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A Preliminary Investigation of Energy Consumption for Turning Ti6Al4V EBM Cylindrical Parts

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Abstract. Sustainability is becoming a central pillar of manufacturing and Additive Manufacturing (AM) processes, thanks to their potentialities, seem to open a new path to reduce the environmental footprint. However, the surface finishing of AM parts is hardly ever adequate for high performances applications so post-process treatments are required. Thus, the assessment of sustainability should inevitably consider both steps. In this study, a Ti6Al4V cylindrical sample was firstly manufactured by Electron Beam Melting (EBM) and then machined by turning as post-treatment process. Surface roughness was measured either before and after the machining process both along the direction parallel and that perpendicular to the axis of the cylindrical sample and a Ra reduction of 84.14% and 95.74% were obtained, respectively. To evaluate the goodness of the machining process from the sustainability perspective, the Specific Energy Consumption (SEC) was calculated to evaluate the unit energy consumption for removal the mass unit. Moreover, power trends during the two turning passes have proved to be useful in understanding the different stages of the machining process, the cutting forces involved, and the amount of material removed.

Introduction

In the current scenarios, Sustainable Manufacturing (SM) is gaining increasing attention in the research community, and it is trying also to gain a wider acceptance in industry. SM consists of the creation of manufactured products through processes that minimize the negative environmental impacts derived from energy consumption, material waste and inefficient use of natural resources. Indeed, manufacturing processes are responsible for a large amount of carbon footprint, energy consumption and material waste and, for these reasons, actions are required for improving the resource efficiency with the aim of achieving sustainable development goals [1]. For this purpose, Industry 4.0 is revealing a driving force as it offers significant potentialities for guaranteeing the three dimensions of sustainability, namely social, economic and environmental. Additive Manufacturing (AM) is an emergent technology that has been rapidly developing thanks to its numerous advantages such as the construction of products having complex geometries and, thus, impossible to be manufactured by the traditional techniques. AM is highly versatile and it is suitable for different industrial sectors such as biomedical, aerospace, automotive. Moreover, AM provides potentialities in improving resources efficiency and minimizing the environmental impact because of reduced material waste involved [2]. Electron Beam Melting (EBM) is one of the most successful AM technique where electron beams have a great energy density that fully melts the metal powder ensuring dense parts with better control of the mechanical properties when compared to Selective Laser Melting (SLM), another AM technique where the energy density is provided by a laser. Ti6Al4V alloy is highly adopted in AM because of its low density, high corrosion resistance, strength as well as biocompatibility [3] . However, it is known that surface quality of AM parts hardly ever meets the standard requirements, thus, they typically need post-treatments. Electrochemical and laser polishing, fluized bed treatment and machining processes are the treatments mostly adopted for reducing surface roughness of AM parts. However, additional processes result in additional resources, material waste, energy consumption. Therefore, an optimization of the process conditions for minimizing the environmental impact of both AM and post-treatments processes is needed. In this study, a Ti6Al4V cylindrical sample was previously manufactured by EBM technique and then surfacely treated by turning process for improving its surface finish. During the machining process, the energy consumption was measured for both the first-pass turning and the second one, and the results show that the energy diagrams provide useful information about the evolution of the process. Furthermore, the Specific Energy Consumption (SEC) was measured as sustainability and efficiency index of the machining process.

Material and Methods

Ti6Al4V plasma-atomized powders having spherical morphology [4] were used for manufacturing a cylindrical sample by Electron Beam Melting (EBM) technology. The spherical shape of the powders, as shown in Fig.1, gives a contribution in improving the flowability and ensuring both accuracy and high build rates. According to [5], the apparent density of the powders was 2.57 g/cm^3 while regarding the particle size distribution, the percentage by mass of particle size in the range 45-106 μm was found equal to 93.7%. The nominal chemical composition of the Ti6Al4V pre-alloys powders used in EBM is summarized in Table 1.

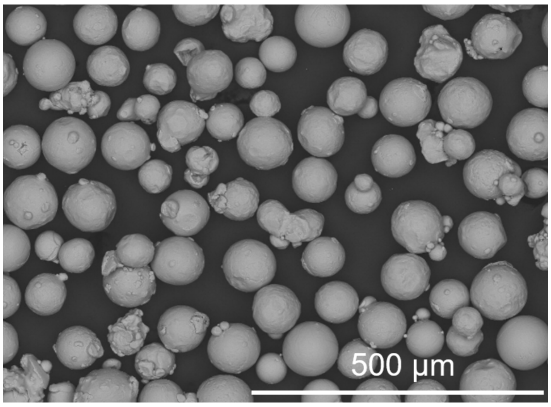

Figure 1. SEM image of typical Ti6Al4V powder particles

Table 1. Nominal chemical composition of the Ti6Al4V powders used in EBM process

Elements	Al	V	Fe	O	N	H	C	Ti
Wt %	6.40	4.12	0.18	0.14	0.01	0.003	0.01	Balance

EBM process was performed by the means of the Arcam A2X machine in a vacuum (10^{-4}– 10^{-5} mbar) as it is of particular importance for metals and alloys having a high affinity to gases like oxygen and nitrogen. Moreover, a small helium pressure called “controlled vacuum” of 10^{-3} mbar was applied to prevent electrostatic charging and so-called smoke events which typically lead to powder spreading and eventually to process termination. The equation correlating the EBM process parameters with energy density [6] is the following:

$$E = V * I/(v * h * t) \tag{1}$$

where V is the acceleration voltage, I is the beam current, h is the line offset and t is the layer thickness. In our experimental campaign, a hot tungsten filament cathode emitted electrons that were accelerated to 60 kV resulting in a maximum beam power of about 3.5 kW. Since the algorithm is covered by copyright, time-dependent diagrams of both beam current and beam speed are hidden to the users, taking into account that the EBM machine worked in automatic mode.

The cylindrical sample having a diameter D of 30 mm and a height of 103.38 mm was manufactured with the axis direction parallel to building one by using a layer thickness t of 50 μm and a line offset

h of 0.1 mm. The standard Ti6Al4V build theme was adopted for manufacturing the sample. In particular, it varies electron beam parameters in a controlled sequence throughout the build according to algorithms developed by the manufacturer with the purpose of achieving fully dense as-built parts having consistent microstructure and properties [7].
The turning process was performed after the EBM process by measuring the energy consumption for improving the surface finish of the sample. Turning was performed by means of a parallel lathe Adria Machine FEL-660HG by using a 60° triangular insert Sandvik Coromant ISO TPM4 16 03 04 2025 as a cutting tool. Moreover, the turning process was carried out by using some lubricant oil Siroil Emulg aiming at preventing wear of the tool and avoid overheating. The process parameters adopted for machining were the following ones: a feed rate *f* of 0.22 mm/rev, a depth of cut *a* of 1.5 mm and a spindle speed *N* of 440 rev/min in accordance with the parameters recommended by the literature [8]. Thus, by substituting the process parameters adopted into the typical formula of turning process:

$$V_c = \pi * D * N \,/1000 \quad (2)$$

the cutting speed V_c adopted was about 42 m/min. To measure both power and energy consumption during turning process, a high-quality analyser called Qualistar Plus Power and Energy Quality Analyser CA8331 (Chauvin Arnoux) was adopted. In particular, it is a three-phase electrical network analyzer and equipped with 3 current sensors MiniFLEX MA193-350, 4 tension cables, 4 crocodile clips, and a software Power Analyser Transfer PAT2 allows the visualization of the variations of the measured parameters over time. As the lathe has a three-phase connection without neutral 32 A 380 V, 3 current sensors and only 3 tension cables with 3 crocodile clips, respectively, were used for measurement acquisition, as shown in Fig.2. A sampling period of one second was chosen for all the measurements.

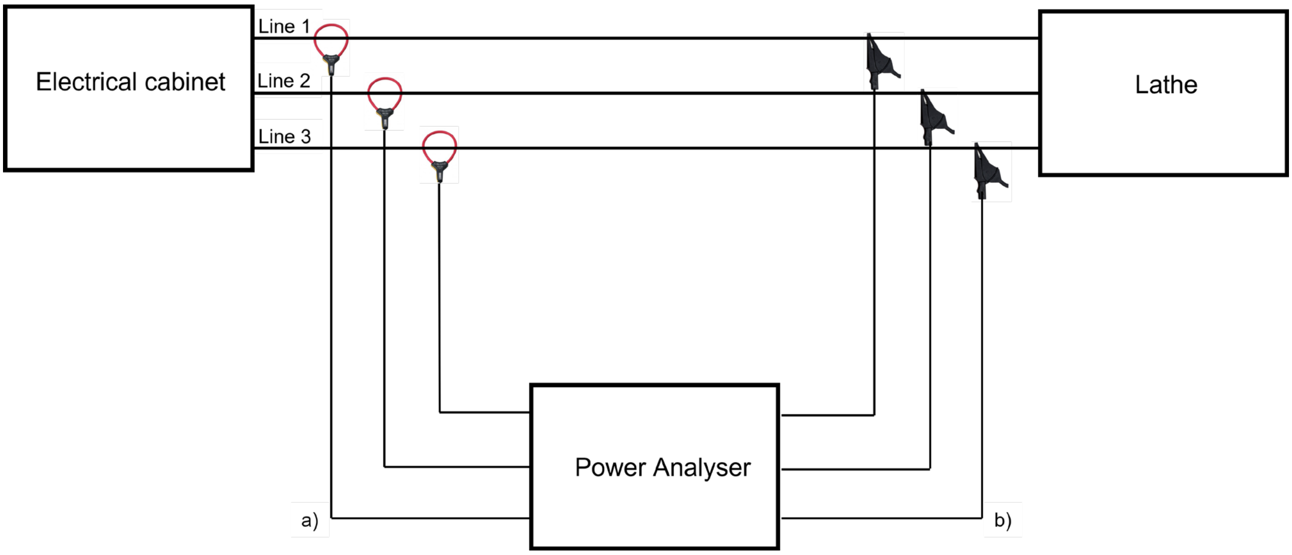

Figure 2. Schematic representation of the experimental set-up with a) current sensors and b) tension cables.

The mass of the sample was measured three times before and after the turning process in order to calculate the specific energy consumption to remove the mass unit, that can be expressed as follows:

$$SEC = E_{removed}/m_{removed} \quad (3)$$

where $E_{removed}$ (MJ) is the electrical energy consumed during the removal mass by the surface of the sample by means of the lathe and $m_{removed}$ (g) is the mass removed through machining process. The mass removed for each sample had been calculated as:

$$m_{removed} = m_{build} - m_{machined} \quad (4)$$

where $m_{machined}$ (g) is the mass of the sample measured after machining process and $m_{removed}$ (g) is the mass removed through machining process.
In order to observe and appreciate the improvement of the surface finish of the sample after the machining process, the surface roughness surface was measured both before and after the turning. For this purpose, a confocal microscope 3D Optical Surface Metrology System Leica DCM3D having a resolution of 0.1 nm was adopted for acquiring the surface of the sample and Leica Map software was used for analysing the surface by measuring the surface roughness.

Results and Discussion

The first result that can be appreciated is that the process parameters adopted in EBM process led to a successful printing process, as shown by the picture in Fig.3.

Figure 3. Picture of the as-built cylindrical sample manufactured by EBM process

As previously mentioned, the weight of the sample was measured three times both before and after the turning process. In particular, the mean of the weight of the as-built sample m_{build}, thus before the machining, was equal to 330 g while the mean of the weight of the sample after the turning $m_{machined}$ was found equal to 300 g. Hence, according to Eq. 4, $m_{removed}$ was equal to 30 g by adopting the process parameters previously mentioned for two times on the surface of the sample. By using a depth of cut a of 1.5 mm for two times, it was possible to obtain a better surface roughness as well as appreciate the difference of the power and energy consumption between the first and the second machining operations. Hence, the total depth of cut was equal to 3 mm.
Fig. 4 shows the output of roughness analysis carried out by the means of Leica Map software on the surface of the sample, acquired by the confocal microscope before (Fig. 4 (a)) and after (Fig. 4 (b)) the turning operation. The color scale on the right of each image helps to appreciate the high improvement of the surface finishing of the sample obtained after turning operation (Fig. 4 (b)).

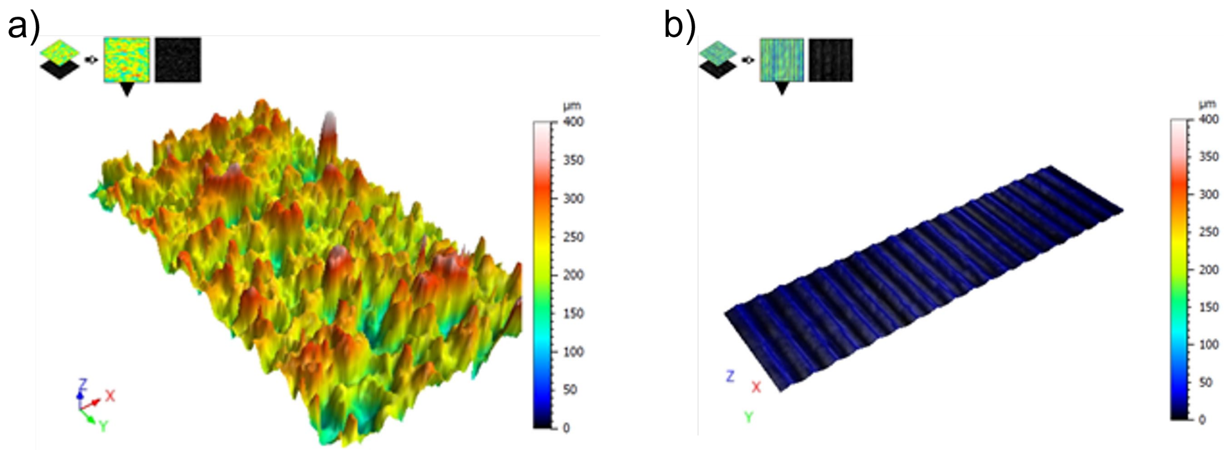

Figure 4. Leica Map images of the surface roughness before a) and after b) machining the sample manufactured by EBM

After acquiring a portion of the cylindrical surface of the sample with the confocal microscope to investigate the roughness, it was necessary to level the surface by removing its shape with the Leica Map software in order to perform a roughness measurement that did not take into account the curvature due to the cylindrical geometry of the sample. The roughness parameter Ra was calculated for three times, according to international standard EN ISO 4287, both along the direction parallel and the direction perpendicular to the cylindrical axis. The following table (Table 2) contains the means of measurement of the roughness parameter Ra made on three selected profiles along the two principal directions of the samples and their reduction percentage obtained thanks to the post-process machining. In particular, $Ra_{//1}$ is referred to the roughness along the direction parallel to the axis calculated before the turning, $Ra_{\perp 1}$ is referred to the roughness along the direction perpendicular to the axis calculated before the turning, $Ra_{//2}$ is referred to the roughness along the direction parallel to the axis calculated after the turning and $Ra_{\perp 2}$ is referred to the roughness along the direction perpendicular to the axis calculated after the turning.

Table 2. Roughness measurement before and after the turning process both along the parallel and perpendicular direction to the axis of the cylindrical sample

$Ra_{//1}$ (µm)	$Ra_{//2}$ (µm)	$Ra_{\perp 1}$ (µm)	$Ra_{\perp 2}$ (µm)	Reduction $Ra_{//}$ %	Reduction $Ra_{\perp}$%
27.09	5.38	23.92	1.02	80.14%	95.74%

Table 2 also shows the significant improvement in surface quality of the sample after the turning process by using the lubricant. A reduction of 80.14% of the roughness along the parallel direction of the axis as well as that of 95.74% of the roughness along the perpendicular direction of the axis were observed.

Power and energy consumption were acquired by the means of the analyser previously described during both the first and the second pass of turning. Fig.4 depicts a representation of the power trends over time during the process. It can be observed that the two curves are almost overlapping, even though the first pass of turning seems to have required a little more energy to cut, and, in fact, the curve of the first-pass turning is slightly shifted upwards compared to the curve of the second one.

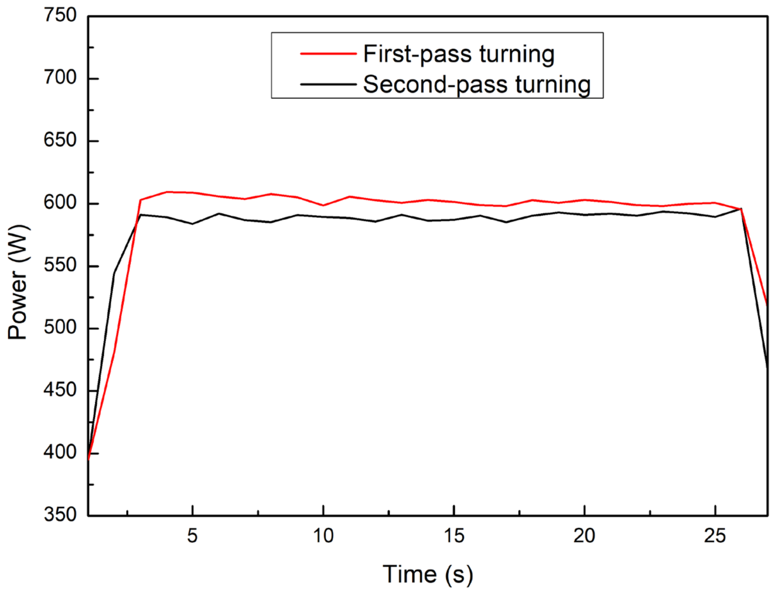

Figure 5. Representative total power curves of both first-pass and second-pass turning process with lubricant of the sample

Moreover, it can be said that during the single-pass turning the power oscillates around 600 W, agreeing with what has been found in the literature [9], and it is called actual cut power (P_{actual}). The graph starts with the instant in which the tool approaches the workpiece, and it is noted that the initial power value is about 400 W. The initial power value corresponds to the power absorption of the lathe operating at the set parameters while the lubricant comes out but the workpiece is not actually turned. We could therefore say that 400 W is the power demand required by the machine tool to perform the basic operations without cutting any workpiece [10] and that in the literature is called air cut power (P_{air}) [11]. The difference between the actual cut power and the air cut power:

$$P_{cut} = P_{actual} - P_{air} \tag{5}$$

gives the power needed for material removal during the single pass turning (P_{cut}), which is equal to 200W.

Both curves show an initial increasing linear trend of the machine power, agreeing with the fact that as the tool is approaching the workpiece, assuming that the specific cutting pressure is always the same, the cutting force increases.

During the advancement, both the specific pressure and the cutting force are almost constant and for this reason we see power oscillations around 600 W all along the workpiece area to be cut. Instead, the final part of the power curve is linear decreasing since, moving away from the piece, the cutting force decreases and therefore the power decreases.

Energy is the area under the power curve over time and in our experimental campaign the energy for removal is the energy to remove the material during the first-pass turning that was found equal to 12600 J. The energy necessary to remove material during the second-pass turning was equal to 11400 J. The first turning pass required more energy than the second one because the first turning phase is a roughing operation aiming at minimizing the presence of undulations due to the high surface roughness on the as-built sample. When the cutting tool comes in contact with the surface finishing of the as-built sample, as it is highly rough, greater cutting forces are involved and, consequently, more demanding power and energy consumption are required. This explains why the curve of the first turning pass is slightly shifted upwards compared to that of the second one.

By summing the energy consumption to remove the material during the first and the second turning pass, we found a total electrical energy consumption during the removal mass by the surface of the sample by means of the lathe, indicated as $E_{removed}$, equal to =24000 J and dividing it by the mass removed $m_{removed}$ =30 g, according to Eq. 3, a specific energy consumption SEC for cutting the mass unit of 800 J/g was found.

Obiko et al. [12] investigated the cutting forces involved in turning Ti6Al4V alloy by varying the process parameters. In particular, the process parameters closest to our study are a cutting speed of 30 m/min, a feed rate of 0.30 mm/rev and a depth of cut equal to 2 mm. The power consumption of the lathe required during the cutting of material was about 1000 W. A paramount parameter in this context is the material removal rate (MRR) which indicates the amount of material removed per time unit and is typically calculated as the product of the feed rate, depth of cut and cutting speed, In their study [12], the MRR corresponding to the combination of process parameters adopted is equal to 300 mm^3/s while the MRR related to our combination of cutting speed, feed rate and depth of cut is 231 mm^3/s. Another way to calculate the specific energy consumption (SEC) is by normalizing the power consumption by MRR [13], and by doing that, our SEC would be of 2.6 J/mm^3 , which is highly close to SEC derived from Obiko et al. results [12] equal to 3.3 J/mm^3.

This article shows only a first result of the energy consumption when turning a cylindrical specimen manufactured by EBM. Further investigations may concern the study of the energy consumption during the turning of the cylindrical samples, manufactured by EBM under the same process conditions, by varying the machining process parameters. Thus, by comparing the energy consumption and the surface roughness obtained, this future study could help to understand which are the optimal process parameters in machining to obtain a good surface finish while minimizing energy consumption. In this perspective, it would be interesting if, once the parameters of the turning process have been set and a total depth of cut of 3 mm as done for this study, it would be better to make more turning passes with lower depth of cut or, conversely, fewer passes with higher depth of cut. In this regard, it would be useful to understand how the power consumption varies over time in these cases as well as how the SEC would vary in those cases.

The investigation of further sustainability indices as well as a study of the tool life when the parameters of the turning process used vary could help to make a more accurate assessment of the entire machining process to obtain a better surface finish while minimizing the environmental impact.

Conclusions

This study demonstrates the possibility of correlating the energy consumption for post-process machining a Ti6Al4V cylindrical sample manufactured by electron beam melting with the cutting forces involved as well as the quantity of the material mass removed to improve the surface finishing. The results obtained and previously discussed allow to explain as follows:

- The process parameters adopted in EBM process resulted in a successful printing;
- Surface roughness Ra of 27.09 μm was obtained along the parallel direction to the axis of cylindrical samples while a Ra of 23.92 μm was obtained along the perpendicular one.
- A percentage reduction Ra equal to 80.14% was obtained along the direction parallel to the sample axis whereas a percentage reduction Ra 95.74% was achieved along to the direction perpendicular to the sample was obtained by the means of the turning process;
- By removing up 9% of the mass of material, the surface quality of a part printed with EBM technique improves considerably. The specific energy consumption SEC for cutting the mass unit was found equal to 800 J/g.
- During the core phase of the turning process, the power oscillated around 600 W for both the first and the second turning pass.
- The experimental acquisitions showed that the first turning pass required a little more energy than the second pass due to higher cutting forces involved in improving the surface roughness of the as-built sample.

This study is a first step towards the assessment of the sustainability of a machining process to minimize its negative impact on the environment. However, it certainly may be improved by varying the turning process parameters and by investigating both energy consumption, material mass removed, and roughness obtained. Furthermore, also the investigation of the sustainability of the EBM additive process could help to evaluate the global environmental impact due to the integration of additive processes and needed post-treatments to understand how to optimize manufacturing processes while minimizing their environmental impact.

References

[1] C. Bai, P. Dallasega, G. Orzes, and J. Sarkis, "Industry 4.0 technologies assessment: A sustainability perspective," *Int. J. Prod. Econ.*, vol. 229, p. 107776, 2020, doi: 10.1016/j.ijpe.2020.107776.

[2] T. Peng, K. Kellens, R. Tang, C. Chen, and G. Chen, "Sustainability of additive manufacturing: An overview on its energy demand and environmental impact," *Addit. Manuf.*, vol. 21, no. April, pp. 694–704, 2018, doi: 10.1016/j.addma.2018.04.022.

[3] A. T. Sidambe, "Biocompatibility of advanced manufactured titanium implants-A review," *Materials (Basel).*, vol. 7, no. 12, pp. 8168–8188, 2014, doi: 10.3390/ma7128168.

[4] J. Dawes, R. Bowerman, and R. Trepleton, "Introduction to the additive manufacturing powder metallurgy supply chain," *Johnson Matthey Technol. Rev.*, vol. 59, no. 3, pp. 243–256, 2015, doi: 10.1595/205651315X688686.

[5] "Standard Test Method for Apparent Density of Free-Flowing Metal Powders Using the Hall Flowmeter Funnel," in *02.05*, .

[6] A. T. Silvestri, S. Foglia, R. Borrelli, S. Franchitti, C. Pirozzi, and A. Astarita, "Electron beam melting of Ti6Al4V: Role of the process parameters under the same energy density," *J. Manuf. Process.*, vol. 60, no. October, pp. 162–179, 2020, doi: 10.1016/j.jmapro.2020.10.065.

[7] M. Koike, K. Martinez, L. Guo, G. Chahine, R. Kovacevic, and T. Okabe, "Evaluation of titanium alloy fabricated using electron beam melting system for dental applications," *J. Mater. Process. Technol.*, vol. 211, no. 8, pp. 1400–1408, 2011, doi: 10.1016/j.jmatprotec. 2011.03.013.

[8] V. Upadhyay, P. K. Jain, and N. K. Mehta, "In-process prediction of surface roughness in turning of Ti-6Al-4V alloy using cutting parameters and vibration signals," *Meas. J. Int. Meas. Confed.*, vol. 46, no. 1, pp. 154–160, 2013, doi: 10.1016/j.measurement.2012.06.002.

[9] K. L. M. Avegnon *et al.*, "Use of energy consumption during milling to fill a measurement gap in hybrid additive manufacturing," *Addit. Manuf.*, vol. 46, no. June, p. 102167, 2021, doi: 10.1016/j.addma.2021.102167.

[10] W. Li and S. Kara, "An empirical model for predicting energy consumption of manufacturing processes: A case of turning process," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 225, no. 9, pp. 1636–1646, 2011, doi: 10.1177/2041297511398541.

[11] M. Younas *et al.*, "Tool Wear Progression and its Effect on Energy Consumption in Turning of Titanium Alloy (Ti-6Al-4V)," *Mech. Sci.*, vol. 10, no. 2, pp. 373–382, 2019, doi: 10.5194/ms-10-373-2019.

[12] J. O. Obiko, F. M. Mwema, and M. O. Bodunrin, "Validation and optimization of cutting parameters for Ti-6Al-4V turning operation using DEFORM 3D simulations and Taguchi method," *Manuf. Rev.*, vol. 8, 2021, doi: 10.1051/mfreview/2021001.

[13] S. Pawanr and G. K. Garg, "Selection of optimum Cutting Parameters for Minimization of Specific Energy Consumption during Machining of Al 6061," *J. Phys. Conf. Ser.*, vol. 1240, no. 1, 2019, doi: 10.1088/1742-6596/1240/1/012064.