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Technological and sustainability implications of wet and dry turning of Ti6Al4V EBM parts

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Abstract. Sustainability is a crucial topic nowadays and Additive Manufacturing (AM) processes are becoming more and more widely used today also because, among its advantages, is claimed to be green technology. However, AM parts usually require postprocessing to improve their surface finishing and result assemblable. In this study, a Ti6Al4V cylindrical sample has been manufactured by Electron Beam Melting (EBM) and then post-processed by turning. Both dry and wet turning has been performed by using the same process parameters. Surface roughness has been measured both before and after each turning pass along the parallel and perpendicular direction to the cylindrical axis and energy consumption has been recorded during each turning pass. Results showed that both dry and wet turning led to a lower roughness along the perpendicular direction to the cylindrical axis than that along the parallel direction, as a result of the technological signature of the turning process. Also, they depict that the first turning pass results in higher cutting forces and, then, the highest values of energy consumption among all the turning passes, both in wet and dry turning. The Specific Energy Consumption (SEC) index has been investigated to evaluate the energy required to remove a unit volume of material; it reflects lower cutting efficiency in the material removal process.

Introduction

Sustainable Manufacturing (SM) is growing its attention focus more and more today both in the industry and research community [1]. The idea behind this concept is to manufacture parts for industrial applications with the objective to minimize the impact on the environment in terms of energy consumption, carbon footprint, and material waste. Additive Manufacturing (AM) is becoming more and more important today, as it plays a key role in the Industry 4.0 context. It consists in manufacturing 3D parts, previously modeled, by adding material layer by layer. AM is claimed to be a green technology because it holds great potential in improving materials efficiency, reducing life-cycle impacts, and enabling greater engineering functionality compared to conventional technologies [2,3]. However, the surface finishing of AM parts hardly ever meets the quality standard requirements, so postprocessing is always required. Machining processes, such as turning and milling, are widely used to reduce the roughness of the parts. Nevertheless, additional steps to manufacturing processes require unavoidably an additional amount of energy and resources. Cutting fluids are typically adopted in machining processes but their usage is crucial because, on the one hand, it helps to reduce friction, heat, and wear and so to increase the tool life but, on the other hand, it has not a negligible impact on the environment. Some studies exist in the

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literature on the dry and wet turning of wrought parts but very few have been carried out on the post-process machining of AM parts [1-3].

In this experimental study, a Ti6Al4V cylindrical sample was manufactured by Electron Beam Melting (EBM) and then machined by both wet and dry turning under the same combination of process parameters to improve the surface finishing. Energy consumption has been recorded during the turning process process with and without lubricant. Also, the roughness has been measured before and after each turning pass. The sustainability index Specific Cutting Energy (SCE) is calculated to evaluate the energy required to remove a unit volume of material, that reflects lower cutting efficiency in the material removal process. The results obtained in this study aim to give some guidelines for better decision-making as a result of a compromise between energy consumption and roughness obtained from a sustainable perspective.

Material and Methods

A cylindrical sample, having a diameter D equal to 30 mm and a height equal to 103.38 mm, has been manufactured by Electron Beam Melting (EBM). Ti6Al4V plasma-atomized powders, having an apparent density of 2.57 g/cm3 [4] and a particle size ranging from 45 µm to 106 µm equal to 93.7%, have been used to manufacture the sample by means of an Arcam A2X machine in a vacuum (10^{-4}- 10^{-5} mbar), that is necessary for metals alloy having high affinity with oxygen and nitrogen. In addition, a helium pressure of 10^{-3} mbar has been applied to prevent electrostatic charging and smoke events leading to eventually process termination and powder spreading. The EBM machine worked in automatic mode: a hot tungsten filament cathode emitted electrons accelerated to 60 kV resulting in a maximum beam power of 3.5 kW. Layer thickness t and line offset h were chosen equal to 50 µm and 0.1 mm, respectively, to manufacture the sample by using the standard Ti6Al4V build theme [5].

Then, the sample was post-processed by turning to improve its surface finishing by means of a parallel lathe FEL-660HG. Turning inserts Sandvik CNMG 12 04 08-SM H13A with a turning tool holder Sandvik PCLNR 2525M have been used to perform the machining processes,

A length of 50 mm of the sample has been turned by using some lubricant oil Siroil Emulg and a length of 50 mm has been turned without the lubricant oil. Two new inserts have been used to perform the machining processes with and without lubricant oil, by selecting the same process parameters, to evaluate the roughness after the postprocessing by avoiding taking into account the wear of the tool. Table 1 contains the process parameters adopted to machine the sample, chosen according to the best results obtained in the literature [6].

Table 1. Process parameters adopted in post-processing of the Ti6Al4V EBM sample by machining.

Feed rate [mm/rev]	**Depth of cut [mm]**	**Spindle speed [rev/min]**	**Number of cutting passes**
0.22	0.6	300	4

The surface finishing of the sample was acquired both before and after the machining process both with and without lubricant by means of the confocal microscope 3D Optical Surface Metrology System Leica DCM3D. Then, Ra roughness parameter was measured, by selecting three profiles, along both the parallel and perpendicular directions to the axis of the cylindrical sample with the Leica Map software.

Energy consumption was measured during the machining processes by means of the power device Quality Analyser CA8331. It is equipped with three current sensors MiniFLEX MA193-350, four tension cables and four crocodile clips. Data over time can be visualized by the Power Analyser Transfer PAT2 software. The lathe adopted for this study has got a three-phase

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connection without neutral (32 A 380 V) so three tension cables, three crocodile clips and three current sensors were adopted in this study to measure the tension and current over time, respectively [7]. By the measurements of the current and tension the device gives as output both power and energy consumption second by second.
Then, the sustainability efficiency index Specific Energy Consumption (SEC) for the machining process, with and without the lubricant, was calculated as follows [8]:

$$SEC = E_{removed}/m_{removed} \tag{1}$$

Where $E_{removed}$ is the total energy consumption to perform the turning process and $m_{removed}$ is the material mass removed, that has been measured by using a Gibertini ETERNITY 200 CAL balance. SEC was calculated after each turning pass to investigate its trend and to compare the results obtained in terms of energy consumption.

Results and Discussion

The first result that can be appreciated in this study is that the post-process machining of the Ti6Al4V EBM sample resulted feasible both with and without the lubricant oil, as illustrated in Fig. 1. Also, both solutions led to an improvement of the surface roughness removing the surface material with the process conditions mentioned above. Roughness was measured both before and after the machining process along the two principal directions of the cylindrical sample, according to international standard EN ISO 4287. Table 2 contains the results obtained in terms of surface roughness.

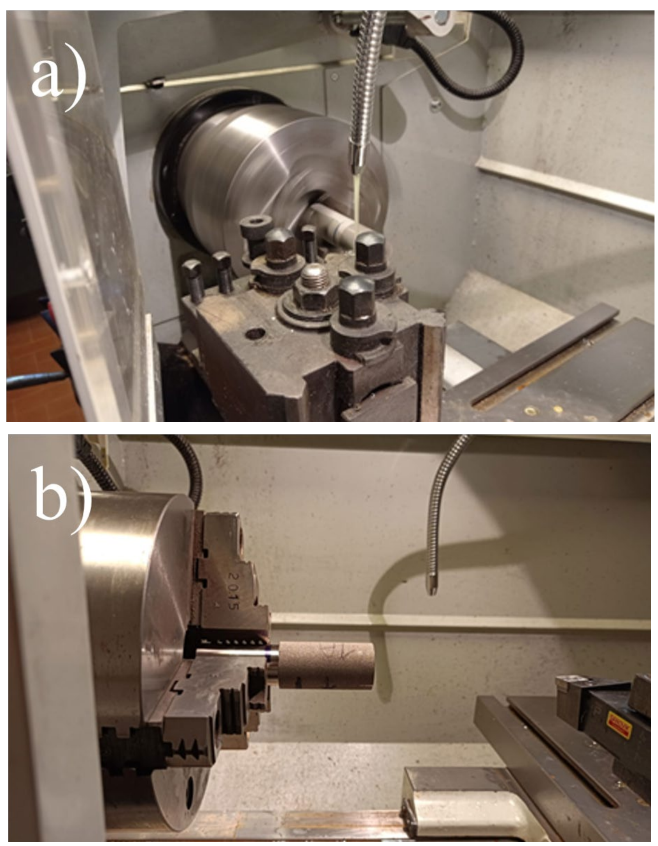

Fig. 1. Turning process of the sample a) with lubrication and b) without lubrication.

Table 2. Results obtained in terms of surface roughness along the parallel and perpendicular direction to the cylinder axis.

$Ra_{//}$ [μm] as built	$Ra_{//}$ [μm] with lubricant	$Ra_{//}$ [μm] without lubricant	Reduction % $Ra_{//}$ with lubricant	Reduction % $Ra_{//}$ without lubricant
30.73	1.86	1.54	93.94	94.99
$Ra_{\perp}$ [μm] as built	**$Ra_{\perp}$ [μm] with lubricant**	**$Ra_{\perp}$ [μm] without lubricant**	**Reduction % $Ra_{\perp}$ with lubricant**	**Reduction % $Ra_{\perp}$ without lubricant**
30.10	0.29	0.45	99.03	98.50

According to the results obtained, the roughness of the as-built sample along the parallel direction to the cylindrical axis is slightly higher than roughness along the perpendicular one. Then, it can be observable that the process parameters selected for this experimental campaign allowed to reach a roughness along the perpendicular direction $Ra_{\perp}$ to the cylindrical axis lower than that obtained along the parallel direction $Ra_{//}$. Indeed, reduction percentages of 93.94 % and 94.99 %, with and without lubricant oil respectively, have been obtained along the parallel direction whereas reduction percentages of 99.03 % and 98.50 %, with and without lubricant oil respectively, have been obtained along the perpendicular direction. These results are direct consequences of the technological signature of the turning process [7].

As mentioned above, energy consumption was measured during each turning pass as well as the material mass removed was calculated by measuring the sample mass before and after each machining process. Based on these measurements, SEC was calculated according to Eq. 1. Table 3 contains all the results obtained in terms of mass removed, energy consumption and specific energy consumption.

Table 3. Results obtained in terms of mass removed and energy consumption during the turning process.

Number of the turning passes	$m_{removed}$ [g] with lubricant	$m_{removed}$ [g] without lubricant	$E_{removed}$ [Wh] with lubricant	$E_{removed}$ [Wh] without lubricant	SEC [Wh/g] with lubricant	SEC [Wh/g] without lubricant
1	2.4	7.1	34.2	55.8	14.25	7.80
2	8.4	9.9	23.9	24.8	2.84	2.51
3	7.5	8.5	22.2	23.7	2.96	2.79
4	7.4	6	20.7	16.8	2.80	2.80

The first result observable regards the trend of the mass removed during each turning pass. At first, just a little amount of surface material of the sample has been removed, both with and without the usage of lubricants. This is because, in the beginning, the undulations are more pronounced according to the higher surface roughness of the as-built sample. The second turning pass allowed the removal of the highest amount of material both with and without the lubricant, by selecting the same process parameters. Results in Table 3 show that the trend of the mass removed over the number of turning passes is very similar between the two process conditions (with and without lubricant). However, a big difference in amount of removed material for the first pass exists (2.4 g with lubricant and 7.1 g without lubricant). This is due to the fact that the first turning pass is a roughing process, friction between the tool and the part is higher as well as the tool is at the beginning of his life. Thus, these conditions help the mass removal at the beginning. In total, the mass removed with the lubricant is 25.7 g while the mass removed in total without the lubricant is 31.5 g.

Fig. 2 depicts the trend of the electrical energy consumption during each turning pass. It is important to premise that lubrication is activated by a sub-unite of the machine used for turning. The contribution of this pump in terms of power consumption is negligible. For this reason, in this study the attention was mostly focused on the energy consumption in dry and wet turning as a result of only different cutting forces during the process. Also in this case, the trend of data related to the machining process by adopting the lubrication is very similar to that the one without the usage of the lubricant as well as the curve related to the turning without lubricant is slightly shifted upwards. This is explained by the fact that the use of the cutting fluids reduces the friction between the tool and the workpiece resulting in a reduction of the heat generation and cutting forces [9], both with and without the usage of lubricant, as the power in machining is linearly dependent from the cutting forces [10] and the roughness of the as-built sample is the higher than that after each turning pass. For this reason, at the beginning of the machining process, the cutting forces are higher, and this explains why the highest values of energy consumption have been obtained during the first turning pass.

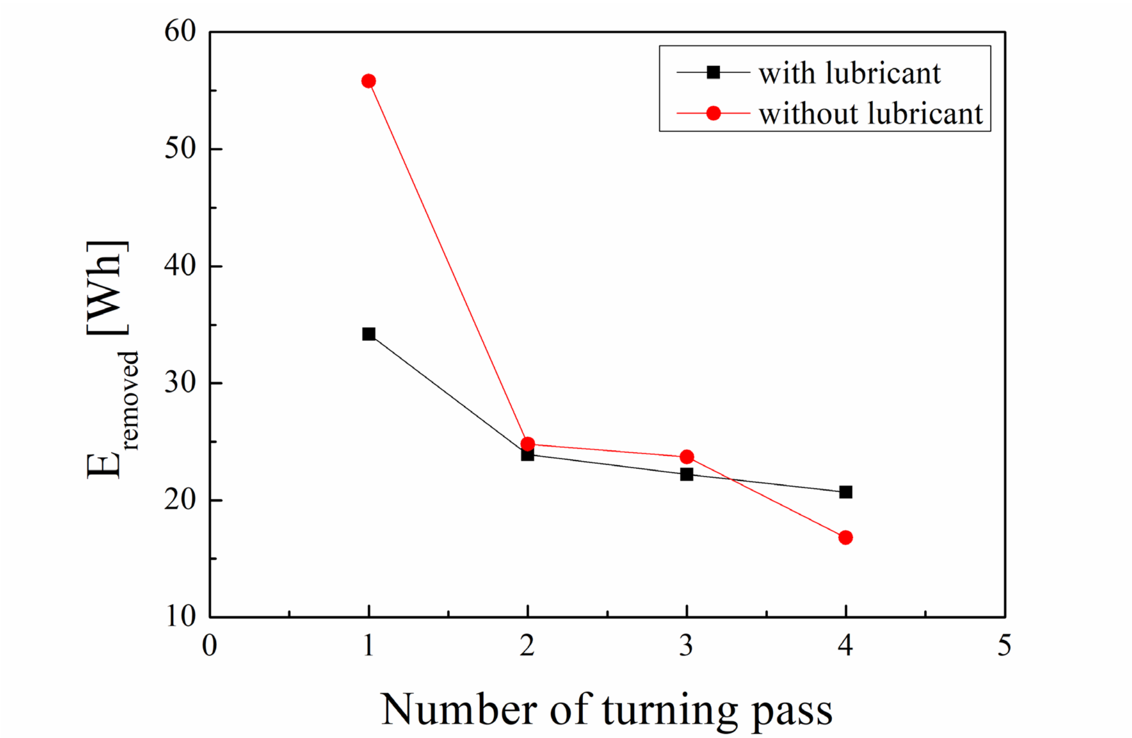

Fig. 2. Energy consumption to remove material after each turning pass with and without the usage of the lubricant.

Nevertheless, Fig. 3 shows that the SEC curve with lubricant oil is shifted upwards to the SEC curve without the lubricant. As indicates that from a sustainability perspective, even if the cutting forces are higher, dry turning can be considered more sustainable in terms of energy consumption than wet turning under the same process conditions. Fig. 3 depicts that at first there is a huge difference in SEC whereas data are very similar from the second turning pass to the end of the process.

By jointly investigating roughness and energy consumption during the turning of an EBM Ti6Al4V sample, it can be said that by selecting the process parameters of our study, it is worthwhile to choose the dry turning rather than the wet turning since it leads to similar results in terms of surface roughness (Table 2) by reducing specific energy consumption to perform the turning process. This study could be improved by including more than one configuration of turning process parameters on EBM parts printed under the same process conditions and by also considering the cutting tool wear. In general, dry turning shortens tool life as well as lubricant has a negative impact on the environment. In this perspective, a joint investigation of surface roughness, energy consumption and tool wear will demonstrate the possibility to prefer dry turning to wet turning by using optimal process parameters.

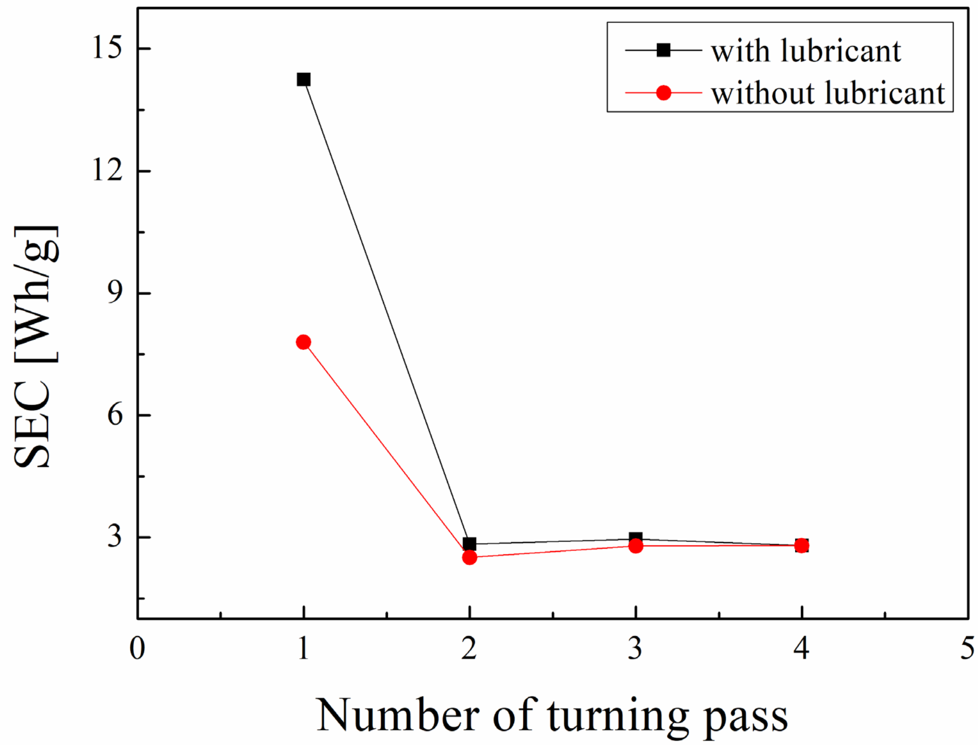

Fig. 3. Specific energy consumption after each turning pass with and without the usage of the lubricant.

Summary

This study demonstrates the possibility of choosing dry turning rather than wet turning as post-process machining for a Ti6Al4V EBMed cylindrical sample by reducing the sustainability index SEC without sacrificing its surface quality. The main results obtained and discussed in this study are:

- Roughness reduction percentages of 93.94 % and 99.03 % have been obtained by wet turning along the parallel and perpendicular directions, respectively. Roughness reduction percentages of 94.99 % and 98.50 % have been obtained by dry turning along the parallel and perpendicular directions, respectively. Thus, for the objective of this study, lubricant is not required to deliver a certain reduction in diameter and final surface finish.
- The same process conditions in machining lead to a lower roughness along the perpendicular direction to the cylindrical axis than that along the parallel direction, according to the technological signature of the turning process.
- The first turning pass, both with and without the lubrication, allows to remove just only a little amount of material as the surface undulations of the as-built sample are more pronounced and the roughness is higher.

- Wet turning leads to a removed mass of 25.7 g whereas dry turning leads to a removed mass of 31.5 g by selecting the same process parameters and by fixing the same number of turning passes.
- The first turning pass results in higher cutting forces and, then, the highest values of energy consumption among all the turning passes, both in wet and dry turning.
- Dry turning can be considered more sustainable in terms of energy consumption than wet turning under the same process conditions as the SEC curve with lubricant oil is shifted upwards to the SEC curve without the lubricant.

This study is among the first steps toward the sustainability assessment of post-process machining of additive manufactured parts. In fact, it is a preliminary investigation of sustainability implications in terms of energy consumption in both dry and wet machining of EBM samples. It is a first step to investigate how different the outputs in terms of both surface roughness and energy consumption are in machining the same parts having a simple cylindrical shape. The next step will regard the sustainability assessment and technological implications in machining a complex EBM part. Also, this study can be extended to other machining operations such as milling. The same cylindrical EBM samples could be post-processed by milling by selecting different process conditions by fixing the output in terms of total depth of cut, and then in terms of final surface roughness.

Also, the wear-cutting tool should be investigated for better decision-making as a result of a compromise between the energy consumption, tool life and roughness obtained from a sustainable perspective.

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