the operation (7) Injection molding, an additional (7A) special control was introduced. Depending on the final requirements of the process, it is possible to introduce: microscopic tests (quantitative analysis of structural components, including analysis of the homogenization of the composition, distribution of magnetic particles), mechanical tests (Brinell hardness test, bending or compression strength test), surface geometry tests (e.g. analysis of roughness parameters).
- After the operation (8) Magnetization, an additional product release control (8A) was introduced - magnetic tests, which enable the classification of materials into the selected range of magnetic properties.

Changes in the course of the process are presented in the Fig. 4.

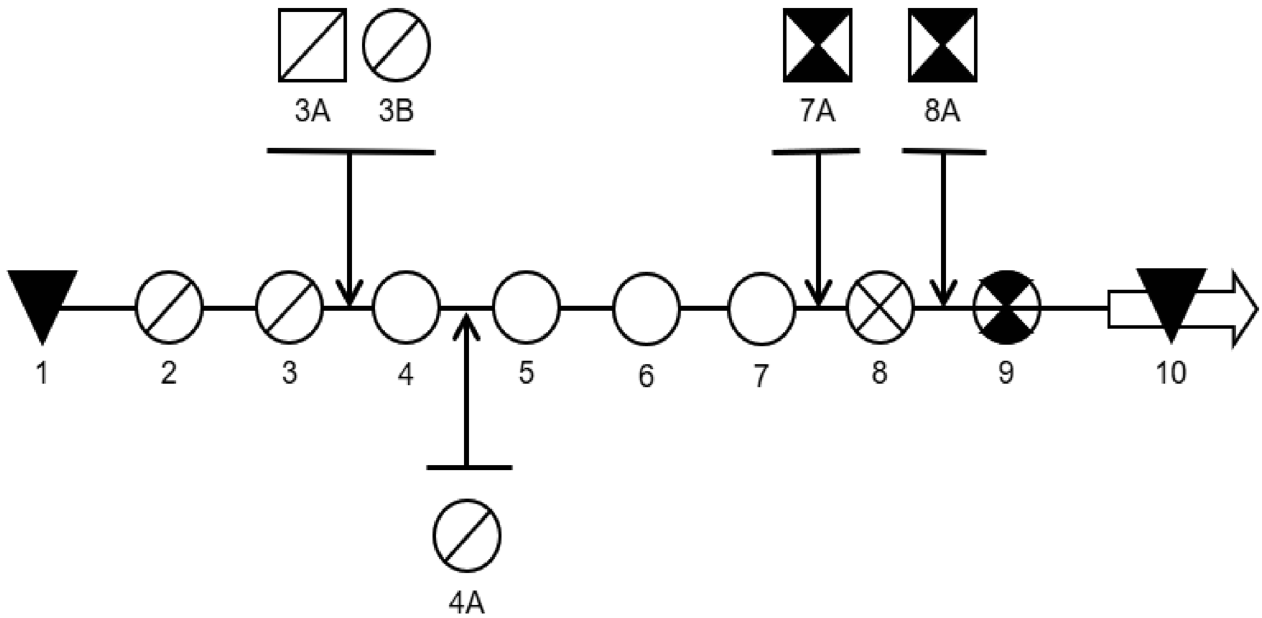

Fig. 4 *Technological approach of magnets recovery process - magnetic scraps/particles with polymer extrusion process (magnetic scraps and particles obtained from WEEE): (1) Storage of electronic waste WEEE; (2) Dismantling of multi-material systems (dismantling of magnets from motors in WEEE); (3) Thermal demagnetization (temperature above the Curie temperature); (3A) Preliminary control of the chemical composition of magnetic materials; (4) Mechanical grinding in a protective atmosphere; (4A) Sieve selection; (5) Homogenization of the composition - aggregate from magnetic materials and plastic (at the temperature of plasticization of the binder); (6) Composite blend extrusion and granulation; (7A) Special control (7) Injection molding; (8) Magnetization; (8A) Product release control; (9) Packaging - protection against the atmosphere; (10) Storage and transport.*

Based on the operation of the prototype magnets recovery line, a re-analysis of PFMEA was performed. Table 3 presents the characteristics and assessment of the three most dangerous irregularities that arise during the magnets recovery process after implementing corrective actions (process according to Fig. 4).

Comparing the data presented in Tables 2 and 3, it can be noticed that the introduction of additional operations significantly minimizes the risk of the process efficiency. With regard to two out of three irregularities, the decrease in the value of the *RPN* indicator is significant. Risk Performance Number (*RPN*) decreas is a consequence of the reduced probability of occurrence (*O*), and the probability of detection (*D*). Therefore, irregularities: "Uneven distribution of magnetic particles in the composite" and "Inappropriate shape of the finished product" no longer pose a significant threat to the correctness of the process flow. However, the changes introduced in the process did not allow to lower the *RPN* for irregularities "Material is inconsistent" for which the final *RPN* = 150. This means that another modification of the process is required. Based on the observation of the process and the possibilities of its organization, it was determined that further improvements will refer to the optimization of the material composition - content optimization of the magnetic powder and polymer as a binder.

***Tab. 3** The PFMEA analysis of magnets recovery process - magnetic scraps/particles with polymer extrusion process (magnetic scraps and particles obtained from WEEE) according to improved process (Fig. 4)*

Process description / functions: The success and efficiency of the magnets recovery process							
1	2	3	4	5	6	7	8
Process	Potential irregularities	Potential effects of irregularities	Severity S	Potential causes	Probability of occurrence O	Probability of detection D	Risk Performance Number RPN
Magnet recovery process	Uneven distribution of magnetic particles in the composite	Isotropy of magnetic properties - classification as incompatible product	10	Insufficient homogenization of ingredients (uneven distribution of scraps / powder particles and polymer binder)	2	1	**40**
	Material is inconsistent	Non-permanent magnetic properties - waste	10	Cracks, holes, voids, chipping, delamination	3	5	**150**
	Inappropriate shape of the finished product	Failure to meet dimensional requirements	5	Lack of proper adhesion between the powder particles and the polymer binder	3	1	**15**

4 Conclusion

On the basis of the PFMEA (process FMEA), three process irregularities, which greatly increase the risk of process failure are selected. In order to ensure the stability of the process of magnets recovery, it is necessary to implement a multi-level inter-operational control and selection of magnetic aggregates (powders) obtained from WEEE.

On the basis of the Risk Performance Number (*RPN*), 5 new operations appeared in the process, which, as shown by the repeated PFMEA analysis, significantly improved the course of the process. On the basis of the conducted research and tests, the following statements were made:

- the process FMEA analysis significantly contributes to the detection of irregularities in the initial phase of designing the process of magnets recovery, and the *RPN* indicators identify the level of risk of the process,
- it is not possible to efficiently carry out the process of magnets recovery without introducing additional stages of control and selection of aggregate from WEEE waste - which was confirmed by very high *RPN* values,
- the introduction of additional preliminary and special control as well as selection of powder materials enables to reduce *RPN*,
- the introduction of additional operations did not bring a satisfactory effect in every case - the improvement of the process in terms of irregularities named "Material is inconsistent" should refer to the design of the chemical composition of the magnetic composite (optimization of the polymer content as a binder) - which is the subject of further research.

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