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MILLING AND MAGNETIC ABRASIVE FINISHING OF DIRECTED ENERGY DEPOSITED-316L STAINLESS STEELS

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Abstract. Additive Manufacturing (AM) technologies, commonly known as 3D printing, show high disruptive potential in current manufacturing industries, and Directed Energy Deposition (DED) is one of the most prominent in metal applications for the creation of near net shape components. Its processes combine material feedstock (powder or wire) and energy (e.g., laser, electron beam or electric arc) for layer by layer deposition, hence, formation of the metallic part. However, both dimensions and surface qualities of parts produced by DED are relatively poor, requiring post-processing operations. Traditional machining processes (e.g., milling) or even some advanced finishing processes (e.g., Magnetic Abrasive Finishing – MAF) are, therefore, necessary for the obtaining of the desired functional performance. This study evaluates the improvements achieved by milling and MAF operations in the surface quality of 316L stainless steels produced by DED, as well as the effects of post-processes on surface morphology and roughness. The roughness results showed $56.06 \mu\text{m Ra}$ and $242.80 \mu\text{m Rz}$ for the DEDed parts - such high values are due to the presence of adhered particles and bead profile. The irregularities of the outer layer and the non-fused powders on the surface were removed by milling, reducing Ra from approximately $56.06 \mu\text{m}$ to $0.08 \mu\text{m}$ and Rz from $242.80 \mu\text{m}$ to $0.56 \mu\text{m}$. MAF produced smoother surfaces ($0.03 \mu\text{m Ra}$, and $0.24 \mu\text{m Rz}$) free of milling marks and with mirror quality, indicating above 99.9% improvement. Milling proved efficient as an intermediate post-processing step between deposition and MAF in reducing the overall processing time in the manufacturing sequence of final components produced by AM technologies. Use of hybrid machines, association of deposition capabilities with machining and polishing in the same equipment, and only one gripping position can improve the manufacturing sequence, saving time, resources, and costs, and performing the whole sequence (AM+milling+MAF) in a same machine.

Keywords: Metal additive manufacturing. Post-processing. Magnetic abrasive finishing. Surface quality.

1. INTRODUCTION

According to Gibson *et al.* (2015), the study and the development of innovative manufacturing processes are essential for the meeting of the ever-growing needs of modern societies. Additive manufacturing (AM), which has excelled as one of the most important processes, is commonly known as 3D printing, and can create components of complex geometries, contributing to materials savings, reductions in both financial resources and manufacturing time, among other benefits. Petrick and Simpsons (2013) highlighted AM technologies have high disruptive potential to 3D-build components of size and shape similar to those of the final product (near net shape), and have been applied to products with high-added value. The 3D Hubs (2020) report indicates the perspectives and value trends of AM market (regarding services, systems, software, and materials). In 2004, market share was valued at \$4B, whereas in 2018, the last real historical data, it was approximately \$9B, with a growth estimate of up to \$45B in 2024. According to Thompson *et al.* (2016), such an evolution has been nothing less than extraordinary. The authors claimed AM can be applied to polymers, wood, ceramics, composites, and metals, and, in 2015, appointed the Directed Energy Deposition (DED) processes as some of the most prominent in metalworking, since they combine material feedstock (powder or wire) with several heat sources (laser, electron beam, or electric arc) for the layer-by-layer deposition until a 3D part is complete. Gao *et al.* (2015) confirmed the versatility of DED processes, which also promote relatively high deposition rates, production of functional gradient materials (FGM), coatings, and repairing, and manufacture components of singular microstructures due to high cooling rates and high thermal gradients.

However, components obtained by DED do not commonly achieve the required levels of dimensional accuracy and surface quality (GIBSON *et al.*, 2015). According to Maleki *et al.* (2021), post-processing operations can overcome those

limitations and broaden AM applications. Subtractive operations, such as machining, can achieve dimensional accuracy, roughness, and some functional properties within required limits. Milling shows versatility and employs a cutting edge for the removal of chip, and has been traditionally used for machining prismatic pieces (TRENT; WRIGHT, 2014, MACHADO *et al.*, 2015). Nevertheless, its surface quality depends on cutting tools and processing conditions; advanced finishing processes are required if such quality limitations are reached and higher levels are demanded for the application of the component.

Magnetic Abrasive Finishing (MAF) has emerged as a viable advanced finishing process defined by Yang and Li (2018) as one that mixes magnetic abrasive particles and abrasives in a magnetic field between poles and the workpiece itself. The material is slowly removed through relative movements and magnetic forces, improving surface quality. MAF has produced roughness at nanometer levels, thus motivating the present study, which evaluated the improvements achieved by milling and MAF operations in the surface quality of 316L stainless steels produced by DED, as well as the effects of post-processes on surface morphology and roughness. A manufacturing sequence was proposed and involves AM, milling, and MAF processes successively applied towards improving surface roughness up to nanometer levels.

2. EXPERIMENTAL WORK

Figure 1 shows a schematic setup of each process, following the manufacturing sequence adopted. DED and post-processing operations were conducted in replicate.

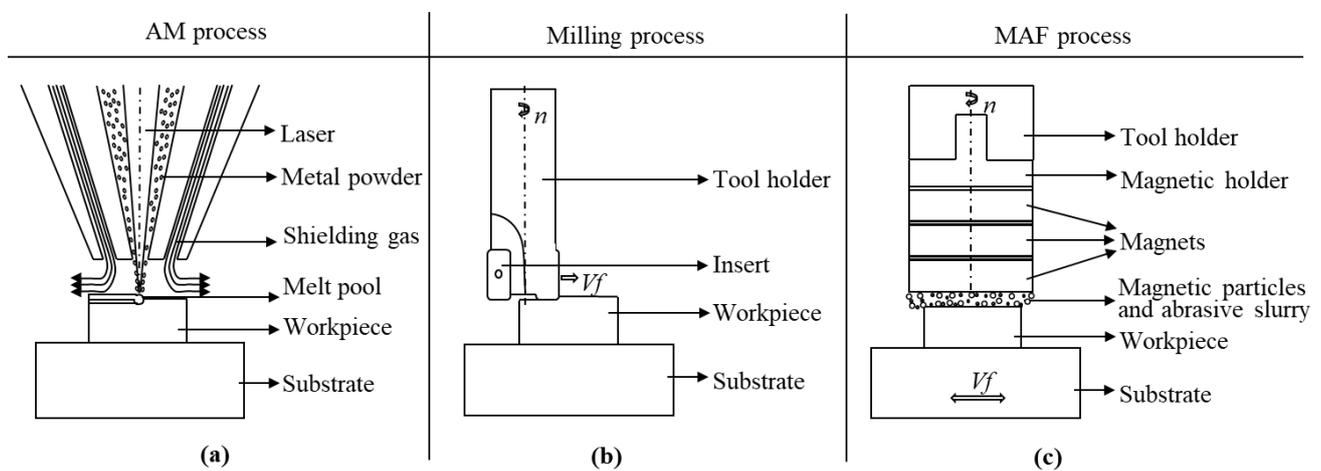


Figure 1. Sequence of manufacturing processes: (a) DED-AM, (b) milling, and (c) MAF.

AISI 316L stainless steel was the material (powder), and AISI 1020 was the substrate. The powder was atomized gas produced by LPW Technology, of predominantly spherical shape and 30 - 120 μm size distribution. Table 1 shows its chemical composition.

Table 1. Chemical composition of 316 L SS powder (LPW Technology, 2017).

Element	C	Cr	Cu	Mn	Mo	N	Ni	O	P	S	Si
% in mass	0.03	17.50-18.00	0.05	2.00	2.25–2.50	0.10	12.50–3.00	0.10	0.02	0.01	0.75

Workpieces shaped as rectangles of 15 x 15 x 5 mm were deposited on a module 250 5-axis BeAM machine, using a Zig-Zag deposition strategy (see Table 2 for the deposition parameters). A coaxial nozzle was used with argon gas to protect the lens, transport the powder, and protect the melt pool, at 3, 3, and 6 l/min flow rates, respectively.

After DED, end milling was carried out by a Romi D800 Hybrid machining center with a two-insert end mill of R390 - 11 T3 08M - PL 1130 code. Table 2 shows a summary of the experimental parameters. All cuts were performed with Vasco™ 6000 cutting fluid (6% concentration), a bio-based semi-synthetic miscible in water. Three different cutting speed values, namely $V_c = 300, 400$ and 500 m/min with same chip load, f_z , in mm/tooth were the parameters for end milling. Hereafter, the parts machined under those conditions will be referred to as M300, M400, and M500, respectively. After the milling tests, the best cutting condition was selected and only the aforementioned parts were subjected to MAF operation.

The MAF process was conducted with a mixture of iron particles and abrasive slurry (alumina paste with oil). Three 22 mm diameter, 10 mm thick Nd-Fe-B magnetic were attached to the magnet holder, which was fixed to the main spindle

rotating at 500 rpm. Besides rotation, the MAF head moved on the machine's X-axis at $V_f = 60$ mm/min, and the clearance between the magnet and the workpiece surface was kept at 2 mm. The magnetic flux density in the clearance was 544 mT – such value was measured at the center of the magnetic and evaluated by a gaussmeter (model TLMP-HALL-15k, MagTek brand). Each sample was processed at 5, 10, and 15 min finishing times. Hereafter, the parts finished under those conditions will be referred to as MAF5, MAF10, and MAF15, respectively. After the MAF process, the workpieces were cleaned for 5 min in an ultrasonic cleaner with isopropyl alcohol. Table 2 shows a summary of the experimental parameters, whose choice aimed at good geometric and surface characteristics during DED and post-processing towards reaching the minimum roughness values possible in each step.

Table 2. Experimental parameters.

Process	DED		End milling		MAF	
Constant parameters	Laser power (P)	300 W (Nd:YAG*)	Feed rate (V_f)	7.5, 10 and 12.5 mm/min	Magnet	3 Nd-Fe-B (N52): Ø 22×10 mm
	Laser spot diameter	0.8 mm	Feed per tooth (f_z) [feed (f)]	0.008 mm	V_f	60 mm/min (displacement 20 mm)
	Focal distance	3.5 mm	Depth of cut (ap)	0.1 mm	Rotation	500 rpm
	Overlap (Δxy)	0.5 mm	Lubricant	Vasco 6000 cutting fluid (bio-based semi-synthetic), 6%	Magnetic particles	Iron particle (60 µm mean dia.), 4 g
	Height (Δz)	0.2 mm			Abrasive	Al ₂ O ₃ (0.05 µm mean dia.), 0.5 g
	Feed rate (V_f)	2000 mm/min			Lubricant	Hydraulic oil, Hydra XP 32 - 3 ml
Variable parameters	Gas	Argon (nozzle and carrier gas 3 L/min and shield gas 6 L/min)	Cutting speed (V_c) [rotation (n)]	300, 400, and 500 m/min (4774, 6366, and 7985 rpm)	Workpiece-magnet clearance	2 mm
		-			Finishing time	5, 10, and 15 min
Referred as	DED		M300, M400, and M500		MAF5, MAF10, and MAF15	

*Neodymium-doped Yttrium Aluminium Garnet (Nd:YAG).

The surface morphologies of the samples were assessed under a confocal microscope (Olympus LEXT 4100) with a 20x magnification objective lens (evaluation area of 641 x 642 µm²). After the DED and milling processes, the surface roughness R_a (average roughness) and R_z (average of the five largest peaks and valleys) were measured by a Talysurf 50 model Taylor Hobson roughness tester with a Gaussian filter and cut-offs according to ISO 4278 (ISO, 1997). Once the surfaces became smooth after the MAF process, their roughness was evaluated under a confocal microscope (Olympus LEXT 4100) with a 50x objective lens (evaluation area of 258 x 258 µm²). Five measurements randomly taken on the surface were averaged for each condition.

3. RESULTS AND DISCUSSION

Figure 2 displays the general aspects of the parts obtained after each sequenced manufacturing process. After DED, the contours of deposition beads were visible, and some voids and adhered powder were present on the surface, which after milling, showed typical cutting marks inherent to the process. Finally, after MAF, the surface had a mirrored appearance, with smoothed (and even removed) milling marks, qualitatively indicating the surface characteristics had been significantly changed through the sequence, thus, directly interfering with its functional performance.

Figure 3 shows images obtained by confocal microscopy after each manufacturing process. Figure 3 (a) displays non-fused powder grains adhered to the workpiece surface, commonly found after DED and that contribute to worsening the

surface quality. Voids were also detected on the surface, mainly in parallel and equally spaced (around 0.5 mm, the same value used for the overlap in X directions), and can be attributed to the lack of fusion between the deposition beads. Figure 3 (b) displays typical cutting tool marks left after milling, and Figure 3 (c) shows they have been removed and a new texture has arisen due to the abrasive-workpiece interaction, with fine directional patterns parallel to the abrasive sliding direction, in accordance with the literature (HASHIMOTO *et al.*, 2016).

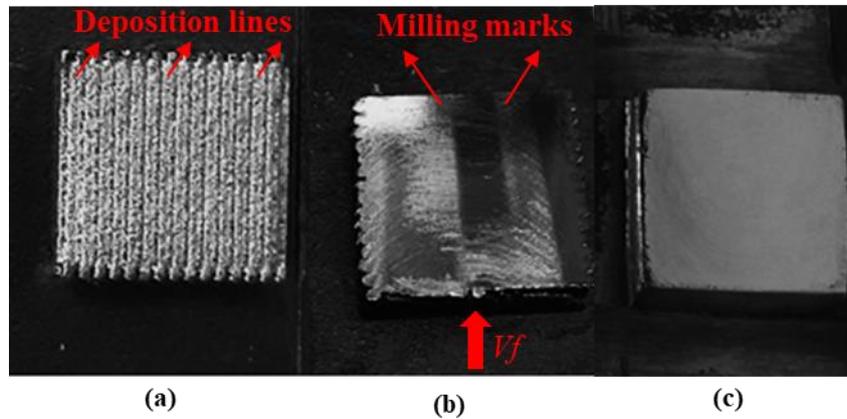


Figure 2. General aspects of the surfaces obtained; (a) DED, (b) milling (M300) and (c) MAF (MAF15).

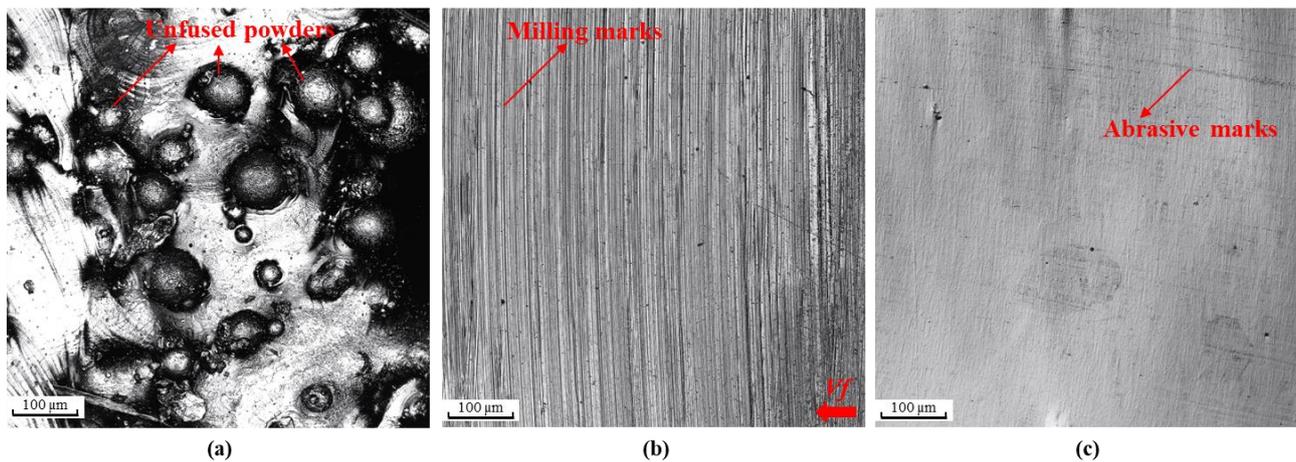


Figure 3. Surface morphologies obtained after each process (20x magnification): (a) DED, (b) milling (M300) and (c) MAF (MAF15).

Figure 4 shows the roughness values obtained after each process (DED; milling - M300, M400 and M500 at V_c of 300, 400 and 500 m/min, respectively; MAF - MAF5, MAF10 and MAF15 at 5, 10 and 15 min, respectively). R_a was reduced from 56.06 μm to 0.08 μm and 0.03 μm by M300 and MAF15, respectively, indicating an above 99% improvement. The R_z values were reduced from 248.80 μm to 0.56 μm and 0.24 μm , respectively, also showing an above 99% improvement.

The roughness results of the DED-ed parts were compatible with those reported by Huckstepp (2019). According to Gibson *et al.* (2015) and DebRoy *et al.* (2018), such high values are due to several factors, such as deposition beads morphology/geometry, balling phenomenon (liquid material does not adhere to the adjacent substrate because of surface tension), presence of non-fused powders adhered to the surface, among others.

During milling operations, increases in V_c caused a variation from 0.07 to 0.11 μm in R_a and from 53 to 0.73 μm in R_z , see Figure 4. Despite the presence of some edge marks, the values were provided at nanometer levels.

MAF also generated roughness at nanometer levels, with R_a between 0.03-0.05 μm and R_z between 0.23-0.24 μm . The roughness results are in agreement with the typical values reached by the process, as claimed by Hashimoto *et al.* (2016). Such low values represent the applicability of the process for the obtaining of low roughness levels and surpassing those achieved by milling. Above 15-minute processing time, the roughness reduction is small, and the process becomes inefficient for surface improvements. R_z remained constant during polishing, probably because the process had reached its limit, and the abrasive particles might have not reached the bottom of the deepest valleys.

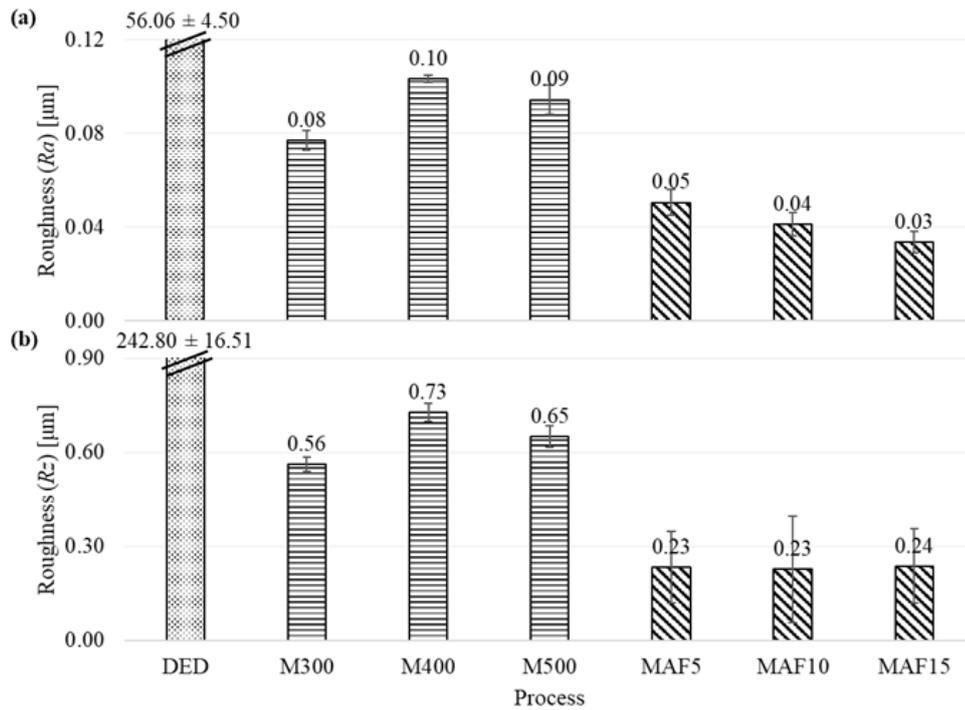


Figure 4. Roughness after each process: (a) Ra and (b) Rz .

Regarding the process sequence, the active processing time for the manufacture of flat surfaces by DED was 337.5 s, whereas for milling under the best condition (M300), the active machining time was 90 s. MAF required 900 s as the minimum time to reach such a roughness level, above which no significant surface improvement was achieved. Therefore, the optimal processing sequence took 1,327.5 s (approximately 22 min). Yamaguchi *et al.* (2017) used MAF to polish 316L SS surfaces made by Selective Laser Melting (SLM), and 240 min of processing time were spent on the reduction of Rz from 102.1 to 0.1 μm . The authors did not report the time spent on deposition. The Rz (242.8 μm) of the DEDed surfaces presented in this study are more than twice that of SLMed. Under the same processing conditions reported by Yamaguchi *et al.* (2017), approximately 330 min (5.5 hours) or more would be necessary for the achievement of the same surface quality, disregarding deposition time (see Figure 5).

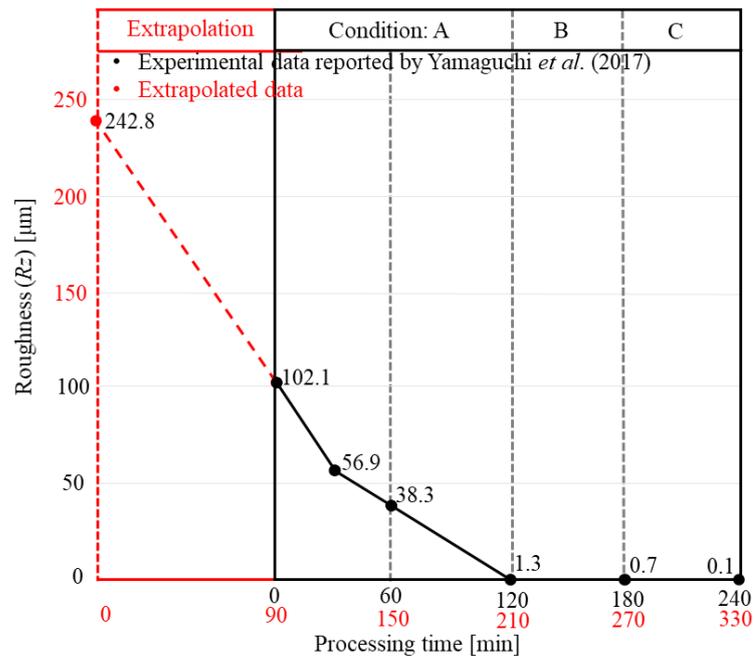


Figure 5. Extrapolation of MAF processing time for the surface made by DED in this study (adapted from Yamaguchi *et al.* (2017)).

Therefore, the achievement of low roughness values in shorter manufacturing times requires milling be used prior to a finishing process, since it has proven efficient in reducing the overall processing time and resulting in a more sustainable process chain of surfaces produced by AM technologies.

According to Nebot *et al.* (2012), a typical manufacturing sequence for medical applications (e.g., implants made of 316L SS) involves a forming process (forging, sintering, or casting), followed by machining processes (milling, turning, and grinding), and finishing ones (manual or automatic). Considering the time of manufacture of the initial component and the processing conditions, the traditional sequence may take a few days to be completed. On the other hand, the possibility of using AM to manufacture net-shape components can reduce the total processing time to hours, indicating an innovative way, since the manufacture of parts can meet all functional aspects required. Zhu *et al.* (2013) claimed processes undertaken simultaneously, or successively, in a single machine are considered hybrid, or combined. The use of Hybrid Machines, association of deposition capabilities with machining and polishing in the same equipment, and use of only one gripping position can improve the process. D800 Hybrid machine has a DED-head, therefore, all processes (DED, milling, and MAF) can be undertaken in a single machine by the current technology. Hybrid manufacture can optimize the production route as a whole, taking advantage of each process and saving costs, time, and space.

4. CONCLUSIONS

According to the results, the following conclusions can be drawn:

- Laser DED produced a rough and irregular surface, with $56.06 \mu\text{m } Ra$ and $242.80 \mu\text{m } Rz$, contributed by presence of adhered particles and bead profile.
- The irregularities of the outer layer were completely removed by milling, reaching values of $0.08 \mu\text{m } Ra$ and $0.56 \mu\text{m } Rz$; with typical cutting-edge marks on the surface. Milling reduced roughness to below 0.01% under the best cutting conditions, i.e. $V_c = 300 \text{ m/min}$, $f_z = 0.008 \text{ mm/tooth}$, and $a_p = 0.1 \text{ mm}$.
- Milling marks were removed by MAF, reducing Ra to $0.03 \mu\text{m}$ and Rz to $0.24 \mu\text{m}$ after 15 min of polishing time. Polishing times higher than that did not improve the roughness value significantly.
- The whole sequence time for the production of a polished surface by AM+milling+MAF was approximately 22 min. Compared to a research article in the manufacturing technology field, which was developed on similar material (obtained by SLM process) and with no milling, the time would be around 5.5 hours.
- Milling used as an intermediate post-processing step between deposition and finishing processes has proven efficient in reducing the overall processing time in the manufacturing sequence of parts obtained by AM technologies.
- Hybrid machines can improve the manufacturing sequence, saving time, resources and costs, and performing the whole sequence (AM+milling+MAF) in a same machine and with only one gripping position.

5. ACKNOWLEDGEMENTS

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