

Development of a prototype shredder for WEEE equipped with NdFeB magnets

Received: 04.07.2023

Accepted: 25.07.2023

Published online: 31.07.2023

Author's affiliations and addresses:

¹ KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

* Correspondence:

e-mail: pfriebe@komag.eu

tel.: +48 322 374 608

Pawel FRIEBE  ¹*

Abstract:

Waste Electrical and Electronic Equipment (WEEE) that contains neodymium magnets (NdFeB) has the potential to serve as a valuable source of elements, including critical ones. These magnets contain Rare Earth Elements (REEs) like Neodymium, Dysprosium, and Praseodymium. A noteworthy method of recycling REEs involves the magnet-to-magnet process, wherein the NdFeB alloy is separated from WEEE and directly reused in the production of new products, specifically new NdFeB magnets. The initial step in this recycling process involves disintegration, a procedure aimed at reducing and segregating the materials within the WEEE. The conventional process of disintegrating WEEE for recycling faces challenges due to the presence of magnetic materials, making it ineffective with existing equipment. To address this, a specialized device called a disintegrator, using counter-rotating cutting shafts, has been developed for efficient shredding of WEEE containing NdFeB. The goal of the research is to develop a prototype shredder to effectively recover valuable metals, including REEs, from WEEE. Specific sub-objectives include motor and gearbox selection, shaft bearings selection, gear design, and cutting blades design. The work involved calculations and 3D modelling of the disintegrator components using Autodesk Inventor 2020 software.

Keywords: NdFeB magnet, recycling, physical processing of electronic waste, shredding



1. Introduction

An alternative approach to mining for obtaining Rare Earth Elements (REEs) is through recycling [1, 2]. Waste Electrical and Electronic Equipment (WEEE) that contains NdFeB magnets (composed of $\text{Nd}_2\text{Fe}_{14}\text{B}$ alloy) exhibits significant potential for reuse [3, 4]. These magnets consist of REEs such as Neodymium (Nd), Dysprosium (Dy), and Praseodymium (Pr) [5, 6, 7]. Efficiency studies conducted on NdFeB magnets produced from recycled raw materials have demonstrated similar performance to conventionally produced magnets [8, 9, 10]. Furthermore, a comparative Life Cycle Assessment (LCA) analysis comparing the production of new and recycled NdFeB magnets revealed lower emissions and energy requirements in the case of recycling [11].

The currently conducted process of disintegration of hard drives causes many difficulties related to the characteristics of the material [12]. The presence of magnetic materials poses difficulties as the existing equipment used for shredding is constructed with ferromagnetic components, making it ineffective for shredding WEEE containing NdFeB magnets [13]. This is because the magnetic particles adhere to the ferromagnetic elements of the machine, resulting in reduced shredding efficiency and requiring manual interruption and cleaning of the machine.

In order to facilitate the initial shredding process in magnet-to-magnet recycling, a specialized device known as a disintegrator has been developed. Disintegrators operate on the principle of counter-rotating pairs of cutting shafts. The functioning of this equipment is as follows: materials placed on the shafts are captured by blades attached to the cutting shafts. The material is then pressed against the adjacent shaft surfaces and shredded. The resulting fragmented material is further transported by the blades and subsequently discharged from the machine after passing over the shafts. The primary components of the machine consist of the cutting shafts and the shaft casing. The cutting shafts are composed of inner shafts on which cutting knives in the form of discs are mounted. The fundamental concept of the design revolves around employing paramagnetic and robust materials, along with optimizing the design parameters of the machine components, to ensure an efficient shredding process for WEEE containing NdFeB magnets. The shredded product is then directed for further recycling. Recycling enables the recovery not only of REEs but also of other metals, including precious metals, and other component materials from WEEE. The closed-loop magnet-to-magnet recycling approach facilitates the reuse of REEs. Assuming selective separation and reuse of other components in the processed equipment, the amount of waste generated will be significantly reduced, aligning with the principles of a closed-loop economy policy.

The objective of the research presented in this publication is to develop a prototype shredder with the capability to effectively shred WEEE containing NdFeB magnets, thus enabling the recovery of valuable metals, including REEs. To achieve this primary goal, the project has established the following specific sub-objectives:

- Motor and gearbox selection: The appropriate motor and gearbox will be carefully chosen to ensure optimal performance and efficient power transmission within the shredder system.
- Shaft bearings selection: The selection of suitable bearings for the shredder's shafts will be conducted to ensure smooth operation and enhance the longevity of the equipment.
- Gears design: Thorough design work will be carried out to develop efficient gears that will enable reliable operation of the shredder, facilitating the effective shredding of WEEE materials.
- Cutting blades design: The design phase will focus on developing cutting blades that enhance the shredder's cutting efficiency, enabling the successful separation of valuable metals from the WEEE material.

2. Materials and Methods

In sections 2.1 to 2.4, the most important stages of designing the aforementioned device were presented, including motor and gearbox selection, shaft bearing selection, gear design, and the selection of construction material and shape of cutting blades. These tasks involved conducting calculations to determine the minimum torque of the device or to determine the geometric parameters of the components. Subsequently, based on the conducted calculations, 3D models of the parts comprising



the disintegrator were designed. The 3D modelling was carried out using Autodesk Inventor 2020 software, which includes functions related to 3D mechanical modelling, CAD design, and visualization of the developed elements. In section 2.5, the designed device is presented.

This project was developed taking into account the specifications described in the patent application titled "Disintegrator for shredding used electrical and electronic equipment" [14].

2.1. Motor and gearbox selection

The selection of the motor and gearbox for driving the device began with calculating the minimum force required to crush the target material. The following dimensions for the cutting blades were assumed: blade diameter - 129 mm, cutting blade thickness - 12 mm. It was also assumed that the material to be shredded would be a 3.5" hard disk drive (HDD). The components of the HDD include neodymium magnets, a positioner arm with a head, disks, and a PCB (Printed Circuit Board). The components that may pose difficulty in the shredding process due to their high durability are the casing, which has a thickness of up to 12 mm and is made of aluminium, as well as the two steel plates inside. The thickness and width of the HDD were assumed to be 12 mm x 101 mm.

The calculations began with determining the surface area on which the destructive force will act.

$$A = S_1 \cdot G \quad (1)$$

where:

A - cutting area, mm²,

S₁ - width of the cutting blade, mm,

G - thickness of the material being shredded, mm [15].

In the shredding process using disintegrators, the primary force acting on the material is cutting. The shear strength of the shredded materials, such as aluminium and steel, which exhibit the highest strength among the other materials contained in the HDD, was obtained from Table 1.

Based on the above calculations, the destructive cutting force for a single cutting blade was determined using the following formula:

$$R_t = \frac{F_t}{A} \quad \Rightarrow \quad F_t = R_t \cdot A \quad (2)$$

where:

R_t - shear strength, N/mm²,

F_t - destructive force on the material, N [15].

The calculated force F_t needs to be increased due to the fact that in the actual shredding process, multiple cutting blades are involved, depending on the dimensions of the material being shredded. In the case of material with the assumed width mentioned above, the number of cutting blades will be as follows:

$$I = \frac{S_2}{S_1} \quad (3)$$

where:

I - number of blades involved in the shredding process, 1,

S₂ - width of the material being shredded, mm.

The total required destructive force on the material in the shredding process is the product of the required force for a single cutting blade and the number of cutting blades involved:

$$F_c = F_t \cdot I \quad (4)$$

where:

F_c - total required cutting force, N.



The next parameter to be determined is the minimum torque of the device. It is a derived parameter from the cutting force F_c and the radius of the blade r_n [16]:

$$M = F_t \cdot r \quad (5)$$

$$M_a = F_a \cdot r_n \quad (6)$$

$$M_s = F_s \cdot r_n \quad (7)$$

where:

F_a, F_s - destructive force of aluminium, steel, Nm,

M, M_a, M_s - destructive torque of aluminium, steel, Nm,

r_n – radius of the cutting shaft, mm.

The assumptions for the calculations are presented in Table 1 [17].

Table 1. Assumptions for the calculations

No.	Parameter	Value	
		Aluminium	Steel
1.	S_1 [mm]	12	
2.	r_n [mm]	64,5	
3.	G [mm]	9	2,5
4.	R_t [N/mm ²]	75	305

where:

r_n - radius of the cutting blade, mm

The previously determined torque applies to the aluminium casing and a single steel plate. Since the HDD disk contains two steel plates, the calculated torque for a single plate has been doubled. Additionally, a safety margin of 25% has been introduced.

$$M_c = (M_a + 2 \cdot M_s) \cdot 125\% \quad (8)$$

where:

M_c - total required torque.

Knowing the required torque, the selection of the gearbox and motor was conducted. It was assumed that the rotational speed of the shafts should be within the range of 11-16 RPM. Firstly, the torque on the output shaft of the gearbox was converted into force.

$$F_g = \frac{M_n}{r_{wz}} \quad (9)$$

where:

F_g - force generated by the gearbox,

r_{wz} - radius of the input shaft of the gearbox [18].

Next, using the previously calculated force and the assumed dimensions of the cutting elements, the rotational torque of the cutting blade located on its circumference was determined.

$$M_{wt} = F_g \cdot r_{wt} \quad (10)$$

where:

M_{wt} - rotational torque on the cutting shaft.



Table 2 presents the technical data of the considered transmissions, which will be used to determine the generated torque on the cutting shafts of the device [19]. This value will be compared to the previously determined required moment of torque. Based on the knowledge of the torque values on the cutting shafts, a specific variant of the gearbox and electric motor will be selected from the table below.

Table 2. Parameters of considered gearboxes

No.	n_1 [rpm]	n_2 [rpm]	I [1]	P_s [kW]	M_n [Nm]
1.	1400	20,5	68,43	11	4710
2.		18,7	74,95	7,5	3520
3.		15,1	92,53	7,5	4360
4.		13,8	101,33	5,5	3500
5.		11,6	120,33	5,5	4170
6.		11,3	123,75	5,5	4280
7.		10,6	131,78	5,5	4560

2.2. Selection of chamber bearings

The calculations related to the selection of bearings for the device started with determining the rotational speed and torque at which the input shaft of the gearbox would operate. Subsequently, the bearing load was calculated, which allowed estimating the bearing durability expressed in revolutions. The calculations assumed that each bearing would be subjected to half of the total torque generated by the gearbox, considering the use of two bearings on the cutting shaft. The remaining assumptions are listed in Table 3.

Table 3. Assumptions for determining bearing durability

No.	Parameter	Value
1.	n_s [rev.]	1460
2.	I [1]	92,53
3.	P [kW]	7,5
4.	r_n [mm]	64,5
5.	L_1 [years]	min, 5

The calculations were performed using the following equations [18]:

$$M = \frac{9550 \cdot P}{n_w} \quad (11)$$

where:

n_w - rotational speed of the gearbox input shaft, RPM,

n_s - rotational speed of the motor shaft, RPM,

I - gear ratio of the gearbox, dimensionless.

$$F = \frac{M}{r_n} \quad (12)$$

where:

F - bearing load, kN,

r - radius of the cutting blade, m.



$$L = \left(\frac{C}{\frac{1}{2}F} \right)^p \quad (13)$$

where:

L - bearing life, million revolutions,

C - dynamic load capacity, kN,

P - power exponent, for ball and roller bearings $p=3$,

$$L_h = \frac{16660}{n_w} \left(\frac{C}{\frac{1}{2}F} \right)^p \quad (14)$$

where:

L_h - bearing life, hours,

n_w – calculated revolutions of cutting shafts, rev.

In the following Table 4, the data of bearings for the durability calculations are presented [20].

Table 4. Bearing life of the considered spherical roller bearings

No.	Bearing	Shaft diameter Ø [mm]	C [N]
1.	22210-E1-XL	50	109 000
2.	22209-E1-XL	45	104 000
3.	22208-E1-XL	40	101 000
4.	22207-E1-XL	35	89 000
5.	22206-E1-XL	30	64 000
6.	22205-E1-XL	25	48 500

2.3. Gear selection

Gear parameters are essential in determining the functionality and performance of gears in various mechanical systems. Selecting appropriate gear parameters, in line with specific application requirements, is crucial for ensuring reliable and efficient performance in mechanical systems. The following assumptions were made for the gear selection calculations: pitch diameter (equal to the gear centre distance) - 110 mm, module - 5 mm. The following equations [21] were used for the calculations:

$$p = m \cdot \pi \quad (15)$$

where:

p - pitch,

m - module, mm.

The pitch of the gear refers to the distance between corresponding points on adjacent gear teeth along the pitch circle. It is commonly denoted by the symbol "p" and is a fundamental parameter used in gear design. The pitch of the gear determines the size and characteristics of the gear and is essential for proper gear engagement and transmission efficiency.

$$z = \frac{d}{m} \quad (16)$$

where:

z - number of teeth,

d - pitch diameter, mm.



The number of teeth of the gear refers to the total count of teeth present on the gear's circumference. It is a critical parameter in gear design and is typically denoted by the symbol "N." The number of teeth directly affects the gear ratio, meshing capabilities, and overall performance of the gear in various mechanical systems. Proper consideration of the number of teeth is essential for achieving desired speed and torque ratios in gear assemblies.

$$h_a = m \quad (17)$$

where:

h_a - addendum height, mm.

$$h_f = 1,25 \cdot m \quad (18)$$

where:

h_f - dedendum height, mm.

$$h = h_a + h_f \quad (19)$$

where:

h - tooth height, mm.

The addendum is the radial distance from the pitch circle to the top of the gear tooth. It is denoted by the symbol h_a and represents the height of the tooth above the pitch circle. The dedendum is the radial distance from the pitch circle to the bottom of the gear tooth. It is denoted by the symbol h_f and represents the depth of the tooth below the pitch circle. Together, the addendum and dedendum define the overall height of the gear tooth and are crucial for ensuring proper meshing and engagement between gears in a gear system. These parameters play a significant role in determining the strength, durability, and performance of the gear during operation.

$$j = (0,015 \div 0,04) \cdot m \quad (20)$$

where:

j - backlash, the highest value in the range (0.04) was chosen due to the small number of teeth in the gear.

$$s = 0,5p - j \quad (21)$$

where:

s - tooth width, mm,

j - backlash, mm.

$$e = 0,5p + j \quad (22)$$

where:

e - gear width, mm.

Backlash, tooth width, and gear width are essential gear design parameters. Backlash is the clearance between meshing gears, tooth width affects load capacity, and gear width influences gear-tooth contact area and overall performance.

$$d_a = d + 2h_a \quad (23)$$

where:

d_a - addendum circle diameter, mm.

$$d_f = d - 2h_f \quad (24)$$

where:

d_f - dedendum circle diameter, mm.



The addendum circle diameter and dedendum circle diameter are important gear parameters that define the tooth profile. The addendum circle diameter represents the outermost extent of the gear tooth, while the dedendum circle diameter defines the tooth depth. These parameters ensure proper gear engagement and transmission efficiency.

$$c = h_f - h_a \quad (25)$$

where:

c - clearance at the tooth tip.

The clearance at the tooth tip refers to the gap between gear tooth tips when not in contact. It is vital for smooth gear engagement, noise reduction, and preventing tooth damage during operation.

2.4. Designing cutting blades

The cutting shaft consists of a set of cutting blades mounted on the inner shaft. The design of the cutting blades began with the selection of the construction material for the prototype disintegrator's blades. This material should be non-magnetic and have higher strength properties than the products intended for shredding in the disintegrator. The disintegrator will be used for shredding WEEE, including used HDDs. By using non-magnetic construction materials with appropriate strength properties and optimizing the technological parameters of the device, it will be possible to recover rare earth elements from WEEE containing NdFeB magnets and manage the remaining materials generated during recycling.

The construction material of the cutting blades should have higher strength than the materials used in the components of the HDD. It should also be non-magnetic to prevent magnets from adhering to the working elements. The most challenging components of the hard disk drive (HDD) to be shredded are its casing and NdFeB magnets. The HDD casing is made of an aluminum-silicon alloy, commonly referred to as silumin alloy. The magnets inside the HDD are made of an NdFeB alloy. The strength properties of the components are presented in Table 5 [22, 23, 24].

Table 5. Strength properties of HDD casing and magnet

No.	Component	Tensile strength Rm [N/mm ²]	Hardness [HRB, HRC]
1.	Casing	240-280	45,15 HRB
2.	NdFeB Magnet	82,7	51,8 HRC

Next, the shape optimization of the cutting blades was carried out using Autodesk Inventor software. Based on this, a 3D model of the cutting blades, which constitute the main working element of the disintegrator, was developed. The shape of the cutting blades should ensure effective liberation of the iron alloy with neodymium, dysprosium, and other rare earth elements from the remaining materials generated during the disintegration/shredding of WEEE. This shape should also provide sufficient fragmentation of the remaining materials generated during recycling, enabling their further recovery processes.

3. Results

In this chapter, the results of the conducted project work are presented, including the selection of the motor and gearbox, the choice of bearings, the selection of gears, and the design of cutting blades. The disintegrator's illustration, along with its construction description and technical data, is also provided.

3.1. Motor and gearbox selection

In this subsection, the determined parameters necessary for selecting a motor and gearbox that meet the previously stated requirements have been presented. Firstly, the shearing area, destructive force, total required cutting force, and destructive torque for the given material were calculated, and the results are shown in Table 6.



Table 6. Obtained results necessary for selecting the disintegrator drive

No.	Material	A [mm ²]	F _t [N]	F _C [N]	M _a , M _s [Nm]
1.	Aluminium	108	8100	30375	1959
2.	Steel	30	9150	34313	2213

Then, utilizing the data from the above table, the total required moment of torque amounted $M_c = 7982$ Nm was determined.

The next step involved determining the values of the rotational torque on the cutting shafts for the given variant of the electric motor and gearbox, which are presented in Table 7.

Table 7. Results of torque calculations

No.	M _{wt} [Nm]
1.	8680
2.	6487
3.	8035
4.	6450
5.	7685
6.	7887
7.	8403

3.2. Selection of chamber bearings

The calculated values of rotational speed, torque, and force on the gearbox input shaft, based on the above formulas, are presented in Table 8.

Table 8. Results of calculations for rotational speed, torque, and force on the gearbox input shaft

No.	Parameter	Value
1	n _w [rpm]	15,78
2	M [Nm]	4539,36
3	F [N]	70378

Then, the hourly bearing life (L_h) was calculated, assuming a weekly working time of 38 hours. It was assumed that the bearings should operate for at least 5 years. The results of the bearing life calculations are presented in Table 9. Due to the challenging working conditions in the shredder, only spherical roller bearings were considered.

Table 9. Bearing life of the considered spherical roller bearings

No.	Bearing [22]	L [rev]	L _h [hours]	L _t [years]
1.	22210-E1-XL	43325098	45763	25,1
2.	22209-E1-XL	37047795	39133	21,5
3.	22208-E1-XL	33603858	35495	19,5
4.	22207-E1-XL	22043705	23284	12,7
5.	22206-E1-XL	7343749	7757	4,3
6.	22205-E1-XL	2913782	3078	1,7



3.3. Gear Selection

Table 10 presents the calculated parameters for the gear. Based on these parameters, a 3D model of the gear was created (Fig. 1) and a 2D drawing was generated (Fig. 2). The 3D model and drawing were created using Autodesk Inventor 2022 software.

Table 10. Calculated parameters of the gear

No.	Parameter	Value	Parameter	Value
1.	p [mm]	15,71	s [mm]	7,65
2.	z [1]	22	e [mm]	8,05
3.	h _a [mm]	5	d _a [mm]	120
4.	h _f [mm]	6,25	d _f [mm]	97,5
5.	h [mm]	11,25	c [mm]	1,25
6.	j [mm]	0,15-0,2		



Fig. 1. 3D model of the gear

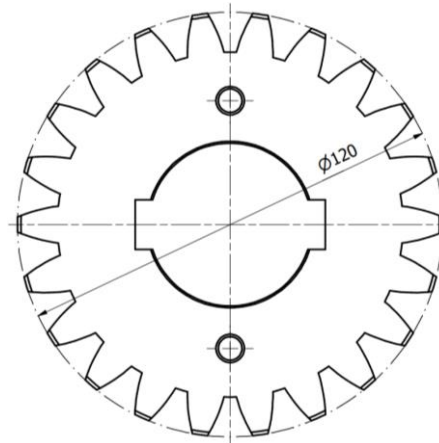


Fig. 2. Side view of the gear

3.4. Designing cutting blades

The SLM (Selective Laser Melting) method has been chosen for the production of the working components of the disintegrator, specifically the cutting blade edges. This method involves the additive manufacturing of parts by selectively melting layers of metal powder. This technology allows for the production of complex-shaped parts with high strength properties. There are various powders available, including titanium-based, nickel-based, iron-based, and others. Among the available powders, a material called PowderRange 718 has been selected, and its properties are further characterized below. This material has a granulation size of 15-45 μm , suitable for SLM technology. It is a nickel-based alloy [25] with a composition of alloying elements presented in Table 11.

Table 11. Chemical composition of PowderRange 718 powder

No.	Element	Ratio [%]	No.	Element	Ratio [%]
1.	Nickel	50,00-55,00	10.	Chromium	17,0-21,0
2.	Niobium + Tantalum	4,75-5,50	11.	Titanium	0,65-1,15
3.	Cobalt	1,00	12.	Magnesium	0,35
4.	Silicon	0,35	13.	Carbon	0,08
5.	Nitrogen	0,03	14.	Phosphorus	0,015



No.	Element	Ratio [%]	No.	Element	Ratio [%]
6.	Molybdenum	2,80-3,30	15.	Sulfur	0,015
7.	Aluminum	0,20-0,80	16.	Iron	Balance
8.	Copper	0,30	17.	Oxygen	0,03
9.	Boron	0,006			

The PowderRange 718 powder allows for the manufacturing of non-magnetic components and exhibits high strength properties (Table 12) [25], surpassing the strength parameters of the materials used in other HDD components, except for the hardness of the NdFeB magnet. Neodymium magnets in hard disks are characterized by their small thickness of approximately 1.5 mm and low strength. Therefore, their disintegration using cutting blades made from PowderRange 718 powder will proceed smoothly.

Table 12. Strength properties of components made from PowderRange 718

Yield Strength Re [N/mm ²]	Tensile Strength Rm [N/mm ²]	Hardness [HRC]
1086	1425	43

The shape of the cutting blades, sketched using Autodesk Inventor software, was designed to ensure effective separation of NdFeB magnet particles from other HDD components such as the casing, disks, positioning arm, head, and PCBs. For this purpose, a cutting blade shape (Fig. 3) was designed with a blade edge (1) that, during operation (rotation), will cause the tip (2) to penetrate into the material being disintegrated, followed by cutting a small piece of material trapped within the surface area formed between the tip (2) and the base (3) of the blade. The remaining surfaces of the cutting blade (4) are rounded, as shown in Fig. 3. By using a small-sized blade edge (1), a sufficient level of fragmentation of the remaining materials will be achieved, enabling them to be directed to further recovery processes.

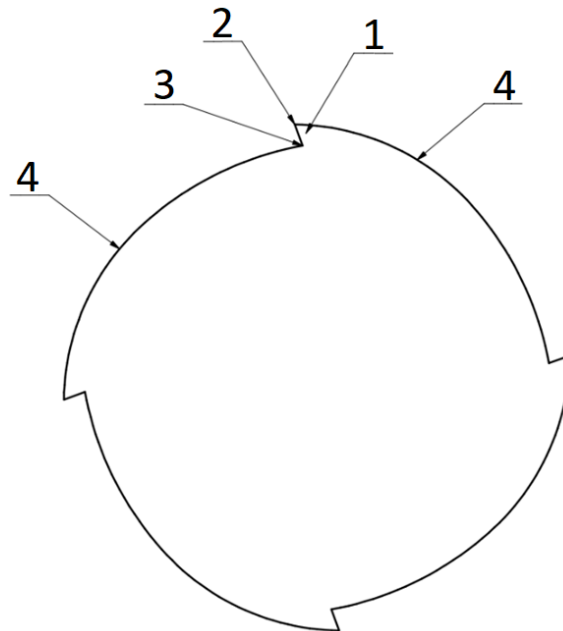


Fig. 3. Drawing of the cutting blade featuring the preferred cutting blade shape

Based on the developed sketch, a cutting blade was designed that corresponds to the intended shape. It consists of an inner part and interchangeable blades that are secured with screws. In conventional designs without detachable blades, any damage to the blade requires time-consuming replacement. By using interchangeable blade tips, the device maintenance is significantly accelerated as it eliminates

the need to dismantle the cutting shafts along with the rolling and securing elements. Taking into account the previously established assumptions presented in Table 1 and the considerations provided in the patent application P.442603, a 3D model of the cutting blade was developed (Fig. 4).



Fig. 4. 3D model of the cutting blade

3.5. Disintegrator prototype

The components presented above were used to construct the prototype of the disintegrator. This device is also comprised of supporting components, components enabling the loading and collection of the disintegrated material, including covers. The 3D models of the components were created using Autodesk Inventor 2020 software and are presented in the side view (Fig. 5) and top view (Fig. 6) of the disintegrator prototype. The components include the casing (1), cutting shaft no. 1 (2), cutting shaft no. 2 (3), feeding structure (4), flap (5), support structure (6), base (7), gear cover (8), drawer (9), comb assembly (10), clutch cover (11), gear wheel (12), gearbox (13), motor (14), and clutch (15).

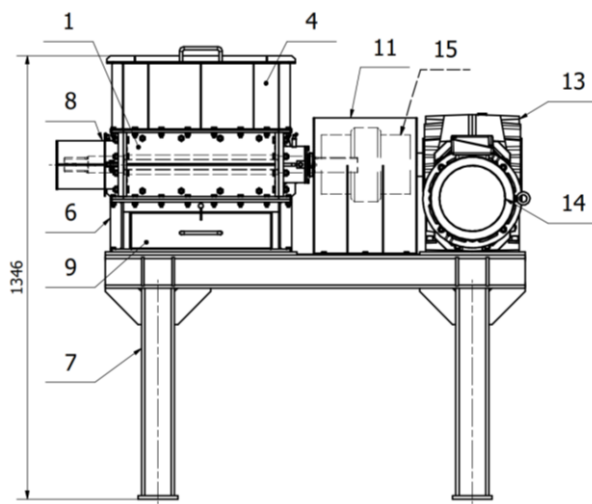


Fig. 5. Side view of the disintegrator prototype.

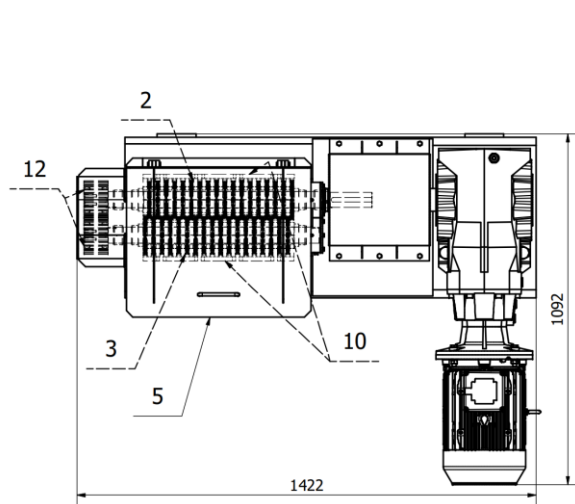


Fig. 6. Top view of the disintegrator prototype.

In the following Table 13, technical data of the designed disintegrator prototype for shredding used equipment equipped with NdFeB magnets are presented [26]. The efficiency of the device at this stage of work is unknown. Currently, detailed technical documentation is being developed.

Table 13. Technical data of the disintegrator prototype for shredding used equipment equipped with NdFeB magnets

No.	Parameter	Value
1.	diameter of cutting blades [mm]	129
2.	width of cutting blade [mm]	12
3.	rotation speed of shafts with cutting blades [min^{-1}]	15,8
4.	gear ratio of gear transmission [1]	92,53
5.	power of the motor [kW]	7,5
6.	motor speed, [min^{-1}]	1460
7.	weight of the shredder [kg]	590,0
8.	maximum weight of the installed component [kg]	118,0

4. Discussion

Based on the above calculations and assumptions, a gearbox with a gear ratio of 92.53 was selected, which ensures the appropriate rotational torque. According to the table, in the variant with the chosen gear ratio, there is a motor with parameters of 7.5 kW, 1400 RPM. However, due to local component availability, a motor with parameters of 7.5 kW, 1460 RPM was ultimately used.

The requirement of a minimum bearing life of 5 years has been achieved for the 22207-E1-XL bearing. This bearing has a bore diameter of $\text{Ø}35$ mm. However, since the shaft that will be supported by the bearing has a diameter of $\text{Ø}50$ mm, it was necessary to use the 22210-E1-XL bearing, which has the appropriate bore size and also exceeds the specified durability requirement. These bearings allow for angular deviation correction and are lubricated with solid grease, periodically replenished using manual lubricators

The parameters of the gear wheel for power transmission were determined, with a pitch diameter of $\text{Ø}120$ mm and 22 teeth. Additionally, a cutting blade, which is a component of the cutting shafts, was developed. The width of the cutting edge was determined to be 12 mm, and its diameter was $\text{Ø}129$ mm.

Considering the strength parameters of the components intended for shredding (WEEE, using HDD as an example), the material for the cutting blade and the manufacturing technology using PowderRange 718 powder for SLM were selected. Details made from this material exhibit higher strength properties than the materials being shredded.

5. Conclusions

The article analyzed the value of metals contained in WEEE, using HDDs as an example. The value of metals contained in 1 Mg of used HDDs was estimated and converted to 100 g of WEEE (HDD), amounting to 3.26 PLN. In southern Poland, 1 million residents discard 13.6 Mg of hard drives per year, resulting in a value of 440,000 PLN for the metals they contain. These estimates illustrate the quantities of valuable elements (including REEs and noble metals) present in WEEE. The Magnet-to-Magnet method allows for the recovery of REEs from WEEE and their reuse in new products - new NdFeB magnets. The first step in processing WEEE using this method is the shredding process, which requires a device with both strong and non-magnetic components.

The publication includes the key elements of the disintegrator prototype project, including calculations and design work using Autodesk Inventor 2022 software. The work involved calculations that resulted in the selection of a gear transmission with a ratio of $I=92.53$ and an electric motor with specifications of 7.5 kW power and 1460 min^{-1} speed. Baryllium roller bearings - 22210-E1-XL were also selected to support the cutting shafts.

The proposed solution is dedicated not only to HDDs but also to the processing of other small WEEE containing NdFeB magnets, such as small motors, power generators, headphones, speakers, mobile



phones, etc. The disintegrator can also be used for the preliminary shredding of other components of computer and telecommunications electronics, such as lithium-ion batteries and printed circuit boards. The approach focused on the recovery and reuse of valuable substances from WEEE aligns with the concept of a circular economy. Due to the low emissions of the proposed Magnet-to-Magnet method, it complies with the principle of "do no significant harm" outlined in Article 11 of Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment and amending Regulation (EU) 2019/2088. Therefore, it can be considered conducive to sustainable development. Negotiations with manufacturers are underway to produce the device prototype.

6. Patents

A project of the disintegrator - was developed based on patent application P.442603 "The method of disintegrating wasted electrical and electronic equipment containing neodymium magnets in order to obtain particles of appropriate sizes for the recovery of neodymium-iron alloy, dysprosium, or other rare earth elements".

References

- [1] Binnemans K., McGuinness P., Jones P.: Rare-earth recycling needs market intervention. *Nature Reviews Materials*. 6, 2021
- [2] Vishwanath G., Deshmane, Syed Z. Islam, Ramesh R. Bhawe: Selective Recovery of Rare Earth Elements from a Wide Range of E-Waste and Process Scalability of Membrane Solvent Extraction, *Environmental Science & Technology*, 2019
- [3] Schönfeldt M., Brouwer E., Dirks A., Rachut K., Gassmann J., Güth K., Buckow A., Gauß R., Stauber R., Gutfleisch O.: Towards an alloy recycling of Nd–Fe–B permanent magnets in a circular economy. *J. Sustain. Metall.* 4(2), 163–175, 2018
- [4] Diehl O., Schönfeldt M., Brouwer E., Dirks A., Rachut K., Gassmann J., Güth K., Buckow A., Gauß R., Stauber R., Gutfleisch O.: Towards an alloy recycling of Nd–Fe–B permanent magnets in a circular economy. *J. Sustain. Metall.* 4(2), 163–175, 2018
- [5] München D.D., Veit H.: Neodymium as the main feature of permanent magnets from hard disk drives (HDDs). *Waste Manage.* 61, 372–376, 2017
- [6] Yang Y., Walton A., Sheridan R., Güth K., Gauß R., Gutfleisch O., Buchert M., Steenari B. M., Van Gerven T., Jones P. T., Binnemans K.: REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review. *Journal of Sustainable Metallurgy*, 3(1), 122–149, 2016
- [7] Yue M., Yin X., Liu W., Lu Q.: Progress in recycling of Nd–Fe–B sintered magnet wastes. *Chin. Phys. B* 28(7), 077506, 2019
- [8] Zakotnik M., Tudor C.O., Peiró L. T., Afiuny P., Skomski R., Hatch G., P.: Analysis of energy usage in Nd–Fe–B magnet to magnet recycling. *Environmental Technology & Innovation*, 5, 117-126, 2016
- [9] München, D.D., Stein, R.T., Veit, H.: Rare earth elements recycling potential estimate based on end-of-life NdFeB permanent magnets from mobile phones and hard disk drives in Brazil. *Minerals* 11(11), 1190, 2021
- [10] Prospero D., Bevan A., Rosillo G.U., Tudor C.O., Furlan G., Dove S., Lucia P., Zakotnik M.: Performance comparison of motors fitted with magnet-to-magnet recycled or conventionally manufactured sintered NdFeB. *Journal of Magnetism and Magnetic Materials*, 2018
- [11] Jin H., Afiuny P., McIntyre T., Yih Y., Sutherland J.: Comparative Life Cycle Assessment of NdFeB Magnets: Virgin Production versus Magnet-to-Magnet Recycling. *Procedia CIRP*, 2016
- [12] Tanvar H., Barnwal A., Dhawan N.: Characterization and evaluation of discarded hard disc drives for recovery of copper and rare earth values. *Journal of Cleaner Production*, 249, 119377, 2020 <https://doi.org/10.1016/j.jclepro.2019.119377>
- [13] Abrahams S. T., Xiao Y., Yang, Y.: Rare-earth elements recovery from post-consumer hard-disc drives. *Mineral Processing and Extractive Metallurgy*. 124. 2014



- [14] Suponik T., Friebe P., Nuckowski P., Król M.: Dezintegrator do rozdrabniania zużytych sprzętów elektrycznych i elektronicznych zawierających magnesy neodymowe w celu odzysku stopu żelaza, zwłaszcza z neodymem, P.442603, Urząd Patentowy RP, zgłoszenie dnia 24.10.2022
- [15] Zwolak J.: Wytrzymałość materiałów w zadaniach, Uczelnia Państwowa im. Jana Grodka w Sanoku, Sanok, 2020, ISBN 978-83-61802-45-7
- [16] Niezgodziński T.: Wzory wykresy i tablice wytrzymałościowe, Wydawnictwo Naukowo-Techniczne, Warszawa, 2013, ISBN 978-83-79260-07-2
- [17] Pater Z., Samołyk G.: Podstawy technologii obróbki plastycznej metali, Politechnika Lubelska, Lublin, 2013, ISBN 978-83-63569-89-1
- [18] Rutkowski A.: Części maszyn, Wydawnictwo szkolne i pedagogiczne, Warszawa, 2011, ISBN 978-83-02-09886-4
- [19] <https://kacperek.com/wp-content/uploads/2018/02/HS-703-HS-704.pdf> [accessed: 28.12.22]
- [20] <https://medias.schaeffler.pl/pl/plp/SphericalRollerBearings1> [accessed: 18.02.2023]
- [21] Żółtowski J.: Podstawy konstrukcji maszyn przekładnie, Oficyna wydawnicza Politechniki Warszawskiej, 2011, ISBN 83-7207-488-7
- [22] <http://lenaal.com.pl/wp-content/uploads/2017/03/Wlasnosc-stopow-1.pdf> [accessed: 16.09.2022]
- [23] https://www.matweb.com/search/datasheet_print.aspx?mat-guid=e7eda0f5b11243a6a9ea46f21d667dc1 [accessed: 6.09.2022]
- [24] Friebe P., Suponik T., Nuckowski P.M.: Research on Hard Drives in the Context of the Construction of Shredding Knives in the Recovery of Rare Earth Elements. In: Benítez-Andrades, J.A., García-Llamas, P., Taboada, Á., Estévez-Mauriz, L., Baelo, R. (eds) Global Challenges for a Sustainable Society. EURECA-PRO 2022. Springer Proceedings in Earth and Environmental Sciences. Springer, Cham, 2023 https://doi.org/10.1007/978-3-031-25840-4_12
- [25] https://www.carpenteradditive.com/hubfs/Resources/Data%20Sheets/PowderRange_718_Datasheet.pdf [accessed: 18.02.2023]
- [26] Friebe P.: Instrukcja Użytkownika Dezintegrator do zużytych sprzętów elektrycznych i elektronicznych zawierających magnesy neodymowe, W73.216IU (unpublished materials of KOMAG)

