The object of this study is the abrasive cutting process using thin grinding wheels, which is applied for cutting materials with various mechanical properties. The problem to be solved is mapping the energy consumption characteristics in this process through the control of cutting parameters such as grinding wheel thickness and feed rate. An experiment was conducted using grinding wheels with 1.2, 1.6, 2.0, and 3.0 mm for cutting metals. Various feed rates were used to cut Al, ST37, and cast iron, which are ductile, ductile-hard, and brittle materials. The results of the experiment show an inverse exponential relationship between the feed rate and specific energy. The 1.2 mm grinding wheel consumes up to 10% less power than the 3.0 mm wheel at low feed rates. The mapping of these characteristics enables the selection of recommended parameters. Achieving stability during the cutting process of ductile materials, the utilization of a 1.6 mm grinding wheel operating at a feed rate of 0.166 mm/s. The rigidity of the wheel determines the stability of the rotation, which depends on the thickness of the grinding wheel. The thickness of the grinding wheel determines the material removal rate of the abrasive process. Ductile-hard materials, such as ST37, require more energy because the abrasive particles must be able to break down the properties of the material to erode its surface. Ductile materials tend to cause high friction and generate heat, melting the material. The space between the abrasive particles can be filled with liquid material, causing BUE to cover the cutting edge of the abrasive particles. The application of the outcome is aimed at the machining, as a scientific basis for energy control at the manufacturing process

Keywords: energy consumption, abrasive cutting, cut-off grinding, energy of cutting, material removal rate, thin grinding wheel

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IDENTIFYING THE ENERGY CONSUMPTION TO MATERIAL REMOVAL RATE IN ABRASIVE CUTTING PROCESS USING THE THIN GRINDING WHEEL

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1. Introduction

Global energy demand continues to grow significantly. According to the International Energy Outlook 2024 report, the industry consumes 170 EJ, which is 38.2% of the energy in the world. Energy consumption is expected to continue to grow, placing enormous pressure on resources and the environment [1]. The manufacturing sector, as one of the main energy consumers, bears a great responsibility to contribute to global energy conservation efforts. Therefore, understanding and optimizing energy efficiency in every manufacturing process has become necessary, not optional [2].

The machining process is one of the most energy-intensive operations. Studies indicate that most electrical energy supplied to machine tools is not directly utilized for the material cutting processes. Instead, the energy is wasted in the form of heat, sound, and vibration [3]. A study observing energy mapping revealed that only a small portion of the total energy consumed by a machine tool is used for material removal. Some energy is used to run supporting equipment, including cooling systems, hydraulic units, and machine control systems [4]. These findings underscore the enormous potential for energy savings if the efficiency of the core cutting process and its supporting systems can be optimized.

Types of machining processes have been studied in relation to energy consumption, ranging from turning, milling, to grinding. In CNC machines, toolpath and feed rate strategies have been proven to have a significant effect on total energy consumption [5]. Similarly, selecting the right cutting parameters, in turning and milling processes, can drastically reduce specific energy consumption (SEC) without compromising product quality [3, 6]. Machining strategies have been developed to help industries choose the most effective energy efficiency improvement strategies [7].

The use of thin grinding wheels is increasingly crucial in the modern manufacturing industry for precision applications such as cutting research specimens, cutting thin hollow materials, and electronic components. However, its unique energy consumption characteristics due to mechanical instability have not been well quantified, particularly cut-off and slotting operations using thin grinding wheels, which have not been extensively studied in terms of energy efficiency. This process is essential in industry for cutting hard and difficult-to-work materials. Although technologically advanced, it is known to be very energy-intensive [8]. Therefore, investigating energy consumption in this process in depth is important.

Therefore, studies devoted to understanding the characteristics of energy consumption on removal rates using thin cutting wheels need are scientific relevance to support modern industrial trends to minimize energy consumption. Cutting with thin cutting wheels is used for careful cutting of specimens that require caution. In industrial applications, these studies will provide a database and empirical model for operators and engineers to select a combination of wheel thickness and feed rate that minimizes energy consumption without reducing production rate, which can be applied in manufacturing process planning.

2. Literature review and problem statement

Several studies have begun to address this issue. Evaluations of the energy efficiency of various state-of-the-art grinding processes have been conducted, highlighting gaps and the need for improvements to increase the efficiency of these processes [8]. On the other hand, recent developments in technology and equipment for cutting various multi-scale cast components have also been discussed, where the use of thin grinding wheels is often a critical component in such applications [9]. In paper [10], the results of research are presented on the influence of cutting conditions on specific energy consumption during abrasive metal cutting with thin discs. The abrasive cutting process with a grinder has different characteristics compared to other machining processes. It was shown that the metal cut-off process carried out at relatively low and moderate feed rates on S235JR steel, Fe-Al (40%) intermetallic alloy, and C45K steel made it possible to determine the cutting power and analyze specific energy consumption through an empirical model. The mechanical characteristics of the material significantly affect the energy consumption pattern, contributing components, and overall cutting power. However, there were unresolved issues related to the type and dimensions of cutting tools. The reason for this may be that the discussion was conducted on a limited cutting process. A way to overcome these difficulties can be to focus on research and development of the topic. Research [10] successfully modeled the influence of cutting conditions on specific energy, but the variation of grinding wheel thickness as the main geometric parameter was not investigated.

The fundamental and quantitative relationship between energy consumption and material removal rate (MRR) in the abrasive cutting process using thin grinding wheels still needs to be studied in greater depth. A comprehensive understanding of this relationship is key to developing models that can predict and optimize process performance. Recent research has begun to utilize machine learning to predict specific energy consumption in cut-off grinding, which demonstrates the complexity and non-linearity of the relationship between input parameters and energy output. The paper [11] applied machine learning techniques to predict specific energy consumption for oxygen-free copper cut-off operations. Energy consumption was estimated based on process parameters feed rate, cutting thickness, and analyzed using three supervised learning models Gaussian process regression, regression trees, and artificial neural networks. Among these approaches, Gaussian process regression showed the best prediction accuracy, providing the lowest error rate during validation and testing. Study [11] was successful in predicting SEC with machine learning, but the model required robust input data on the influence of tool dimensions, which is not yet available.

The parameters studied are still limited to the dynamic parameters of the cutting process, while dimensional parameters have not been significantly addressed, so, robust data and a mechanistic understanding are required to connect this gap. Understanding the relationship between energy consumption and cutting parameters in grinding processes is essential to improving production efficiency in the manufacturing industry. Adopting more energy-efficient methods and technologies allows industries to balance productivity, cost efficiency, and environmental sustainability [12–14].

A way to observe energy consumption can be studied in more detail using modeling approaches. In paper [15], specific energy is explicitly modelled as the sum of sliding, plowing, and cutting components, enabling a deeper understanding of the interaction between material properties, abrasive grain characteristics, and process parameters. This observation allows for analysis of particle characteristics, process parameters, and material properties that affect the cutting process. This study forms a comprehensive model for specific energy consumption in abrasive cutting operations. Experiments on SS201, Inconel 718, Al 1100, Al 7075, and oxygen-free copper using semi-super abrasive Cubitron cutting wheels confirmed that cutting conditions and material properties significantly affect total specific energy consumption, the dominance of particular energy components, and overall machinability. While paper [15] provides a deep understanding of the cutting mechanics and energy specific, it does not explore the dynamic structural behavior of the thin wheel itself. This gap exists because combining these two complex areas of physics into a single, predictive model is a significant scientific and engineering challenge.

In the grinding process, the dimensions of the grinding wheel and abrasive material play an important role. In paper [16] provided statistical and mathematical analyses that establish the basic dimensions of the working surface relief of abrasive tools and pore space dimensions. The researchers established an analytical relationship between these parameters and grain size, particle distribution, and tool structure. The methods used were to determine the average particle distance, relative profile reference length, pore dimensions, and particle irregularities at various surface profile levels. All this suggests that the grinding wheel structure is a critical factor in determining grinding performance and quality. The study objective was focused on developing a method for measuring and characterizing the profile of wheel. However, the unexplored from the paper is the effect of profile of the grinding wheel parameters on energy and cutting forces, and final workpiece quality.

Cutting speed is an essential machining parameter. High-speed grinding can cause burns and surface defects. To address this challenge, paper [17] reviews recent advances in high-speed grinding (HSG) technology, analyzing strain in the workpiece material, stress in the grinding wheel, and thermodynamic aspects of material removal. The results indicate that high-speed grinding produces better surface roughness and lower grinding forces than slow grinding. The cooling was used to reduce temperature, affecting the force and roughness of the material, with NMQL coolant providing the best results. The effect of high-speed grinding is reviewed, but the energy consumption and optimization of thin grinding wheels in cut-off and slotting remain largely unexplored.

The energy released during the grinding process is in the form of heat. Various methods are used to prevent the temperature from damaging the abrasive tool or workpiece. In paper [18], efforts to reduce the temperature during grinding were carried out for rigid and elastic schemes. It was shown that intermittent grinding effectively reduces friction intensity by shortening wheel–workpiece contact time, while in elastic grinding schemes, lower wheel speed and normal pressure can reduce temperature build-up. A comparison between surface grinding and end surface grinding shows that end surface grinding produces lower temperatures due to increased contact length with the workpiece. The objective of the study was to develop a general theoretical approach for analyzing grinding temperatures. However, it did not focus on the effect on thermo- mechanical and energy efficiency in cut-off operations.

During grinding, energy is rapidly converted into heat, producing a thermal field on the workpiece characterized by high temperatures. Monitoring the temperature of the workpiece is important to prevent grinding burn. In paper [19], an accurate measurement method for steep temperature gradients in creep-feed grinding was introduced, reducing thermocouple deviations from more than 200 K to about 20 K at lower feed rates. These conditions keep the workpiece safer during the grinding process. However, there is an observation gap between the measured temperatures and the total energy consumption of the grinding process.

Temperature control was studied [20] to prevent thermo-mechanical damage to the surface layer of components during the grinding process. This study highlights the potential of controlling the grinding process using soft sensors that combine thermal thresholds in the temperature diagram with in situ magnetic Barkhausen noise analysis (BN). Specific grinding power is analyzed as a function of contact time. The results showed that BN is effective in detecting residual tensile stresses before the formation of the tempering zone, providing a reliable early-warning system for grinding burn. The proposed control system optimizes process parameters to minimize thermo-mechanical surface damage while maintaining high productivity, but it did not control increases of temperature.

The literature allows to identify one problem that remains despite significant scientific research, namely, improving the acquisition of more significant energy consumption characteristics. The results indicate energy in the cut-off grinding process occurs in the frictional interaction between the material and the abrasive tool. The energy generated is mostly in the form of heat. In the review, the parameters developed in the cut-off process are influenced by the dimensions of the grinding wheel. There is a gap that has not been addressed regarding the effect of thickness variation. This research is a development that can provide more in-depth information about the cutting parameters that affect energy consumption.

From this review, it was identified that the quantitative effect of grinding wheel thickness variation on energy consumption and MRR has not been a major focus, even though this parameter determines stability and contact area. Therefore, this study aims to emphasize the importance of tool geometry on cutting stability through energy consumption.

3. The aim and objectives of the study

This study aims to identify the energy consumption characteristics required for the abrasive cutting process. This study is expected to produce the energy consumption characteristics of electric motors used in the abrasive cutting process.

To achieve this aim, the following objectives were accomplished:

– to study and quantify the effect of grinding wheel thickness variation on cutting power and specific energy during the cutting process;

– to study the functional relationship between feed rate and energy consumption during the cutting process;

– to study and compare energy consumption characteristics during cutting on ductile and brittle materials.

4. Materials and Methods

The object of this study is the cut off abrasive cutting using thin grinding wheels, which is applied for cutting materials with various mechanical properties. Based on the theoretical framework, it is predicted that specific energy consumption in cut-off grinding is determined simultaneously by wheel thickness, feed rate, and material properties. Thinner wheels are expected to produce higher specific energy than thick wheels at equivalent material removal rates, due to parasitic deflection and side friction. The feed rate affects the energy required for the cutting process. Furthermore, material properties influence the basic mechanism: brittle materials require the lowest energy, ductile-strong materials require the highest energy for plastic deformation, while ductile-soft materials experience an increase in specific energy. The specific energy consumption is defined by formula (1)

$$Es = \frac{P_{Cut}}{MRR}. \quad (1)$$

Specific energy consumption Es is calculated from the measurement results of cutting power P_{cut} and material removal rate MRR. Material removal is expressed by the cross-sectional area of the grinding wheel A_c, relative to the feed rate V_f, as shown in formula (2)

$$MRR = A_C \cdot V_f. \quad (2)$$

The research design uses independent variables that are treated and the results of the dependent variables that are observed. The independent variables used were the feed, motion of the cutting wheel, the geometry of the new cutting wheel cross-section, and the type of material being cut. The variables observed were the energy consumption required for cutting. Cutting was performed at feed rates of 0.077 mm/s, 0.125 mm/s, 0.166 mm/s, and 0.250 mm/s. This study uses a cutting tool that has been modified with a 4-inch (108 mm) grinding wheel. The main abrasive material of the grinding wheel is brown fused alumina oxide. The variations in the thickness of the cutting wheel are 1.2 mm, 1.6 mm, 2.0 mm, and 3.0 mm. To maintain uniformity of dimensions and shape of the grinding wheel, before cutting, a careful inspection is carried out to ensure that the cutting edge is in good condition. The variations in the workpieces being cut are provided to determine the cutting performance against the differences in the materials being cut. The materials cut included cast iron, mild steel, and Al. Cutting was performed using a single-phase AC electric motor drive. The motor specifications used had an input voltage of 200 ~ 240 V, 50/60 Hz, with a maximum power of 1600 W (Max. 8 A), and a maximum no-load speed of 10400 RPM at a voltage of 220 VAC/50 Hz. The energy measurement process is carried out by measuring the current entering the electric motor. The measurement is carried out with an electric induction sensor, using a PZEM-004T device to read the current and voltage. The data obtained on the serial monitor is from a wattmeter, voltmeter, and ammeter. To read the measurement results, the PZEM-004T sensor is connected to a PC and displayed on the serial monitor. The calibration process was carried out by comparing measurements with a multimeter with the same load as the replication. The accuracy of the PZEM-004T sensor was declared acceptable with standard comparison measurement. PZEM-004T has measuring Voltage 80 ~ 260 V AC ± 0.5%, Current 0 ~ 100 A ± 1% The highest accuracy is above 1% of the maximum current, Power 0 ~ 23 kW, Frequency 45 ~ 65 Hz ± 0.5% accurate for standard electrical systems (50/60 Hz), Power Factor 0.5 ~ 1.0 ± 2%. Data were collected three times for each experimental condition. This was done to minimize random errors and ensure consistent results. The three repetitions were averaged to find the most representative value, and the data distribution was observed through standard deviation. This strengthened the statistical validity of the conclusions.

The energy increase pattern for rotating the grinding wheel as an abrasive cutting tool during the cutting process is seen on the computer monitor. The graph of the power increase required in the cutting process is observed and analyzed. To run the test, the equipment settings used are shown in Fig. 1.

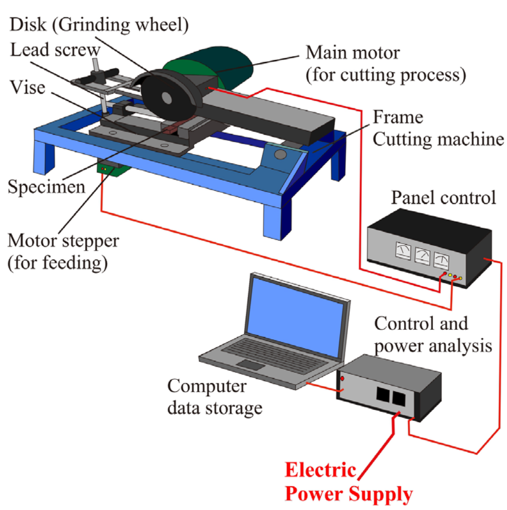

Fig. 1. Settings of the experiment equipment

The functions of the components in the equipment circuit for the experiment are arranged based on requirements. An electric motor is used to rotate the grinding wheel, which is connected to the shaft. The grinding wheel moves to perform cutting, and its movement is regulated using a lead screw. The feeding movement is controlled according to the cutting parameters. The material being cut is clamped using a vise under the grinding wheel. Feed rate is regulated by a controller. Energy consumption data is taken from the energy entering the machine from the power cable, which consists of changes in the incoming current and existing voltage. The maintenance of the workpiece operating temperature is achieved through the circulation of air over the workpiece using a blower.

5. Results of the investigation of energy consumption and material removal

5. 1. The effect of abrasive wheel thickness on energy consumption

The rotating motion of the grinding wheel causes abrasion on the workpiece. The grinding wheel grains cut alternately. Fig. 2, *a* show the cutting that occur during the workpiece cutting process. The abrasive grains of the grinding wheel function as multiple micro cutting edges. When the grinding wheel rotates at high speed in contact with the workpiece, the abrasive grains cut the surface of the material and lift a small amount of material in the form of chips. Each abrasive grain works individually due to the rotational motion, but the particles produce a simultaneous cutting effect. The effectiveness of the cutting process is highly dependent on the distribution of abrasive grains on the surface of the grinding wheel. An even distribution of grains and an optimal number of active grains result in even cutting. When the number of grains is too many and uneven, the cutting process experiences cutting disturbances, such as excessive friction, increased temperature, and premature wear.

The cutting results show that there is residual material on the bottom of the cut surface. This is because the vise is only positioned on one side of the cutting wheel. The cutting results show that there are grains remaining at the bottom that are not completely consumed. This is due to the plastic nature of the workpiece material. When the cutting process is about to be completed, the pressure of the grinding wheel presses the material, and the plastic property of the material moves the material to the side, causing a small cutting area to remain uncut. The cutting results can be seen in Fig. 2, *b*.

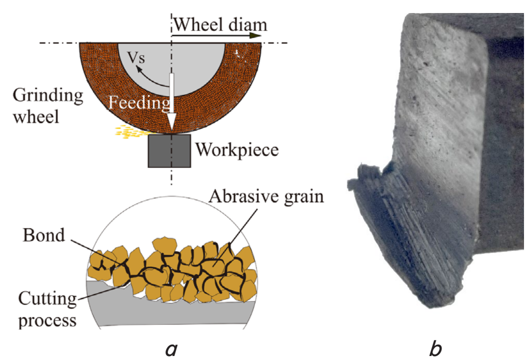

Fig. 2. Interaction between the cutting process and the cutting results: *a* – cutting process; *b* – cutting results a deformed side

The results of electrical current measurements taken during the grinding process show a relationship between the thickness of the grinding wheel and the energy required in the cutting process. The electric current entering the electric motor have pattern variation that is contingent upon the thickness of the grinding wheel and the duration of the cutting process. As illustrated in Fig. 3, the initial phase of the process is characterized by a rapid escalation in the electric current. This condition manifests at the inception of all cutting processes involving varying grinding wheel thicknesses. This finding suggests that the energy necessary for the initial rotation of machine is substantial. In the subsequent process, an increase in movement during the cutting process is observed. A general observation indicates that the 3.0 mm grinding wheel demonstrates enhanced stability, exhibiting a gradual increase in current requirements. This finding suggests that the thickness of the grinding wheel exerts a significant influence on the initial response of machine to the workload. Based on the test results, it can be seen that the average electric current used during the cutting process increases as the thickness of the grinding wheel increases. At a thickness of 1.2 mm, the average current was recorded at 1.402 A, then increased to 1.412 A at a thickness of 1.6 mm. Furthermore, at a thickness of 2 mm, the average current reached 1.420 A, and a more significant increase occurred at a thickness of 3 mm with an average value of 1.556 A.

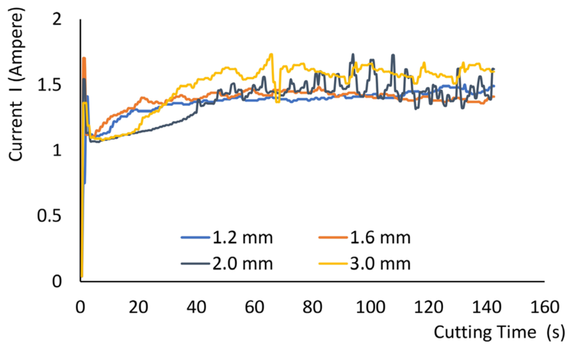

Fig. 3. Effect of grinding wheel thickness on electrical current at the feed rate 0.077 mm/s

At the initiation of the cutting process, an increase in electric current is observed over time, though with varying patterns associated with each grinding wheel thickness. This data shows that the grinding wheel performs the initial cutting. After the cutting process is complete, the electric current shows a more gradual increase in power consumption at the same time. In some cases, there is a surge in current. This may be due to heat accumulation, grinding wheel wear, or changes in the characteristics of the material being ground.

Power measurement data indicates a relationship between feed rate and grinding wheel thickness in the cutting process. Fig. 4 shows the correlation between the power used in the cutting process and variations in feed rate and grinding wheel thickness. At low feed rates, the power required is relatively stable for all grinding wheel thicknesses, with the 3.0 mm grinding wheel requiring the highest power. However, as the feed rate increases, there is a significant increase in power, especially for the 3.0 mm grinding wheel. This pattern shows that thicker grinding wheels tend to require more power when the feed rate is increased.

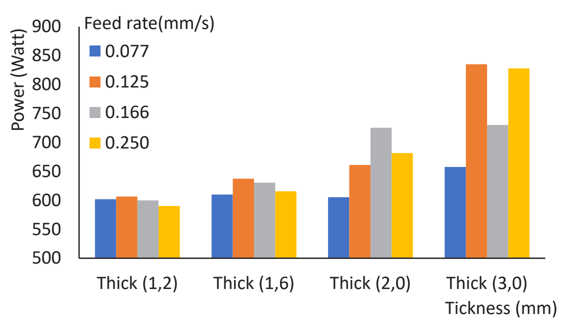

Fig. 4. Effect of feed rate and grinding wheel thickness on cutting power

The effect of grinding wheel thickness is illustrated in Fig. 4. The data indicates that the 1.2 mm grinding wheel show the lowest power consumption for a range of feed rates, from low to high. The material's reduced thickness enables a constrained cutting gap width, thereby yielding a diminished removal rate. The 3.0 mm grinding wheel necessitates a significant amount of power when operating at medium to high feed rates. This phenomenon can be attributed to the substantial cutting gap, which leads to an elevated removal rate and a considerable cutting load. The selection of the combination of grinding wheel thickness and feed rate should consider the trade-off between processing speed and energy efficiency. A 2.0 mm grinding wheel may be a suitable compromise for many applications. This phenomenon suggests the presence of specific characteristics in the relationship between feed rate and grinding wheel thickness with regard to power requirements.

5. 2. The effect of feed rate on energy consumption

The effect of feed rate on the energy consumption required in the material cutting process can be seen from the specific cutting energy in the grinding process, against feed rate variations. The specific cutting energy data shows a clear relationship between feed rate and grinding wheel thickness in the grinding process. At low feed rates, the specific cutting energy required is quite high. The thickness of the grinding wheel also affects the specific cutting energy value. A 1.2 mm grinding wheel has a high specific energy value, while a 3.0 mm grinding wheel has a low specific energy value. This shows that, at low feed rates, thicker grinding wheels tend to be better in terms of energy consumption. This pattern is consistent with the basic principles of grinding, where wider contact between the material and a thicker grinding wheel can distribute the load more evenly, thereby reducing the specific energy required. Fig. 5 shows the relationship between the increase in feed rate and the specific cutting energy.

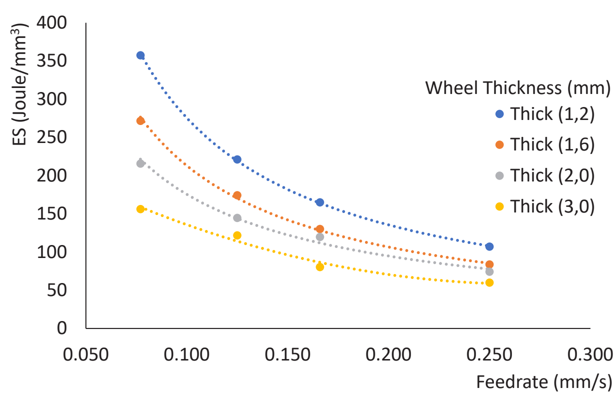

Fig. 5. Correlation feed rate and specific cutting energy

The relationship between feed rate and specific cutting energy is indicative of an inverse exponential relationship. An increase in the feed rate has been shown to result in a substantial decline in specific energy for all grinding wheel thicknesses. The 1.2 mm grinding wheel continues to require the greatest energy input. At lower feed rates, the specific energy decreases further. This decline suggests that increasing the feed rate may result in a reduction of the specific cutting energy. It is important to note that increasing the feed rate may also have a direct impact on the surface quality of the grinding results. Therefore, it is essential to identify an optimal point that balances energy consumption and product quality.

A comparison of grinding wheel thickness at high feed rates is explained in Fig. 5. This difference further supports the hypothesis that thicker grinding wheels exhibit better stability during cutting operations. The thickness of the cutting grinding wheel has been explained to affect its rigidity, thereby creating optimal cutting stability. Therefore, as illustrated in Fig. 6, it can be concluded that the selection of the combination of feed rate and grinding wheel thickness exerts a substantial influence on the specific energy in the grinding process. Despite its relatively high energy, the 1.2 mm dimension grinding wheel remains a critical component for applications that demand precise cutting and minimal chip formation. Therefore, the selection of parameters must consider the trade-off between energy efficiency, result quality, and specific application requirements. Therefore, the selection of parameters must consider the trade-off between energy efficiency, result quality, and specific application requirements.

5. 3. The effect of material on energy consumption

The cross-section of the material resulting from the process of abrasive cutting is shown in Fig. 6. Different types of materials produce different surfaces. In Al, the surface experience friction that produces molten material, which is result in a surface with a cut covered by molten material. This condition produces a blackened cross-section due to the heat from the molten material. Mild steel produce smooth cut marks. However, it does not produce molten material that covers the surface of the abrasive material. The chips produced can be removed completely. Cast iron is a material that is more brittle than others. This condition cause chips to be easily removed during the cutting process.

The energy requirements for the cutting process can be seen from the test results of several materials. Fig. 7 shows the changes in current during the cutting process at low feed rates. The data obtained from the cutting processes of cast iron, mild steel, and Al shows the energy consumption in the form of current used by the machine when cutting the three different materials. In the initial period, the current surges, indicating that the machine requires more energy for the initial rotation of the motor. The cutting process begins with an increase in the current entering the electric motor. The energy required to cut mild steel is higher than that required for cast iron. This is in accordance with the properties of mild steel, which is more ductile and requires greater cutting force.

The comparison of current levels in cast iron and mild steel shows different trends in value. The measurement results show differences in average current between the three materials. ST37 had the highest current value, which was around 1.55 A, followed by Al with an average of 1.51 A, while cast iron had the lowest current, which was around 1.45 A. The difference in average current increase between ST37 and Al is relatively small, only about 0.04 A, while between Al and cast iron the difference is greater, at about 0.08 A. The most notable difference is between ST37 and cast iron, with a current difference of 0.09 A.

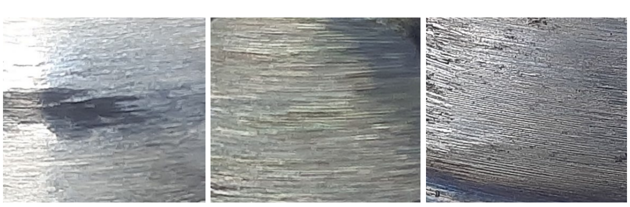

Fig. 6. Cross-section of the cutting specimens of: *a* — Al; *b* — mild steel ST37; *c* — cast iron

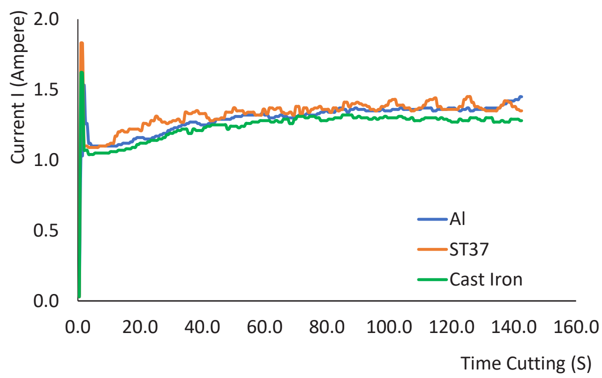

Fig. 7. Electric current for cutting Al, mild steel ST37, and cast-iron at feed rate 0.077 mm/s

Increasing the feed rate causes an increase in energy requirements. As illustrated in Fig. 8, the graph demonstrates the development of electric current during the cutting process. At the start of the cutting process, there is a significant increase in the electric current entering the machine. Based on the measurement results, ST37 showed the highest average current of around 1.45 A, followed by Al with an average value of around 1.37 A, while cast iron recorded the lowest average of 1.26 A. The difference in current between ST37 and Al is relatively small, only about 0.08 A, while between Al and cast iron it is greater, at about 0.11 A. The most striking difference is between ST37 and cast iron, with an average current difference of 0.19 A.

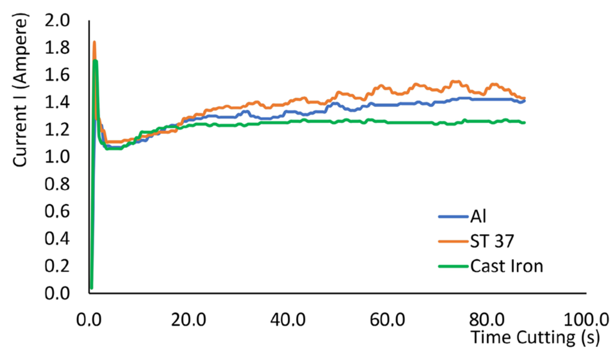

Fig. 8. Electric current for cutting Al, mild steel ST37, and cast-iron at feed rate 0.125 mm/s

At a feed rate of 0.165 mm/s, the cutting process has increased friction. The cutting edge of the grinding wheel is known to reach elevated temperatures, causing a portion of the abrasive material to melt. Melting the grit can increase the cutting ability of the grinding wheel. Cutting force and pressure force play a major role in the material removal process. This causes materials that are hard and ductile to require more energy for cutting. Fig. 9 shows that the energy required for cutting mild steel is greater than that required for cutting Al and cast iron. Based on measurement data, it is known that the average current achieved by ST 37 is around 1.65, and Al has a stable average current of 1.43 A, while cast iron shows the lowest value, which is around 1.33 A. The difference in current between ST 37 and Al is relatively large, around 0.21 A, while the average difference between ST37 and cast iron is approximately 0.32 A.

The cutting process with a high feed rate, requires more energy to cut Al material. This occurs because soft Al material heats up quickly and creates molten material on the surface that covers the sharp edges of the abrasive grains.

The condition causes the cutting process to be disrupted and creates high friction. The energy required increases because the feed rate continues to move with decreasing cutting ability. Fig. 10 shows the change in electric current against the cutting process of Al, mild steel, and cast iron, with a feed rate of 0.250 mm/s. This condition shows that the grinding wheel performance decreases with the increase in the amount of electric current entering the machine. Ductile materials tend to require more energy in the cutting process. The current measurement results indicate that the average current values for ST37 and Al are nearly equivalent, at approximately 159 and 1.60 A, while cast iron exhibits the lowest average current, at around 1.38 A. The difference in current between ST37 and Al is negligible. The difference is noticeable when comparing ST37 with cast iron, with a value of 0.20 A.

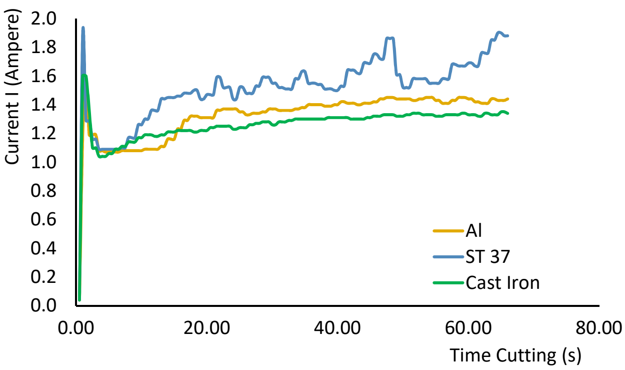

Fig. 9. Electric current for cutting Al, mild steel ST37, and cast-iron at feed rate 0.165 mm/s

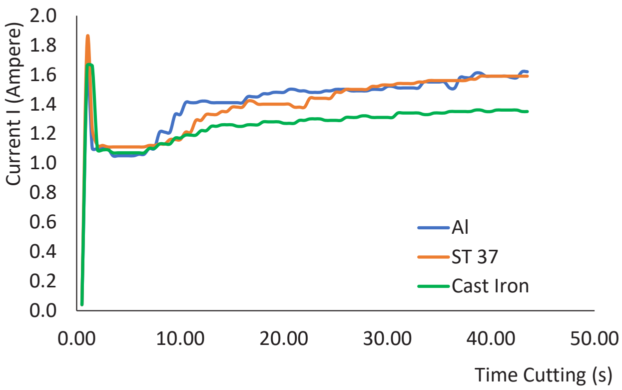

Fig. 10. Electric current for cutting Al, mild steel ST37, and cast-iron at feed rate 0.250 mm/s

Energy requirements can be expressed as specific energy for the process being carried out. Variations in material types, with ductile, ductile-hard, and brittle characteristics, are compared to determine the specific energy for each material property. Brittle materials require less energy than ductile materials. This is due to the fact that brittle materials release material easily. Ductile materials with low melting temperatures cause molten material to enter the abrasive gap. The combination of hard-ductile in steel causes a greater energy requirement to release material. Ductile properties cause materials to have high plastic and elastic capabilities. The energy required to separate plastic materials is very high. Fig. 11 shows the power used in the cutting process for the three materials at different feed rates.

In the process of cutting ductile materials with a low melting point, the generation of heat leads to the melting of the chips. Melted material can enter the sharp edges of the grinding wheel. The sharp edges of the abrasive grains become covered by molten material due to build up edge (BUE) formation. The coverage reduces the cutting ability, as the obstructed sharp edges interfere with the machining process. This condition increase friction between the grinding wheel and the workpiece. The greater the friction, the greater the heat generated and the greater the thickness of the BUE on the grinding wheel. Fig. 12 illustrates the phenomenon of BUE covering the sharp edges of the grain. It causes an increase in pressure due to constant cutting motion, while the cutting ability of the abrasive material decreases.

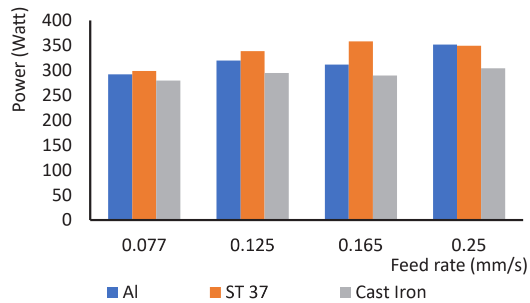

Fig. 11. Power for cutting Al, mild steel ST 37, and cast iron

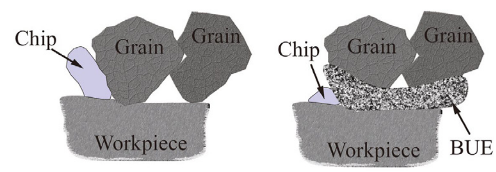

Fig. 12. Build up edges covers the sharp edge of the grain

A decrease in cutting power cause energy requirements to increase. From this phenomenon, it can be seen that cutting energy with abrasives is determined by the type of material being cut. The hardness and ductility of the material affect the cutting energy of the material. Materials with high hardness and ductility require a large amount of energy for the cutting process.

Materials with high ductility produce high specific energy consumption and specific cutting energy values, as shown in Fig. 13. The carbon content in mild steel is lower than in other specimens, making this low-carbon steel more ductile. This ductility means that the machining process for low-carbon steel requires more energy than medium-carbon steel. Ductile materials undergo more significant plastic deformation before breaking. The amount of plastic deformation in ductile materials requires high specific energy to break them.

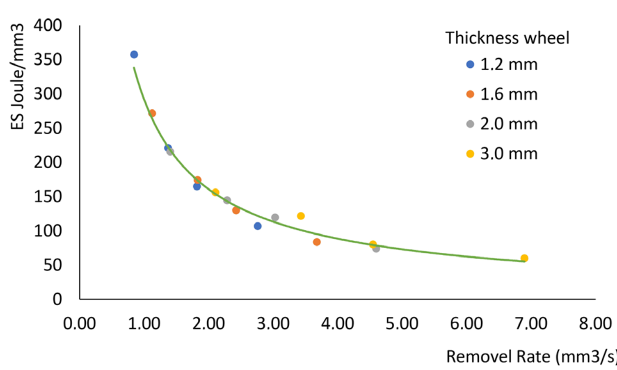

Fig. 13. Specific energy in material remove rate at various wheel thicknesses (ST37)

The thickness of the grinding wheel provides adequate stability during the cutting process however the cutting process requires a wider cross-section. The thickness of the wheel results in a larger area that must be removed. The use of thick grinding wheels provides good stability and produces a consistent cross-section that moves in the direction of feed.

Thin grinding wheels can be used for narrow cutting area, but due to vibration and high elasticity, the sides of the grinding wheel tend to come into contact with the wall. The condition cause increase in energy consumption in the drive motor. Fig. 13 shows the specific energy characteristics of changes in material removal speed with differences in wheel thickness with various grinding wheel sizes. A coefficient of determination R^2 value of 0.96 was obtained based on the results of a regression analysis conducted on experimental data. This value indicates a very strong relationship between the variation in specific energy and the variation in the material removal rate parameter. This suggests that changes in RR significantly impact the amount of energy consumed during grinding.

6. Discussion of energy consumption in abrasive cutting

An understanding of the relationship between energy consumption and removal rate is essential in planning an efficient machining process. By controlling cutting parameters, selecting the appropriate grinding tool geometry, and using suitable cutting materials, the cutting process can achieve high productivity while optimizing energy use. In metal cutting processes, specific energy consumption and material removal rate are key parameters that are interrelated in the material cutting process.

During the cutting process, several forces are generated as a result of the interaction between the abrasive grains and the workpiece material. The tangential force, otherwise known as the cutting force, acts in the same direction as the motion of the grinding wheel. The tangential force is defined as the force that lifts material from the workpiece. The magnitude of this force also affects power consumption during the grinding process. The normal force, otherwise known as the pressure force, exerts a perpendicular force on the surface of the workpiece, and it acts inward. The normal force exerts an inward pressure, penetrating the workpiece material. It has been demonstrated that the magnitude of the normal force directly correlates with the pressure exerted by the grains. The application of normal force has been demonstrated to result in increased deformation, elevated temperature, and accelerated wear on the grinding wheel. In the process of cutting material with a grinding wheel, the axial force generated is relatively minimal. Normally, the feed motion moves in the same direction as the cutting motion, so that the feed force is in line with the cutting plane of the grinding wheel thickness. The cutting is in accordance with the resulting MMR. The finding that specific energy decreases exponentially with increasing feed rate is in line with the model proposed by [15], where at high MRR, the energy component for chip formation P_c becomes more dominant and efficient than friction P_s. However, the research reveals that the slope of this curve is also greatly influenced by the thickness of the wheel, a factor that was not explored in [10] or [11]. The energy calculated in the cutting process includes friction between the grinding wheel and the workpiece (sliding), plastic deformation without fracture (plowing), and chip formation through a sliding mechanism [15]. The power consumed by the sliding mechanism Ps, plowing Pp, and chip formation Pc is expressed as $P = Ps + Pp + Pc$. To determine the energy value that can be used under widely used conditions, the amount of energy per unit of material removal is used. The specific energy value indicates the energy required to remove one unit of material volume.

Axial force emerges as a consequence of vibrations in the grinding wheel. It has been demonstrated that the magnitude of vibration is directly proportional to the degree of abrasion on the side wall of the grinding wheel. This condition increases the cutting power requirement because the grinding wheel also cuts the side wall of the workpiece. Thin grinding creates axial instability that occurs on the shaft and causes lateral deflection of the grinding wheel. This vibration causes the side face, which should not be cutting, to rub against the wall of the resulting cut. Fig. 3, 4 illustrate that thinner discs, 1.2 mm and 1.6 mm, have more fluctuating current consumption patterns than the 3.0 mm disc. These fluctuations reflect the vibrations that cause intermittent friction on the sides of the disc. Fig. 5 show that thinner discs have higher specific energy. This proves that thin discs require more energy to remove each 1 mm^3 of material. This extra energy is used to counteract side resistance due to axial instability, not to cut material. Thin grinding wheels have axial instability, which causes friction on the side surfaces, increasing energy requirements.

The cutting process on a grinding machine is the relative motion between the abrasive tool that moves toward the workpiece. The forward motion of the abrasive tool continues to move across the entire thickness of the grinding wheel. The cutting area is the thickness of the grinding wheel multiplied by the contact area with the workpiece. With a larger area, the contact area of the feed will be greater. Friction and material cutting forces resist the rotational torque of the grinding wheel. Torque is a representation of rotational energy, so the greater the torque required cause the greater the cutting energy required.

To build a model of the forces acting on the grinding process, it is necessary to consider all the force components acting in the direction of the cutting speed on each abrasive grain of the grinding wheel. The cutting force is developed based on the principles of metal plastic deformation mechanics in the cutting contact area of the grinding wheel and the kinematics of the cutting process. The contact area is the interaction of abrasive grains in the multiple cutting process. The multiple cutting process results in an increase in temperature. The contact area of the grinding wheel with the workpiece is the thickness multiplied by the arc of the contact area. The contact area determines the amount of pressure received by the workpiece due to the feed-rate movement. The stress received by the abrasive tool is equal to the compressive force per unit area of the contact area. The same feed rate causes the pressure on a wider contact area to experience wider friction and wear, which shows that a larger contact area requires higher energy. Variations in feed rate at various grinding wheel thicknesses increase the cutting power required by the machine as illustrated by Fig. 4.

It has been observed that changes in the speed of cutting operations always result in changes in the value of MRR. The use of a thin grinding wheel produces a low removal rate. Specific energy is inversely proportional to the removal rate, so the power required in the cutting process per removal rate experience an increase in specific energy when cutting material. Fig. 5 illustrates that specific energy is a function of the cutting power of the machine per volume removed in a unit of time. A large feed rate increases the grinding force. The condition increases torsional resistance and causes an increase in the energy required to counteract the increased friction force. Fig. 13 describes the specific energy in the material removal rate at various wheel thicknesses. This condition is in line with studies [10, 11] which show the relationship between specific energy material remove rate.

The material factor greatly affects the high energy consumption value in grinding. Materials with high hardness, such as steel, are harder than soft materials, such as Al. Material properties also affect chip formation, where more ductile materials tend to require higher cutting energy. Grinding on brittle materials facilitate the release of cut chips. The process of releasing chips is easily separated from the parent material, so that heat is easily dissipated through the discarded chip fragments. Grinding clay materials with low melting points generate heat that causes the chips to melt as BUE. Liquid material can enter the gaps and sharp edges of the grinding wheel. Covered sharp edges reduce the cutting ability of the grinder. This condition becomes a friction field between the grinding wheel and the workpiece. The greater the friction, the greater the heat generated, and the greater the thickness of the molten layer on the grinding wheel. As Fig. 7–10 show, there are variations in the average current between materials. The difference between ST37 and Al is relatively small, ranging from 0.6% to 15%, indicating that their current values are almost comparable. Meanwhile, the difference between Al and cast iron is more pronounced, with Al showing an increase in current of around 5% to 16% compared to cast iron. The largest difference is seen in the comparison between ST37 and cast iron, ranging from 6% to 24%. This confirms that cast iron consistently has the lowest average current while ST37 tends to have the highest. These results demonstrate the significant differences in electrical properties between materials, particularly between ST37 and cast iron. Fig. 12 illustrates BUE covering the sharp edges of the grains. The decrease in cutting ability causes an increase in friction due to constant cutting motion, and a decrease in the cutting ability of the abrasive material.

This study is applied research conducted directly in a production workshop, so that the results can be directly applied in industrial processes. The results of this study can be used as a basis for selecting the thickness of grinding wheels and determining the feed rate and dimensional parameters of grinding wheels for cutting materials.

This study has limitations in the application of the method to single-phase electric motors with fixed rotation. It is important to note that testing has not been conducted on three-phase electric motors.

As further research, the next step in this study is to develop a method that involves the use of various equations and parameters to calculate the energy lost in the abrasive cutting process. The study can be done using software applications or mathematical methods. Observation variables can be improved by considering the cutting force and cutting method, such as intermittent cutting with frequency changes.

7. Conclusions

1. The geometry of the abrasive tool is an important factor in the grinding process. The thickness of the grinding wheel causes the cutting surface of the abrasive cutting process to be wide. The contact area is the area that must be removed during the cutting process. A large contact area results in a large cutting volume so requires more cutting energy. The thickness of the grinding wheel is directly proportional to the cutting power but inversely proportional to the specific energy in the material removal rate. A grinding wheel with good rigidity is used. A thickness of 1.6 mm is recommended because it provides the best stability during the cut-off process.

2. The cutting process requires a cutting motion at a specific feed rate which is directed toward the workpiece being cut. High feed rate causes the grinding wheel to press against the workpiece, generating greater pressure and creating a higher normal force. Normal and friction forces are the main variables of cutting force in the grinding process. Therefore, a large feed rate significantly increases cutting force and increase the energy consumption used in cutting. A feed rate that is too slow has very high specific energy. Feeding rates of 0.166–0.250 mm/s provide better conditions for this experimental configuration.

3. The mechanical properties of the material affect the energy consumption required in the material cutting process. Brittle materials are easier to cut using the abrasive cutting process. Plastic materials require more energy in the cutting process. Materials with low melting points can cause BUE on the cutting edge of abrasive tools. The cutting process cannot run properly when the cutting edge of the tool is covered by molten material from the workpiece. In order to effectively cut ductile materials, it is essential to consider parameters that can prevent excessive heat accumulation, thereby mitigating the occurrence of BUE.

Conflict of interest

The author declares that there is no conflict of interest related to this study, whether financial, personal, authorial, or other form, that could influence the study and the results presented in this article.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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