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Comparison of specific cutting energy in dry and wet post- process turning of Ti6Al4V EBM parts

Ersilia Cozzolino[1,a *], Stefania Franchitti[2,b], Rosario Borrelli[2,c], Antonello Astarita[1,d]

[1]Dipartimento di Ingegneria Chimica, dei Materiali e della Produzione Industriale, Università degli Studi di Napoli Federico II, Piazzale Tecchio 80, 80125 Napoli, Italy

[2]CIRA (Italian Aerospace Research Center), 81043 Capua CE, Italy

[a]ersilia.cozzolino@unina.it, [b]s.franchitti@cira.it, [c]r.borrelli@cira.it, [d]antonello.astarita@unina.it

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Abstract. Additive Manufacturing (AM) is accelerating more and more today. Among its advantages, AM is claimed to be green technology. However, AM parts usually require postprocessing to improve their surface finishing and to be assembled. In this study, some Ti6Al4V cylindrical samples have been manufactured by Electron Beam Melting and then post- processed by turning. Both dry and wet turning has been performed under 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. Specific Cutting Energy (SCE) has been calculated to evaluate the energy efficiency of the turning process. The results of this study demonstrate that dry turning is more energy efficient than wet turning by selecting the same machining process parameters while obtaining a comparable surface roughness.

Introduction

Sustainable Manufacturing (SM) is a crucial topic today in both the research community and industry. It 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. There is also an excellent diversity of interpretations and concepts related to SM [1].

Concerning the materials investigated, the titanium alloy Ti6Al4V was noted as the most popular material utilized in the latest SM technology research due to its superior material properties, such as corrosion resistance, high strength, low density, high fracture toughness, biocompatibility, high industrial demand, including its well-established history in the aerospace sector [2], and its suitability for various manufacturing technologies, including additive manufacturing. Among the nickel alloys, Inconel 718 was observed to be the foremost popular workpiece material due to the fact that it is a high-performance superalloy that provides corrosion resistance along with strength at both atmospheric and high-temperature ranges [3].

Additive Manufacturing (AM) consists of producing three-dimensional objects by adding layers of material based on a three-dimensional computer model. AM is currently becoming a key technology in industries such as aerospace, biomedicine, and manufacturing as it allows fabricating customized products thanks to its ability to create complex objects with advanced attributes. 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. Nevertheless, the literature lacks guidelines for obtaining AM having good mechanical properties while saving energy and reducing environmental impacts. Also, surface finishing of AM parts hardly ever is acceptable for the industrial quality standards. For this reason, postprocessing is always required. Very few studies exist in the literature having as objective the minimization of both Ra roughness parameter and power and energy consumption in post-process machining of Ti6Al4V EBM parts. This study aims to fill this gap of knowledge. In particular, in this study a cylindrical sample has been post-processed by both dry and wet turning by selecting the same process parameters. Power consumption has been acquired in both situations and surface roughness has been measured before and after the turning processes. The sustainability of the turning processes has been evaluated by means of the sustainability index called specific energy consumption (SEC), calculated by means the power measurements and process parameters adopted in this study.

Materials and Methods

A cylindrical sample has been manufactured by EBM with the axis parallel to the building one. It has a height of 103.38 mm and a diameter of 30 mm. The sample has been built by means of the Arcam A2X machine by using Ti6Al4V powders having the 93.7% of particle size between 45 µm to 106 µm. As usual, EBM has been performed under a vacuum to reduce contamination and minimize electron collisions with air molecules. Also, to prevent electrostatic charging and smoke events, a helium pressure of 10^{-3} mbar has been applied. The standard Ti6Al4V build time, the layer thickness equal to 50 µm and the line offset of 0.1 mm have been fixed to build the sample in the EBM machine, which worked in automatic mode [4].

The sample has been then post-processed by machining, by means of the FEL-660HG lathe, to improve its surface finishing and to meet industrial quality requirements. Dry turning and wet turning have been performed on two sides of the sample, both for a length equal to 50 mm, under the same process conditions. The lubricant oil Siroil Emulg has been employed for the wet turning process. New inserts, Sandvik CNMG 12 04 08-SM H13A, have been used to perform both dry and wet turning by adopting a spindle speed of 300 rev/min. Table 1 contains the process parameters adopted in this study, according to the best results obtained in the literature in terms of surface roughness by turning [5].

Table 1. Process parameters in post-process machining of the cylindrical sample

Feed rate (mm/rev)	**Depth of cut (mm)**	**Number of cutting passes**	**MRR (mm^3/s)**
0.28	0.8	3	105.5

Surface roughness has been investigated before and after the turning processes by means of the confocal microscope 3D Optical Surface Metrology System Leica DCM3D. After the surface acquisition, the Ra roughness parameter has been measured by selecting three profiles on both the parallel and perpendicular directions to the build one.

Power consumption has been recorded over time by means of the power quality analyser CA8331. It measures current and tension by means of specific sensors, whose number depends on the electrical connection of the machine to be analysed. The lathe adopted in this study has a three-phase without neutral connection 32 A 380 V. Thus, three tension cables, three crocodile clips and three current sensors were employed to measure power over time, by selecting a sampling period of 1 second.

To evaluate the energy efficiency of the turning processes, the specific cutting energy (SCE) has been calculated as follows [6]:

$SCE = P_{cut}/MRR$ (1)

Where $Pcut$ is the cut power, that is calculate as:

$P_{cut} = P_{actual} - P_{air}$ (2)

Where $Pactual$ is the actual power, that is the average power measured by means of the power device during the material removal, and $Pair$ is the air power, which is the power measured while the lathe is energized but there is no contact between cutting tool and the workpiece. In other words, air power is the power consumption measured when the lathe is working, under the process conditions fixed, but the material is not removed. The air power was measured both during wet and dry turning as it is affected by the pump energy contribution. Material removal rate (MRR) is calculated as follows:

$MRR = V_c * a * f$ (3)

Where a is the depth of cut, f is the feed rate, and V_c is the cutting speed calculated as:

$V_c = \frac{\pi D n}{1000}$ (4)

Where D is the diameter of the sample to be cut and n is the spindle speed.

Results and Discussion

A result of our study is the feasibility of the post-process machining by means of the parallel lathe on the EBM Ti6Al4V cylindrical sample either with and without the lubricant usage. Fig. 1 shows the machining process performed with the lubricant.

As previously described, surface roughness has been investigated before and after the turning process with and without the lubricant along both the parallel and perpendicular directions to the cylindrical axis. Table 1 contains all the numerical results in this regard. Each Ra measurement is the average of three profiles taken on both the principal directions of the cylinder.

Figure 1. Post-process turning of the EBM Ti6Al4V sample with the lubricant

It can be observed that the roughness parameter Ra along the parallel direction is higher than Ra measured along the perpendicular directions. In particular, before the machining, Ra along the parallel direction to the building one is found equal to 35.81 µm whereas Ra along the perpendicular direction is 28.79 µm, as a result of the staircase effect. That is due to the fact that EBM technology consists in melting the material layer by layer. Thus, the cylindrical sample has been post-processed to improve its surface roughness to meet the industrial quality requirements. As previously mentioned, two lengths have been machined on the same cylindrical sample with and without lubricant by using the same process parameters. The results displayed in Table 2 show that a higher percentage reduction has been obtained after three passes without lubricant along both the parallel and perpendicular directions.

Moreover, it can be observed that the reduction percentage of Ra in the perpendicular direction is always higher than that obtained in the parallel direction, with and without the lubricant. This is due both to the higher roughness to be smoothened, according to the EBM staircase effect, and the technological signature of the turning process [7][8].

Table 2. Surface roughness along the principal directions of the cylindrical sample

Ra// [µm] as built	**Ra// [µm] with lubricant**	**Ra// [µm] without lubricant**	**Reduction % Ra// with lubricant**	**Reduction % Ra// without lubricant**
35.81	2.20	1.77	93.86	95.05
Ra⊥ [µm] as built	**Ra⊥ [µm] with lubricant**	**Ra⊥[µm] without lubricant**	**Reduction % Ra⊥with lubricant**	**Reduction % Ra⊥ without lubricant**
28.79	0.34	0.42	98.81	98.17

As previously described, power consumption has been measured by means of a power device that gives as output of current and tension measurements the power recorded over time. Fig. 2 shows the power trend during the three turning passes to remove a depth of cut equal to 2.4 mm with and without lubricant.

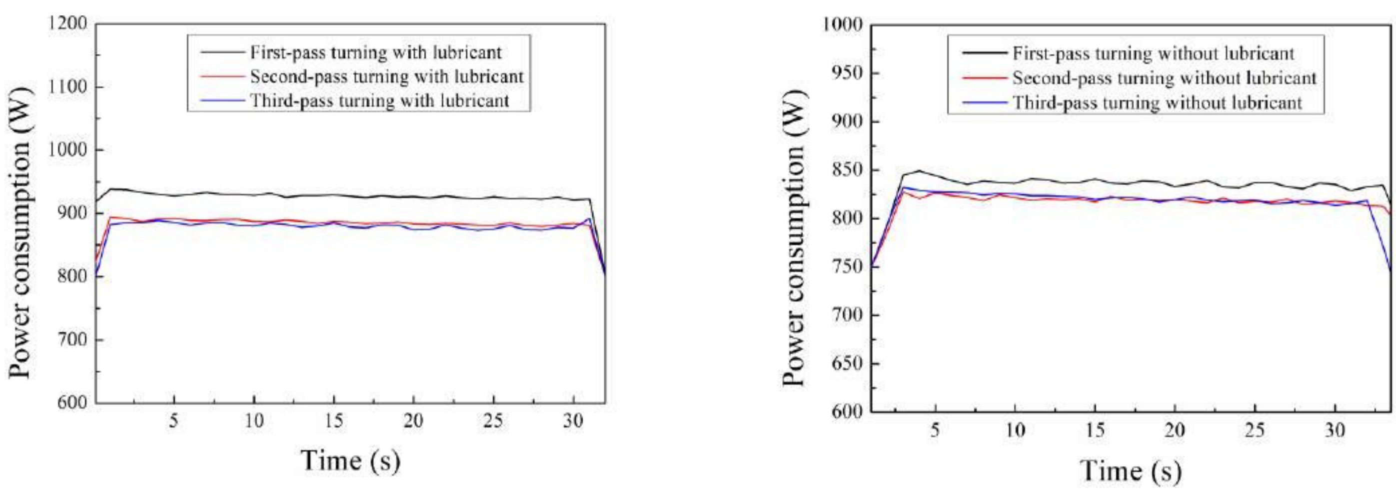

Figure 2. Power consumption over time of all the turning passes with and without the lubricant

The curves on the two diagrams show the same trend, just the curves representing the power consumption of all the turning passes with lubricant are translated upwards because of the contribution of the lubricant pump. All of them show an increase in power consumption at the beginning, when the cutting tool become in contact with the workpiece and, in opposite, power decreases at the end of the machining process, when the cutting tool turns away from the sample.

Also, it can be seen that in both situations the power curve related to the first-pass turning is the highest one, as at the beginning surface roughness is the highest one and cutting forces involved are higher. Therefore, power consumption to remove the material is higher at the beginning of the process. In fact, second-pass turning and third-pass turning are represented by lower curves as the cutting forces and then the power consumption required is lower.

Moreover, the first-pass turning without lubricant shows some oscillations over time: this is due to the fact that at the beginning the surface roughness is very high as well as the cutting forces involved are higher, as a result of the absence of the lubricant oil, which helps to reduce wear and tear.

In general, higher power consumption is required during the first pass turning since the roughness is higher. However, by comparing dry and wet first-pass turning, such difference is lower in the "without lubricant" phase. This is due to the fact that, even the surface roughness is lower, after the first pass turning, higher cutting forces are involved in dry turning than wet turning, so higher power consumption is required. We can say that, after the first-pass turning, cutting forces effect prevails on the roughness effect.

Table 3 contains the results derived from the power measurements (actual power and air power) and calculations (cut power, material removal rate and specific cutting energy), according to the equations described in the previous sections. Air power is the power consumption of the lathe when it is energized but the tool is not in contact with the material whereas the actual power is the power consumption during the material removal. It can be observed that the air power is higher than the air power without the lubricant usage, as expected, because of the energy consumption of the lubricant pump.

Table 3. Results of the power analysis in the post-process machining

Number of the turning pass	$Pactual$ **(W) with lubricant**	$Pactual$ **(W) without lubricant**	P_{air} **(W) with lubricant**	P_{air} **(W) without lubricant**	$Pcut$ **(W) with lubricant**	$Pcut$ **(W) without lubricant**	**MRR (mm^3/s)**	SCE **(J/ mm3) with lubricant**	SCE **(J/ mm3) without lubricant**
1	917	835	800	750	117	85	105.5	1.1	0.8
2	886	818	800	750	86	68	102.6	0.8	0.7
3	878	815	800	750	78	65	99.9	0.8	0.7

The material removal rate has been calculated according to Eq. 3 by considering the current diameter after each turning pass. Obviously, after each turning pass, the diameter to be cut decreases, so cutting speed decreases and then material removal rate decreases. Also, cut power decreases after each turning pass according to the fact that the surface roughness decreases. Fig. 3 depicts the relationship between cut power and material removal rate. It can be noted that cut power increases by increasing the material removal rate both with and without lubricant usage. This is probably the effect of the changing diameter between the turning passes.

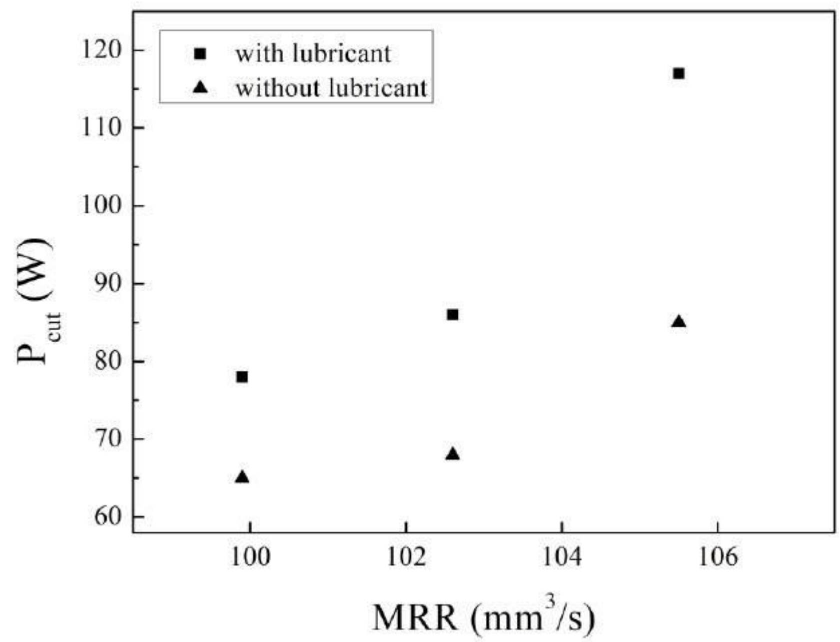

Figure 3. Cut power for each material removal rate with and without the lubricant

Specific cutting energy (SCE) has been calculated according to Eq. 1 by means of the power measurements. Numerical results ranging from 0.7 and 1.1 J/mm^3 have been obtained (Table 3). Fig. 4 displays specific cutting energy results for each turning pass with and without lubricant. It represents the energy spent to cut a material volume equal to 1 mm^3. Both with and without the lubricant, SCE decreases with the increase of the turning passes. Also, SCE is higher for turning with the lubricant as the cut power is higher.

These results underline that dry turning is more energy efficient than wet turning by selecting the same machining process parameters. Also, comparable results have been obtained in terms of surface roughness (Table 2) with and without lubricant along both the parallel and perpendicular direction tot the building one. For these reasons, according to our results, it is worthwhile to select the dry turning rather than the wet turning as it results in similar results in terms of surface roughness by minimizing the specific cutting energy.

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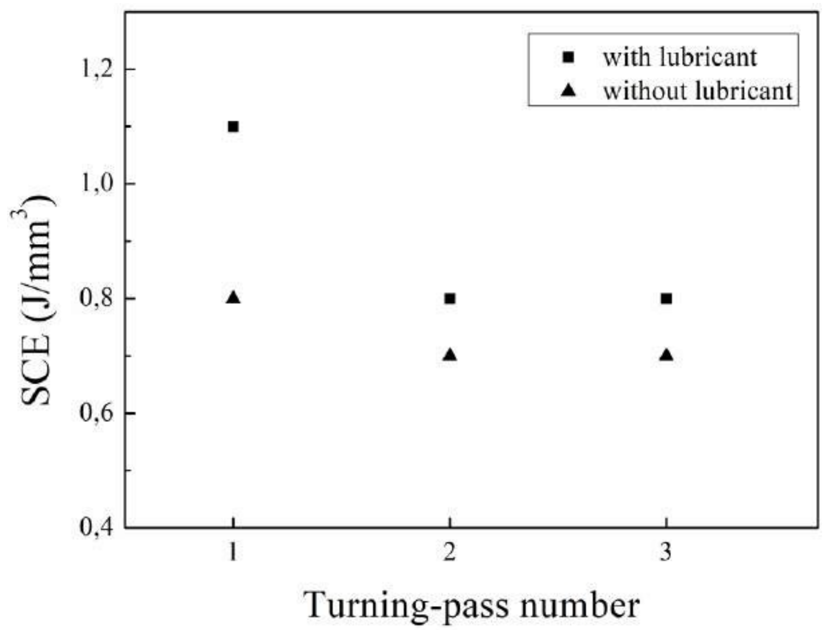

Figure 4. Specific cutting energy for each turning pass with and without the lubricant

Conclusions

This experimental study demonstrates the feasibility of performing dry turning as postprocessing of an EBM Ti6Al4V cylindrical sample. Roughness has been measured before and after the turning process with and without lubricant along the parallel and perpendicular directions to the build one. Power consumption has been recorded to investigate the energy efficiency of the process.
The main conclusions of this study are:

- Roughness parameter Ra along the parallel direction to building one was found equal to 35.81 μm whereas Ra along the perpendicular direction was 28.79 μm. Thus, in the parallel direction the roughness is higher than that in the perpendicular direction, as a result of the staircase effect.
- A higher power consumption is required to remove the first layer of material as higher are the cutting forces involved, as a consequence of the higher surface roughness.
- Power curves show the same trend both with and without the lubricant. The first layer is always the most energy consuming.
- Air power is 800 W with the lubricant, and it is 750 W without the lubricant. Thus, the power consumption of the lubricant pump is about 50 W.
- After each turning pass, cut power decreases according to a reduction in surface roughness.
- Cut power increases by increasing material removal rate both in dry and wet post-process turning.
- Specific cutting energy values ranging from 0.7 and 1.1 J/mm^3 have been obtained in our experimental study. It decreases with increasing the turning pass number.
- As comparable Ra numerical measurements have been obtained with and without lubricant and dry turning is more energy efficient, it is good to choose dry postprocess turning whenever possible.

This is just a preliminary study on the feasibility of performing dry turning as postprocess machining of an EBM Ti6Al4V part. Further investigation will include additional tests with different parameters to deeply investigate the two strategies, with and without lubricant oil during machining of AM parts, to find the best scenario for minimizing specific energy consumption. Also, a comprehensive sustainability assessment will be carried out to consider the impact of both the lubricant and tool wear on the environment.

References

[1] A. Sartal, R. Bellas, A.M. Mejías, A. García-Collado, The sustainable manufacturing concept, evolution and opportunities within Industry 40: A literature review, Adv. Mech. Eng. 12 (2020). https://doi.org/10.1177/1687814020925232

[2] S. Liu, Y.C. Shin, Additive manufacturing of Ti6Al4V alloy: A review, Mater. Des. 164 (2019) 107552. https://doi.org/10.1016/j.matdes.2018.107552

[3] R. Vaßen, J. Fiebig, T. Kalfhaus, J. Gibmeier, A. Kostka, S. Schrüfer, Correlation of Microstructure and Properties of Cold Gas Sprayed INCONEL 718 Coatings, J. Therm. Spray Technol. 29 (2020) 1455-1465. https://doi.org/10.1007/s11666-020-00988-w

[4] M. Koike, K. Martinez, L. Guo, G. Chahine, R. Kovacevic, T. Okabe, Evaluation of titanium alloy fabricated using electron beam melting system for dental applications, J. Mater. Process. Technol. 211 (2011) 1400-1408. https://doi.org/10.1016/j.jmatprotec.2011.03.013

[5] V. Upadhyay, P.K. Jain, 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. 46 (2013) 154-160. https://doi.org/10.1016/j.measurement.2012.06.002

[6] F. Hojati, A. Daneshi, B. Soltani, B. Azarhoushang, D. Biermann, Study on machinability of additively manufactured and conventional titanium alloys in micro-milling process, Precis. Eng. 62 (2020) 1-9. https://doi.org/10.1016/j.precisioneng.2019.11.002

[7] E. Cozzolino, A. Astarita, R. Borrelli, S. Franchitti, V. Lopresto, C. Pirozzi, A Preliminary Investigation of Energy Consumption for Turning Ti6Al4V EBM Cylindrical Parts, 926 (2022) 2355-2362. https://doi.org/10.4028/p-vm4f1y

[8] E. Cozzolino, S. Franchitti, R. Borrelli, C. Pirozzi, A. Astarita, Energy consumption assessment in manufacturing Ti6Al4V electron beam melted parts post processed by machining, Int. J. Adv. Manuf. Technol. (2023) 1289-1303. https://doi.org/10.1007/s00170-022-10794-z