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Estimating Electric Power Requirements for Mechanically Shredding Massage Chairs and Treadmills at a Recycling Plant

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Abstract: South Korea has operated under laws to collect and recycle the waste of electrical and electronic equipment (WEEE) utilizing a system based on the Extended Producer Responsibility (EPR) system since 2003. In 2020, the number of products managed by the EPR increased from 27 to 50. Among the 50 products, massage chairs and treadmills are recognized as the items avoided in recycling centers or by recyclers due to their large volume, large weight, and long disassembly times. This study was a preliminary study in which the physical shredding process for massage chairs and treadmills could be introduced, and the electrical power requirements calculated. In the methodology, Vickers hardness was measured by sampling two actual products, and the tensile and shear strength were calculated from the hardness. Based on the shear strength, the force affecting the cutter was calculated and converted into torque and horsepower. In particular, the actual specifications of the crusher, designed and operated in the recycling center, were applied to the study, and the design was based on the treatment capacity of 10 tons per hour. Conclusively, the proper electrical power for crushing the massage chair and treadmill was analyzed as 719.5 and 459.7 HP, respectively.

Keywords: WEEE; proper electrical power; shredding; massage chair; treadmill; Vickers hardness

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1. Introduction

South Korea has operated under laws requiring the collecting and recycling waste of electrical and electronic equipment (WEEE) utilizing the Extended Producer Responsibility (EPR) system, which was first conducted in 2003. The Ministry of Environment (MOE) has enhanced the EPR system to secure procedural fairness and management guidelines for hazardous materials from the WEEE. As a result, the Eco-Assurance System (Eco-AS) was introduced in 2008 to minimize environmental loads through the systematic management of the entire life cycle of electrical and electronic equipment (EEE) from design and production to disposal to reduce wastes and promote recycling activities. Currently, the Target Management (TM) system, implemented in 2014, is designed to set an annual recycling target quantity, similar to the European Union (EU). According to the TM system, the Ministry of Environment (MOE) announced the recycling target goal based on the manufacturer's and importer's production and sales quantities from the previous year. Additionally, the first target was set at 3.9 kg per capita in 2014. The first long-term TM period was primarily from 2014 to 2018, with the target goal increasing yearly: 4.5 kg (2015), 4.8 kg (2016), 5.4 kg (2017), and 6.0 kg (2018). Besides, the MOE announced a secondary long-term TM period from 2019 to 2023, with the target goal increasing yearly: 6.52 kg (2019), 7.04 kg (2020), 7.54 kg (2021), and ultimately, 8.6 kg/capita in 2023 [1–3].

In 2003, when the EPR was first started, only refrigerators, washing machines, televisions (TVs), and air conditioners were included as mandatory EEE to collect and recycle in South Korea. Since 2008, the number of EEE subject to mandatory recycling increased to 10 items and by 2014, 27 EEE products were included as mandatory target items collected and recycled in four different groups: large-size, medium-size, small-size, and telecommunications products as per the TM system. In 2018, to achieve the secondary long-term recycling target goal for 2019 to 2023, the MOE announced that it would increase the compulsory products from 27 to 50 (Table 1), which was applied from 2020. According to the South Korea MOE, the expanded EEE that were previously classified by the weight and volume criteria (large, mid, small, and telecommunications), would now be classified by the functional features of the electronic equipment, such as temperature exchange, display, telecommunications, general equipment, and photovoltaic panel [4,5].

Table 1. Four groups and 50 electrical and electronic equipment subject to collection and recycling in South Korea since 2020.

Equipment Categories	Specific List of EEE Items	
Temperature Exchange Equipment	Refrigerator Air-conditioner Vending Machine	Water Purifier Dehumidifier
Display Equipment	Television Navigation	Computer (Monitor, Laptop)
Telecommunication Equipment	Copier Printer Beam-Projector Router	Computer (Desktop) Facsimile Scanner Mobile Phone
General Equipment	Oven Microwave Food-disposal Heater Audio Rice-cooker Iron Blender Video Player Kettle Frying Pan Exercise Treadmill Food Dryer Foot Bath Videogame Machine Deep fryer Boiling pot	Washing Machine Bidet Dish Dryer Air-cleaner Humidifier Water Softener Vacuum Cleaner Fan Toaster Water Heater Hair Dryer Security Camera Massager (Massage Chair) Sewing Machine Bread Machine Coffee Maker Dehydrator
Photovoltaic Panel Equipment	Photovoltaic Panel	
Total	51 units	

The computer was divided into 'Display' and 'Telecommunication' equipment groups because the main body and monitor should be separated based on functional features.

As mandatory EEE products are classified by function, various products are included in the general equipment group. In other words, if it does not have temperature exchange, display, or telecommunicator functions, it is mostly included in the general equipment group. Therefore, the general equipment group contains about 35 products, with very diverse product ranges and lists. Massage chairs and treadmills, which are the target products of this study, were included in the 50 mandatory target products subject to recycling obligations and belonged to all general equipment groups [4]. A massage chair is composed of a module, rollers, and airbags that automatically move inside and refers to a machine that can control a person's legs, arms, hands, feet, etc., with a wired or wireless controller for massage. In Korea, as massage chair products have recently undergone a trend toward high-end, large-sized products, performance and price have diversified. A treadmill is an exercise machine used for aerobic exercise and weight management and they are used in fitness clubs or at home. In particular, due to the COVID-19 pandemic, the demand for purchasing and using a treadmill at home is gradually increasing. The treadmill is operated by rotating a roller with the power of an electric motor. Previously, they provided just a simple speed, but the recently-released products display various information, such as weight, a calorie consumption measurement, roller angle adjustment, and the distance run. The operating system combined with the communication network performs various tasks such as web surfing or recording the exercise contents of a treadmill simultaneously.

According to the Korea Electronics Recycling Cooperative (KERC), which is a Producer Responsibility Organization (PRO) that implements the EPR system in South Korea, about 17,112 massage chairs were collected, and about 1237.2 tons by weight were recycled; approximately 11,062 treadmills were also collected and about 813.1 tons by weight were recycled in 2020 [6]. In 2020, KERC recycled about 390,000 tons of WEEE; among them, massage chairs and treadmills accounted for less than 1% (about 0.526%). However, as user demand in South Korea for massage chairs and treadmills is steadily increasing, it is expected that the occupancy rate and amount generated in the future will increase gradually. Meanwhile, the average weight of the massage chair and treadmill is 72.3 kg and 73.5 kg, respectively. These results were jointly investigated and published by the KERC and Korea Environment Corporation (KEC). In other words, this weight information was used as reference material to confirm and approve the results of WEEE recycling at the national level [7,8].

At WEEE recycling centers in South Korea, massage chairs and treadmills are generally recycled via dismantlement and disassembly by hand. As a result of experimental measurement, the disassembly work time was found to be roughly 65 min and about 42 min for massage chairs and treadmills, respectively, despite the skill level of the worker at the recycling center. The reasons for the extended time needed to dismantle treadmills and massage chairs, even for skilled workers, include the following: in order to meet consumer interests and needs, each product must go beyond simple exercise and massage functions. For treadmills, complexity is added through various settings and functions, as well as by increasing the tightness of the waling plate. They are more robustly designed by adding functions to change the height, slope/incline, and degree of strength training. Massage chairs are made more intricate by adding various functions, including massage zones/areas, internal rollers, heating functionality, and multiple reclining degrees (even to complete horizontalization). For the aforementioned reasons concerning consumers, it is expected that treadmill and massage chair designs will become even more complicated in the future, making it even more difficult to dismantle these products [9–11] manually.

Due to the large weight of the two products in the manual disassembly recycling process, workers are continually exposed to work-related risks, such as jamming accidents. Therefore, to improve the inefficiency due to the large weight and the long time taken in manual dismantlement, we aim to find an alternative approach to mechanically recycle massage chairs and treadmills by mainly using a shredding process. In other words, this study attempts a theoretical approach to calculating the required electrical power for crushing massage chairs and treadmills by investigating and analyzing preliminary research on the crushing process and actual engineering design data among the mechanical recycling methods [8,12].

2. Literature Review

2.1. Shredder Design for Refrigerators

In conducting this study, the most important data required the results from a previous review, e.g., the determination of the specifications of the actual shredder designed to crush refrigerators. There are many recycling centers or personal recyclers in South Korea but there are no shredders dedicated to shredding massage chairs and treadmills. Therefore, we investigate a crusher manufactured to recycle refrigerators in actual recycling centers and use the shreddable capacity and essential specifications of the shredder as basic data for calculating the required electrical power of the massage chair and treadmill crusher.

The refrigerator shredder referred to in this study was used by the Metropolitan Resource Circulation Center (MERC) from 2012 to 2018. It was a twin-axis shear shredder designed and used as a pre-shredder with an electrical power of roughly 250 horsepower (HP), converting to 183.9 kilowatts (kW) [1,5]. On average, this shredder was designed with a refrigerator shredding capacity of about 10 tons per hour. However, according to the actual operational data of the MERC, the shredding capacity for recycling refrigerators averaged approximately 7–8 tons per hour [1,12]. A literature search was conducted to collect details on the specific shredder manufactured to crush massage chairs and treadmills. There were articles propounding shredders for disposing of various wastes, including automobiles, food, and wood; however, there was no literature on shredders for processing large household appliances [13,14].

Although literature directly related to the calculation of crushing power needed for treadmills and massage chairs does not exist, literature dealing with other waste (e.g., food) has presented information on the materials, motors, cutters, shafts, etc., required to design such a shredder, as well as the torque calculations and safety factor [15]. In the case of the shredder having a twin-axis shaft, it is crucial to set the specifications of the shafts and numerous cutters. In order to apply the design data for the shredder used to crush the refrigerators in the MERC for this study, a specific list and contents for shaft and cutters were determined (Table 2). Detailed information about the cutters includes the cutter's diameter, thickness, quantity, hook height, and hooks per cutter. The shredding geometry of hooks and counter hooks guarantee an optimal grip, breaking, tearing, and cutting of all kinds of products. For information on the shaft, the shaft's maximum and minimum velocities are required and are expressed in revolutions per minute (rpm). Table 2 displays the lists and specific values related to the shaft and cutter. Alternatively, through the specification information listed in Table 2, additional specifications necessary for calculating the shreddable capacity of the shredder used to crush the refrigerator in the MERC are summarized in Table 3. As a result, via information in Tables 2 and 3, all the details about the cutter and shaft of the shredder designed to shred the refrigerator were secured; that is, this information was used as basic data to set the initial crushing capacity of a crusher capable of crushing massage chairs and treadmills.

Table 2. Specifications related to the cutter and shaft of the shredder used to crush refrigerators at the Metropolitan Electronics Recycling Center.

Category		Actual Value
Specifications for cutter	Cutter Diameter	810 mm
	Cutter Thickness	65 mm
	Quantity of Cutter	23 EA
	Hook Height	69 mm
	Hook per Cutter	2.5 EA
Specifications for shaft	Fast Shaft	16 rpm
	Slow Shaft	14 rpm

2.2. Hardness and Vickers Hardness Testing

Hardness is a characteristic of a material, not a fundamental physical property. It is defined as the resistance to indentation, and it is determined by measuring the permanent depth of the indentation. More simply put, when using a fixed force (load) and a given indenter, the smaller the indentation, the harder the material. The indentation hardness value is obtained by measuring the depth or area of various test methods' indentations [16]. Vickers hardness (VH) test, also referred to as a microhardness test, is mostly used for small parts, thin sections, or case depth work. The VH method is based on an optical measurement system. The VH test procedure (ASTM E-384), a standard test method for the micro-indentation hardness of materials, specifies a range of light loads using a diamond indenter, which is then measured and converted to a hardness value [17]. It is very useful for testing numerous types of materials, but test samples must be highly polished to enable impression-size measuring. A square-based, pyramid-shaped diamond is used for testing in the Vickers scale. In other words, micro-hardness methods are used to test metals, ceramics, and composites, almost any type of material.

Table 3. Symbols, units, and values related to the calculation of the shreddable capacity from refrigerator crushing at the Metropolitan Electronics Recycling Center.

Symbol	Category	Unit or Value
V	Shreddable capacity from a single cutter	(ℓ/rev)
V′	Shreddable capacity from the whole cutter	(ℓ/rev)
V″	Shreddable capacity in terms of volume per hour	(m^3/h)
W	Shreddable capacity in terms of weight per hour	(tons/h)
D	Outer diameter of the cutter	※ rev: revolution ※ ℓ: liter
d	Effective diameter of the cutter	
Z	Number of cutters	
t	Thickness of the cutter	
H	Number of hooks per cutters	
N	Shredding angle of the cutter in shredding performance	

One important factor in determining the electrical power required for crushing is the type of material to be crushed and the material's strength. In fact, the shredder design information for crushing refrigerators excludes information regarding the primarily used materials for massage chairs and treadmills as well as their strength. Thus, we determined that it is necessary to sample and measure the hardness of massage chairs and treadmills in order to determine the proper electrical power. In other words, when calculating the required power necessary to crush massage chairs and treadmills, the difference in hardness and thickness of the ferrous material used in the actual products must be investigated and used as a major factor in calculating the electrical power [1,12].

Alternatively, the results of the hardness measurement using the VH method can be converted to tensile strength. According to ISO 18265:2013 (Metallic materials—Conversion of hardness values), the converted values can be applied directly to materials measuring viscous hardness. Tensile strength estimates provide the most unreliable conversion values in ISO 18265:2013; as such, many researchers officially utilize this ISO 18265:2013 reference to leverage the conversion from hardness to tensile strength values [12–14]. Meanwhile, tensile strength can be converted to shear strength by empirical experiments. Shear strength can be estimated using relational expressions for major ferrous, alloy, and non-ferrous metals through the relationship between the ultimate tensile strength, ultimate shear strength, tensile yield strength, and shear yield point, respectively [18–20].

$$S_{su} = \text{Approximately } 0.90 \times S_u \quad (1)$$

Equation (1) is a relational formula that calculates the ultimate shear strength (S_{su}) using ultimate tensile strength (S_u) and a formula applied to ductile iron [21–23].

3. Method

3.1. Standard Shreddable Capacity

As mentioned in the introduction and literature review sections, the specific information of the shredder, designed and used to crush refrigerators, to estimate the proper electrical power for crushing the massage chairs and treadmills, is used as a basic source. In this section, through Tables 2 and 3, the basis for calculating the shredder capacity for shredding a refrigerator of 10 tons per hour is secured. The shreddable capacity of a single cutter is extended to the crushing capacity of the total number of cutters, and the shreddable capacity per hour is calculated based on volume and weight, respectively. In this step, with a density equal to 1.0, this study was conducted, assuming a shredder has a processing power of 10 tons per hour. Here, the density is assumed to be 1.0 because the refrigerator, massage chair, and treadmill are not all made of iron. In other words, since it is composed of various products, including synthetic resin, the specific gravity of iron was not applied directly. The proper power for shredding a massage chair and a treadmill was estimated based on empirical equations for designing the shredder to crush refrigerators. These products have been mechanically recycled by shredders in recycling plants. Eventually, the capacity calculation to crush refrigerators becomes the criteria for estimating the shredding capacity for crushing the massage chair and treadmills in this study.

The shreddable capacity standard based on the shredding capacity of about 10 tons per hour of the refrigerator-crushing machine can be calculated using the following calculation equations. The shreddable capacity (V) from the single (1 EA) cutter can be calculated as shown in Equation (2).

$$V = \frac{\pi}{4}\left(D^2 - d^2\right) \times t \times \frac{H}{N} \tag{2}$$

In Equation (2), V is the shreddable capacity from a single cutter (1 EA), D indicates the outer diameter of the cutter, d indicates the effective diameter for crushing the single cutter, H indicates the number of hooks per cutter, N indicates the shredding angle of the cutter in the shredding performance, and t indicates the thickness of the cutter (Table 3) [24,25].

Based on the results of the shredding capacity for a single cutter (Equation (2)), the whole shreddable capacity can be calculated by multiplying the shreddable capacity of a single cutter and the number of cutters as expressed in Equation (3).

$$V' = V \times Z \tag{3}$$

In Equation (3), V' is the shreddable capacity of all cutters in the shredder used to crush the refrigerators (V is calculated in Equation (2)), and Z indicates the number of cutters found in the actual shredder (Table 3). From Equations (2) and (3), V' and V are expressed using the units, liters per revolution. According to the results in Equations (2) and (3), we can calculate the shreddable capacity in terms of volume per hour V'' with the unit of cubic meters per hour (m^3/h) as follows.

$$V'' = V' \times rpm \times \frac{t}{1000} \tag{4}$$

In Equation (4), V'' is the shreddable capacity in terms of volume per hour, rpm indicates the cutter velocity in revolutions per minute; the average rpm of the shredder was used as the reference value. The variable t indicates the cutter's thickness value.

From the V'', we can convert the shreddable capacity in terms of volume per hour to weight per hour using a specific gravity of approximately 1, as shown in Equation (5).

$$W = V'' \times \text{specific gravity}(\cong 1.0) \tag{5}$$

In Equation (5), W (tons/h) is the shreddable capacity in weight per hour. As mentioned earlier, the specific gravity (density) is expressed as 1.0; thus, the volume-based shreddable capacity converts to the weight-based shreddable capacity [26,27].

3.2. Vickers Hardness and Thickness Correction Factor

Among the various materials constituting the massage chair and treadmill, it is generally known that the ferrous material has the strongest strength. Experimental disassembly data for ferrous material used in massage chairs and treadmills showed that massage chairs and treadmills, approximately 48.5% and 59.7% of each product's total components (materials) were composed of ferrous material. Therefore, the difference in the ferrous materials' thickness used in each product can be an important factor in determining the proper electrical power. In this study, the Vickers hardness was measured to calculate or convert the tensile and shear strength. For the experiment, Vickers hardness was individually measured by collecting experimental samples from each of five massage chairs and treadmills. In addition, Vickers hardness was also measured for samples taken from 10 different refrigerators. In other words, the meaning to be obtained through the VH measurement can be considered as follows: first, the comparison of the types of ferrous materials used in the three products, and second, the calculation of tensile strength and shear strength by securing VH data. The Vickers hardness measurement method used the Korean standard (KS) B 0811 (Metallic materials-Vickers hardness test-Part 1: Test method), which was established by making the ISO 6507-1 standard IDT (Identical). Since there is no change in the phase and no need for additional revision in the industrial field, it was applied as is to the results of this study. Measured environmental conditions included: temperature—23 ± 5 °C, humidity—55 ± 10% R.H. (relative humidity), test loading holding time—10 s, and test loading—1.96 N (Newton). Additionally, each sample was measured five times [12,14].

Meanwhile, the sample thickness of each product collected for the VH measurement was determined using vernier calipers. The massage chair and treadmill were measured five times to calculate the average value, and the refrigerator was measured ten times to calculate the average value. The unit was measured in mm, and the thickness correction factor was set according to the thickness difference (ratio) of the iron material of each product. The thickness correction factor is not a factor with a standardized name or methodology and is a set limiting factor in this study, assuming that the proper electrical power may vary depending on the thickness of ferrous and can only be used in this study.

3.3. Proper Electrical Power

In the previous step, to calculate the proper electrical power to crush the massage chair and treadmill, we assumed and calculated the appropriate shreddable capacity of 10 tons per hour from the design data of the refrigerator shredder. The HV and thickness measurements were completed through the sample collection of massage chairs, treadmills, and refrigerators. In addition to the data collected in the above steps, data on the specifications of the actual shredder at the MERC related to the electrical power calculation were additionally prepared and are presented in Table 4. We can calculate the force-effect on the cutter via Equation (6), expressed as P [15,28].

$$P = I \times A \times \eta \tag{6}$$

Table 4. The symbols, units, and values related to the calculation of the required electric power from crushing the refrigerators in Metropolitan Electronics Recycling Center.

Symbol	Category	Unit or Value
P	Force affecting the cutter	
I	Shear strength of the cutter	
W	Width of the cutter	65 mm
H	Height of the cutter	69 mm
N_1	Revolution per minute (RPM) at a high-speed shaft	16 rpm
N_2	Revolution per minute (RPM) at a slow-speed shaft	14 rpm
A	Area affected by shear strength from the hook of cutter	154 cm^2
D	Outer diameter of the cutter	810 cm (pi)
Z	Number of cutters biting the product	10~24 EA (17 EA)
T	Torque	kgf/cm

The shear strength, calculated and converted from the VH measurement, is provided, where A indicates the area affected by shear strength, and η describes the thickness correction factor from the experimental measurement using vernier calipers. Eventually, the force acting on the cutter is calculated by multiplying the shear strength, affected area by shear strength, and thickness correction factor; the final unit is expressed as kg/cm^2.

Alternatively, the torque can be calculated using force affecting the cutter. The formula for calculating the torque is as follows.

$$T = P \times \frac{D}{2} \times Z \tag{7}$$

In Equation (7), T indicates the torque. P indicates the force affecting the cutter calculated in Equation (6), D designates the outer diameter of the cutter, and Z describes the number of cutters working on the product in the shredding process. Here, the number of cutters working on the product was investigated from a minimum of four to a maximum of twelve; a median value of eight was used in the calculation [29]. When calculating the torque, the unit of torque is expressed as the multiplication of kilogram-force (kgf) and meters (m). When completing the torque calculation, the proper electrical power can be calculated using torque and rpm, with the unit of horsepower (HP). Moreover, horsepower can be converted to kilowatt (kW) using an empirical equation relating HP and kW [30].

$$HP = \frac{T \times N}{716.2} \times a \tag{8}$$

In Equation (8), HP indicates horsepower (HP) as a unit of electrical power. Additionally, T indicates the torque calculated in Equation (7), N indicates rpm at a medium value between high-speed and low-speed shafts, and a means the safety factor concerning the number of cutters working during the shredding process of the product. Here, the number of cutters working on the product was investigated from a minimum of four to a maximum of twelve; a median value of eight was used in the calculation [28,31]. When completing the torque calculation, the proper electrical power can be calculated using torque and rpm, with the unit of horsepower (HP). Additionally, horsepower can be converted to kilowatts (kW) using an empirical equation that relates HP to kW and vice versa. Finally, the safety factor represents the recommended power margin when designing a crusher based on the torque-to-horsepower conversion result. In other words, when purchasing a motor (power) at the stage of manufacturing with an appropriate crusher capable of crushing the product, it means purchasing a motor with 150% higher performance than the theoretical calculation result.

4. Results

4.1. Shreddable Capacity Calculation

Based on the shredder designed and used in MERC, information regarding the shredder capable of crushing a refrigerator at a rate of 10 tons per hour was analyzed. First, according to Equation (2), the shreddable capacity from the single cutter was calculated as 0.5058 L per revolution (Equation (9)).

$$V = \frac{\pi}{4}\left(810^2 \times 565^2\right) \times 65 \times \frac{2.5}{8.5} = 0.5058(\ell/\text{rev}) \tag{9}$$

According to Equations (2) and (9), the unit of the outer diameter (D), effective diameter (d), and thickness of the cutter are expressed as millimeters (mm). In order to apply and make the units consistent (liters per revolution), the calculated value was divided by 10 to the 7th power (107). The number of hooks and the shredding angle of the cutter were used as experienced values based on information on the actual shredder. Based on the V and Equation (9), the crushing capacity of the entire cutters can be calculated (Equation (3)).

$$V' = V \times Z = 0.5058 \times 25 = 12.6450(\ell/\text{rev}) \tag{10}$$

Equation (10) shows the shreddable capacity (V') results for the whole cutters by multiplying the shreddable capacity of the single cutter (V) by the number of cutters (Z) in the actual shredder. Subsequently, the shreddable capacity (V') was used to calculate the volume-based shreddable capacity for the whole cutters in a certain amount of time (1 h) using Equation (11).

$$V'' = V' \times \text{rpm} \times \frac{t}{1000} = 12.6450 \times 15.0 \times \frac{65}{1000} = 12.3776\ \text{m}^3/\text{h} \tag{11}$$

The volume-based shreddable capacity (V'') in a given time (hour) was calculated via Equation (11). This showed that result was calculated as 12.3776 m^3/h. Here, the rpm is the average rpm of the actual crusher (15 rpm), and t is the thickness of a single cutter (65 mm), respectively. By using the volume-based shreddable capacity (V'') calculated via Equation (11), the crushing capacity based on the weight can be finally calculated. As mentioned in the methodology, the relative density of electronic products was assumed to be 1.0. Thus, the shreddable capacities of all cutters in terms of weight was 12.3776 tons per hour using Equation (5). Notably, if the shreddable capacity is set to about 85% of the calculated stable operation results for the shredder, the actual shreddable capacity becomes 10.5209 tons per hour. This result extracts the primary information from the refrigerator shredder and uses it as the basic result of the shreddable capacity calculations for shredding massage chairs and treadmills. As mentioned in Equation (5), to calculate the shredder throughput per hour, the specific gravity was assumed to be 1.0 before proceeding with the calculation (Equation (12)).

$$W = \frac{12.3776\ \mathrm{m}^3}{\mathrm{hr}} \times \text{specific gravity}(\cong 1.0) = 12.3776\ \mathrm{ton/h} \tag{12}$$

4.2. Vickers Hardness Measurement and Calculating Shear Strength

Five samples were used in the massage chair and treadmill experiments for the Vickers hardness, and ten samples were used in the measurement experiment. As a result of measuring the Vickers hardness of the massage chair, the minimum was 182.1 HV, and the maximum was 192.7 HV, and the average value of the five samples was 186.4 HV. In the case of the treadmill, it was measured from a minimum of 153.4 to a maximum of 165.0 HV, and the average value of the five samples was 159.8 HV. Finally, in the case of the refrigerator, through analyzing ten samples, the minimum value was analyzed as 157.7 HV, the maximum value was analyzed as 167.8 HV, and the average value was 161.9 HV. Based on the average value of HV, the hardness value of the treadmill was the lowest, followed by the refrigerator, and the highest hardness value could be obtained from the iron material of the massage chair (Table 5). Based on the results of Table 5, Vickers hardness values were converted into tensile strength using ISO 18265-2003. The tensile strength value was converted into shear strength based on the empirical equation presented in Equation (1). Massage chairs, treadmills, and refrigerators have Vickers hardness values of 186.4 HV, 159.8 HV, and 161.9 HV. These values are converted into tensile strength values of 0.6110 kg/cm^2, 0.5194 kg/cm^2, and 0.5278 kg/cm^2, respectively. Furthermore, the calculated tensile strength value is finally converted into shear strength and has tensile strength values of 0.54 kg/cm^2, 0.46 kg/cm^2, and 0.47 kg/cm^2, respectively, for massage chairs, treadmills, and refrigerators. After conversion, it was found that the shear strength of the iron material used in the refrigerator was the highest (0.54 kg/cm^2), and the iron material used in the treadmill (0.46 kg/cm^2) and refrigerator (0.57 kg/cm^2) had similar shear strength (Table 6).

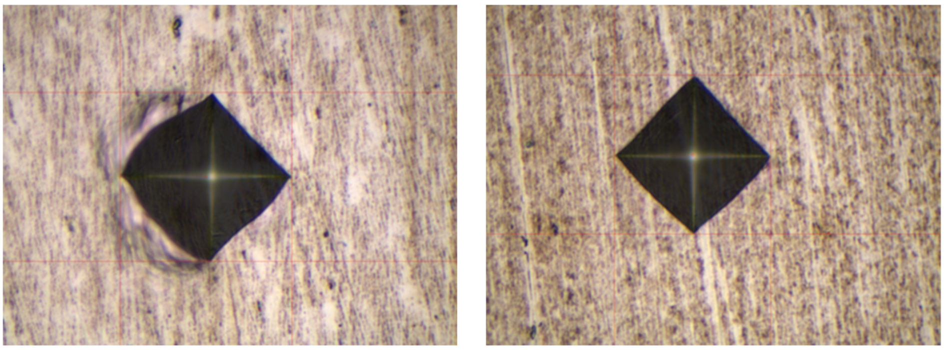
Meanwhile, the thickness of the ferrous samples, prepared for measuring and analyzing the Vickers hardness, was 0.2 cm, 0.15 cm, and 0.05 cm for the massage chair, the treadmill, and the refrigerator, respectively (Figure 1, Table 7). That is, as the thickness of the ferrous material is thicker, the required electrical power of the shredder would be increased, so we set a thickness correction factor based on the thickness of the ferrous sample. In the end, the thickness of the iron material based on the refrigerator is three times thicker in the case of the treadmill and four times thicker in the case of the massage chair. Thus, the thickness correction factor was set according to the weighting ratio (this factor is a constant), and that of the massage chair is 4.0, the treadmill is 3.0, and the refrigerator is 1.0 (Table 7).

Table 5. Results of Vickers hardness measurement for the massage chair, treadmill, and refrigerator samples.

Product	Number of Measurements		Hardness Value (Individual)		Hardness Value (Average)
Massage chair	1		183.9		186.4
	2		192.7		
	3		189.5		
	4		182.1		
	5		183.9		
Treadmills	1		160.0		159.8
	2		163.0		
	3		165.0		
	4		157.6		
	5		153.4		
Refrigerator	1	6	160.6	157.7	161.9
	2	7	163.1	162.1	
	3	8	162.6	167.8	
	4	9	157.7	160.1	
	5	10	163.1	164.2	

Table 6. Hardness, tensile strength, shear strength conversion results.

Classification	Massage Chair	Treadmill	Refrigerator
Vickers hardness (HV)	186.4	159.8	161.9
Tensile strength (kg/cm^2)	0.6110	0.5194	0.5278
Shear strength (kg/cm^2)	0.54	0.46	0.47



(**a**) (**b**)

Figure 1. Measurement picture in Vickers hardness test: (**a**) massage chairs; (**b**) treadmill samples.

Table 7. Specimen thickness, cross-sectional area, thickness difference, and thickness correction factor.

Classification	Massage Chair	Treadmills	Refrigerator
Thickness (cm)	0.20	0.15	0.05
Cross-sectional area (cm^2)	0.04	0.0225	0.0025
Thickness difference (%)	400% (4 times)	300% (3 times)	100% (Criteria)
Thickness correction factor	4.00	3.00	1.00 (Criteria)

4.3. Proper Electrical Power Calculation

Equation (6) is used to calculate the proper electrical power for shredding the massage chairs and treadmills, and the required factors are shear strength, shear area, and the thickness correction factor for each product (massage chair and treadmill).

$$= \frac{0.54 \text{ kg}}{\text{cm}^2} \times 154.00 \text{ cm}^2 \times 4 = 332.6 \text{ kg (Massage chair)} \tag{13}$$

$$= \frac{0.46 \text{ kg}}{\text{cm}^2} \times 154.00 \text{ cm}^2 \times 3 = 212.5 \text{ kg (Treadmill)} \tag{14}$$

$$= \frac{0.47 \text{ kg}}{\text{cm}^2} \times 154.00 \text{ cm}^2 \times 1 = 72.4 \text{ kg (Refrigerator)} \tag{15}$$

Based on the calculation results of Equations (13) to (15), we calculated the force affecting the shredder cutter for crushing a massage chair, treadmill, and refrigerator, respectively. The force affecting the cutter P was calculated as 332.6 kg in the massage chair with the highest ferrous hardness and the thickest material of the sample. In the case of the treadmill, the hardness of ferrous material was relatively less strong than that of refrigerators. However, because the iron was three times thicker than in refrigerators, the force applied to the cutter was 212.5 kg, which was the second-largest after the massage chair. The force applied by the cutter to crush the refrigerator was relatively lower than that of the massage chair and treadmill because the thickness of the iron material used in the actual refrigerator is 1/4 thinner than the massage chair and 1/3 thinner than the treadmill.

Since the force affecting the cutter P is calculated, the torque (T) can be calculated using P. The factors required to calculate the torque are the outer diameter of the cutter and the number of cutters, as shown in Equation (7).

$$= 332.6 \text{ kg} \times \frac{81 \text{ cm}}{2} \times 17 \text{ EA} = 229,022.6 \frac{\text{kg}}{\text{cm}} = 22,902.3 \text{ kgf·m (Massage chair)} \tag{16}$$

$$= 212.5 \text{ kg} \times \frac{81 \text{ cm}}{2} \times 17 \text{ EA} = 146,320.0 \frac{\text{kg}}{\text{cm}} = 14,632.0 \text{ kgf·m (Treadmill)} \tag{17}$$

$$= 72.4 \text{ kg} \times \frac{81 \text{ cm}}{2} \times 17 \text{ EA} = 49,883.6 \frac{\text{kg}}{\text{cm}} = 4983.4 \text{ kgf·m (Refrigerator)} \tag{18}$$

In Equations (16) to (18), we calculated the torques (T) for the three products. As a result of multiplying the force affecting the cutter (P), the outer diameter of the cutter (D), and the number of cutters (Z), it was found that the massage chair required 22,902.3 kg of force per meter (kgf·m), the treadmill 14,632.0 kgf·m, and the refrigerator 4983.4 kgf·m torque. Resultantly, as observed in Equations (13) to (15), the difference in the force affecting the cutters of the three products is maintained until the torque calculation.

Finally, the horsepower (HP) is converted using the calculated torque value (T). HP is calculated as the product of the torque and rotational speed of the shaft, and a conversion constant of 716.2, widely used empirically, is utilized. This constant is used when converting torque into HP based on a meter criterion. Moreover, the safety factor (150%) was collectively applied to calculate the proper electrical power (Equation (8)).

$$= \frac{22,902.3 \text{ kgf·m} \times 17 \text{ EA}}{716.2} \times 1.50 = 719.5 \text{ HP (Massage chair)} \tag{19}$$

$$= \frac{14,632.0 \text{ kgf·m} \times 17 \text{ EA}}{716.2} \times 1.50 = 459.7 \text{ HP (Treadmill)} \tag{20}$$

$$= \frac{4983.4 \text{ kgf·m} \times 17 \text{ EA}}{716.2} \times 1.50 = 156.6 \text{ HP (Refrigerator)} \tag{21}$$

In Equations (19) to (21), the proper electrical power calculation results for the massage chair, treadmill, and refrigerator, respectively. As the primary crushing device, the proper power to crush the massage chair was analyzed to be 719.5 HP. The treadmill and refrigerator were determined to require 459.7 HP and 156.6 HP, respectively, for proper crushing. Additionally, the proper electrical power for shredding was calculated based on the actual shredder, mainly with a shreddable capacity of 10 tons of each product per hour. The design data of the shredder were used as reference values for the actual refrigerator crushers in the recycling centers.

5. Summary and Limitations

5.1. Summary

Since 2008, South Korea has operated an Extended Producer Responsibility (EPR) system for collecting and recycling the Waste of Electrical and Electronic Equipment (WEEE). Starting in 2020, EPR targeted products included massage chairs and treadmills. Due to continuous economic growth and the development of advanced leisure electric products, the distribution rates for massage chairs and treadmills have increased in South Korea. Nevertheless, these products have been recycled by manual dismantling and component sorting in the recycling stage. Manual dismantling work is not only operationally inefficient but can also cause worker fatigue. The main purpose of this study is to calculate the proper electrical power required to mechanically shred massage chairs and treadmills that were manually recycled. Accordingly, basic data were collected based on previous studies related to the shredding (crushing) theory. The possible crushing power of the two products was calculated using practical shredder design empirical equations utilized in the WEEE recycling industry in South Korea. In order to perform this study, the hardness of steel components used in massage chairs and treadmills was measured and converted to shearing strength. Based on the above data, we calculated the shredding electrical power.

In the methodology, we analyzed the detailed specifications of previous designs used to manufacture the shredders and used them in this study while calculating the appropriate crushing power, using various empirical formulas. By applying the detailed specifications of the crusher designed for shredding the refrigerator, the power to crush the massage chair and the treadmill was calculated based on the shreddable capacity of 10 tons per hour. In calculating the force required for crushing, the Vickers hardness and iron thickness were measured by collecting an iron sample of the product under study. Based on these data, the tensile strength, shear strength, and iron thickness of the product could be corrected. A thickness correction factor was created and applied. Through this, research was conducted in the following order: After calculating the force applied to the cutter, the torque value was calculated using this result, and finally, the horsepower was calculated.

According to the results of the VH measurement, the average VH of the massage chair is 186.4 HV, and the average hardness of the treadmill is 159.8 HV. Alternatively, the Vickers hardness of the refrigerator iron averaged 161.9 HV, which is lower than the massage chair and higher than the treadmill. Using the VH measurements, the values converted to shear strength were 0.54 kg/cm^2 (massage chair), the treadmill was 0.46 kg/cm^2, and the refrigerator was 0.47 kg/cm^2, respectively. Simultaneously, since the thickness of the experimental ferrous samples used in the VH test for the massage chair and the treadmill was three to four times thicker than the sample of the refrigerator, the difference was considered by applying the correction factor when finally calculating the proper crushing power. The difference in shear strength, including the difference in VH and the difference in the thickness of the ferrous material mainly used in the product, eventually determines the difference in the force affecting the cutter. As a result, the force affecting the cutter during the shredding process was calculated as 332.6, 212.5, and 72.4 kg for the massage chair, treadmill, and refrigerator, respectively. Additionally, the torque required for crushing was calculated as approximately 22,902.3 (massage chair), 14,632.0 (treadmill), and 4983.4 (refrigerator) in the decreasing order. Conclusively, based on the shredding capacity of 10 tons per hour, the proper electrical power required for shredding is approximately 719.5 HP for massage chairs and 459.7 HP for treadmills.

5.2. Limitations

The calculation of the required shredding power is focused on the 'primary crushing' or the 'pre-shredder' machine. In other words, the results of this study are applicable to the first crushing (primary crushing) process. The processing power criteria were considered at 10 m^3/h (volume basis). The study was conducted using a density of 1.0, assuming a shredder has a processing power of 10 tons per hour. However, the fact that the density was assumed to be 1.0 in the changing step of the standard unit of the treatment capacity from volume to weight may serve as a limit. In other words, applying a density of 1.0 means that refrigerators, massage chairs, and treadmills are recognized simply as electronic products. The product density considered when designing a crusher is similar. However, strictly speaking, massage chairs, treadmills, and refrigerators have different internal components and ratios; thus, even if the relative density is selected, they will have to be changed little by little. This part can be highlighted as a limitation to be supplemented in the next study.

Another limitation is the measurement of Vickers hardness and calculating the shear strength by converting it into tensile strength. The part where the shear strength could not be measured directly remains somewhat regrettable. However, it is comforting that the hardness was converted into tensile strength by applying international standards and that the iron used in massage chairs and treadmills was converted into shear strength using an empirical formula considering that ductile iron is used. In the future, when additional and supplementary studies for this study are in progress, a method that can directly measure the shear strength should be devised and proposed to improve the quality of the study.

The final limitation of this study is that no verification process was provided for whether the proper electrical power suggested throughout the study results can be practically used. In fact, no workplace in Korea's electronics recycling center systematically shreds massage chairs or treadmills. Further research is needed to verify whether the theoretical and empirical crushing-power values calculated through this study can be used in the final crushing-machine design.

6. Conclusions

In this paper, the shredder crushing power was calculated based on the design of refrigerator-crushing equipment used to crush treadmills and massage chairs, all classified as large home appliances. For the theoretical approach, the Vickers hardness values for a refrigerator, treadmill, and massage chair were measured; the measured values were then converted into tensile strength and experimentally applied. Since the tensile strength value of each home appliance was judged to be somewhat different from the converted value, we intend to secure accurate data by making tensile strength specimens in the future. In order to obtain data on the physical properties of each home appliance, the yield strength and breaking strength will also be measured. Via product steel-plate analysis, a theoretical review will be conducted on the selection of consumable materials, such as the cutters used in crushing equipment.

In order to actually apply the calculated crushing-power value for crushing treadmills and massage chairs, crushing equipment similar in design to the theoretically applied crushing equipment showing the derived horsepower performance was tested. After securing additional theoretical data, the test results were checked, and the insufficiency of the equation used in the calculation was identified to reduce the error ranges and increase the synchronization rate between the theoretical and experimental values.

The increase in large home appliances is not limited to South Korea. Currently, the foundation-laying stage is in progress, aiming to determine a theoretical approach through preliminary research. As a preliminary test, a treadmill and massage chair were put into a 2000-HP shredder to secure data on shredding capability and throughput. Future research will proceed with empirical studies. This thesis contributes to resource circulation by exchanging and providing information on equipment (e.g., shredders) that are currently experiencing or will experience problems in the processing of large home appliances.

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