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Surface finishing of Additively Manufactured Aluminum parts through Fluidized Beds

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Abstract. This study investigates the potential of fluidized bed finishing (FBF) of square specimens manufactured via Laser-Powder Bed Fusion additive manufacturing technology. Rotation-assisted FBF tests are carried out for two different specimens materials, AlSi10Mg and AA6061 alloys using irregular steel abrasive particles as bed material. Experiments are performed with an average relative tangential speed between the exposed surface of the specimen against the abrasives of 2 m/s, while varying the tilt angle of the specimen. Results are reported and compared between the two materials in terms of finishing parameters like mean areal surface roughness, skewness and finishing process indicator. Results highlight that rotation-assisted FBF represents a viable finishing treatment for both the AlSi10Mg and AA6061 alloys. The tilt angle is a key operating parameter, as it allows to maximize sliding and shear. In particular, at low tilt angle the best results are obtained, with a reduction of surface roughness of 67% and 47% for AlSi10Mg and AA6061 alloys, respectively.

1. Introduction

Additive Manufacturing (AM) represents one of the most intriguing manufacturing processes to fabricate objects directly from CAD 3D models [1]. AM covers the production of complex, composite and hybrid structures with several advantages compared to traditional manufacturing technologies, such as rapid prototyping, design flexibility, high level of customization and high materials efficiency [2].

The most widespread AM technologies for metals, i.e. Laser-Powder Bed Fusion (L-PBF), Electron Beam-Powder Bed Fusion (E-PBF) and Laser Metal Deposition (LMD), use powders as the material feedstock [3]. One of the main reasons that hampers the expected high employment of these technologies is the high surface roughness of the as-built parts, due to the well known stairstep effect and the balling effect [4], resulting in rough surfaces with overhangs and sintered powders. For this reason, a consistent series of pre- and post-process operations are required to meet the desired final product specifications, as for instance, operations aimed at controlling the powder properties [5], post-process heat treatments to increase parts density and to achieve the desired microstructure [6], post-process surface finishing to improve the surface quality [7]. The most common finishing methods such as CNC machining, shot peening, electrochemical polishing and laser polishing have high limitations just for parts characterized by high geometrical complexity which represent the most promising objects achievable with Additive Manufacturing. In the field of finishing methods based on mechanical interaction, the Fluidized Bed Finishing (FBF) technology is gaining more and more attention. As the abrasive particles used are brought in the fluidized state, their subsequent interaction with the part leads to the desired surface re-modeling and roughness reduction [8,9]. Rotation-assisted fluidized bed finishing (R-FBF) proved to be more efficient in comparison to the case of the static dipping of the part into the fluidized abrasive, as it helps to establish the proper relative speed conditions between the part and the abrasives required for a satisfactory roughness reduction [10]. In this study R-FBF is investigated for flat square specimens produced by L-PBF. Two different specimens materials have been studied, namely AlSi10Mg and AA6061 alloys. Experiments are carried out with irregular steel abrasive particles, at fixed relative tangential velocity, while varying the tilt angle of the specimen. The experimental tests aim at investigating the effectiveness of the finishing process for different materials and the optimal operating parameters.

2. Experimental

2.1. Materials

The R-FBF experiments were carried out on square flat specimens (20 mm x 20 mm x 1.5 mm) produced through L-PBF orthogonally to the build platform and starting

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from AlSi10Mg and AA6061 powders supplied by EOS GmbH. The printing parameters for AlSi10Mg were the following: laser power P = 370 W, hatch spacing h = 0.19 mm, scanning speed v = 1300 mm/s and layer thickness LT = 30 μm, while for AA6061 specimens they were: Laser Power = 400 W; Scanning speed = 230 mm/s; Layer thickness = 30 μm; Hatch spacing = 110 μm.

Steel abrasive particles with irregular shape are used in this work as bed material, as their balance between density and hardness compared to the ones of the alloys to be processed proved to be effective in the smoothing of aluminum parts. The characteristics of the particles are: density equal to 4.2 kg/m^3, mean size 0.53 mm, d_{10}= 0.33 mm, d_{50}=0.57 mm, d_{90}=1.04 mm.

2.2. R-FBF apparatus and operating conditions

The experimental setup used for the FBF experiments is reported in Fig. 1 [10]. It consisted of a Plexiglas fluidization column (inner diameter 0.21 m) which comprises a windbox and an upper section, 1.4 m high, where the abrasive material was located. The fluidizing gas, technical air, was fed at the bottom of the windbox and flowed through a steel bubble caps plate acting as gas distributor to the fluidization section of the column. The carrier gas was controlled by a mass flow meter with a maximum operating flow rate of 45 Nm^3/h. The specimen clamping system was inserted into the column from the side and connected to an inverter-controlled electrical motor. The specimens were clamped on a custom fixture mounted on the motor rotation axis, that allowed therefore the rotation of the specimen as well as to fix its tilt angle.

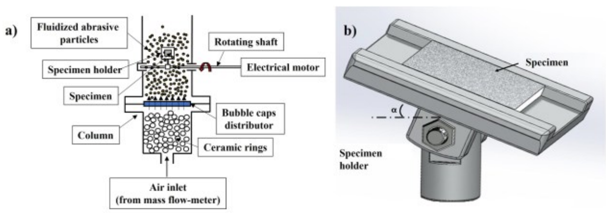

Figure 1. Scheme of the experimental apparatus used for the R-FBF experiments (a) with an inset of specimen positioning and tilt angle (b).

Experiments were carried out to investigate the effect of target inclination (α) on the finishing process during the rotation-assisted FBF tests at fixed average relative tangential speed (v) between the exposed surface of the specimen against the abrasives of 2 m/s. The bed was operated under incipient fluidization conditions and the processing time was fixed at 30 min for each test. The operating conditions and process parameters used in the experimental campaign are reported in Table 1.

Table 1. Process parameters and operating conditions used of rotation-assisted FBF experiments for both AlSi10Mg and AA6061 parts.

Tilt angle [°]	*v* range [m/s]	Process time min]
25	2±0.18	0.15
65	2±0.5	0.25
90	2±0.6	0.90

2.3. Characterization of the specimens

Before the R-FBF tests, the specimens were accurately cleaned in ethanol by means of an ultrasonic bath for 15 min and then dried at 80°C for 1 h. Before and after FBF tests, a quantitative description of the surface texture was obtained by confocal microscopy (Leica DCM3D). For each acquisition, an 8 × 8 mm^2 area was considered, taking the sample center as a reference point. The acquired surfaces were then post-processed to correct tilt errors, to fill the missing points and to extract the surface texture parameters by means of the software Leica Map® v7. In particular, the surface quality was analyzed through the following parameters, all defined by the ISO25178 and ISO4287 standards: the mean areal surface roughness, S_a; the areal skewness, S_{sk}; the root mean square of the primary profile slope, P_{dq}. Moreover, on the basis of the values of the parameter S_a, the indicator of finishing performance I_{fp} was considered, defined as the change of S_a during the finishing step divided by S_a of the untreated specimen. For the sake of repeatability, each evaluation was carried out on three specimens for each investigated condition.

3. Results and discussion

The comparison of the selected texture parameters before (NT) and after (T) the R-FBF experiments at fixed rotation speed and for different tilt angles of the specimen are reported in Table 2 and 3 for AlSi10Mg and AA56061 specimens, respectively. Mean values of the selected parameters are reported with standard deviation.

Table 2. Surface texture parameters of AlSi10Mg specimens (results are reported as mean ± σ).

	Tilt angle [°]	NT	T
S_a [μm]	25	21.7±1.1	7.2±0.2
	65	20.9±3.7	9.0±2.9
	90	19.7±0.6	11.9±0.4
Ssk	25	0.02±0.0	-0.89±0.04
	65	-0.01±0.13	-1.94±0.34
	90	-0.2±0.14	-1.66±0.2
Pdq [°]	25	36±3.2	9±3.1
	65	36±2.6	8±2
	90	34±2.8	12±2.6

Table 3. Surface texture parameters of AA6061 specimens (results are reported as mean ± σ).

	Tilt angle [°]	NT	T
S_a [μm]	25	9.4±1.1	5.0±0.8
	65	8.8±0.7	5.3±0.8
	90	9.3±0.9	7.1±0.6
Ssk	25	0.39±0.21	0.15±0.39
	65	0.82±0.3	-0.15±0.30
	90	1.35±0.11	0.09±0.08
Pdq [°]	25	7.2±2.2	2.7±0.1
	65	7.3±2.6	2.9±0.2
	90	7.9±3.6	4±0.9

Results showed an appreciable and robust improvement of all the surface quality parameters for both the materials, even considering the chemical composition and the texture parameters of the untreated specimens were very different for the two alloys. In fact, for AlSi10Mg specimens initial S_a was around 20 μm, while for AA6061 specimens initial S_a was around 9 μm. Also P_{dq} values of the untreated specimens were very different, around 36° and 7.5° for AlSi10Mg and AA6061 specimens, respectively. The best results were achieved when adopting a tilt angle of 25°, for which sliding and shear between the specimen and the abrasive bed material are maximized. In fact, under these operating conditions, all the investigated texture parameters were remarkably improved. Instead, for the 90° angle condition, the smoothing ability of the abrasives decreased significantly.

Results in terms of the finishing parameter I_{fp} are reported in Figure 2 as a function of the specimen tilt angle for both the materials, AlSi10Mg and AA6061. Data showed that for a small tilt angle maximum values of I_{fp} are obtained, i.e. around 67% and 47% for AlSi10Mg and AA6061 materials, respectively. This result confirms that, although the two alloys are very different, being AlSi10Mg a more brittle material, while AA6061 a more ductile material, R-FBF can be still effective, especially using small tilt angles, i.e. maximizing sliding and shear.

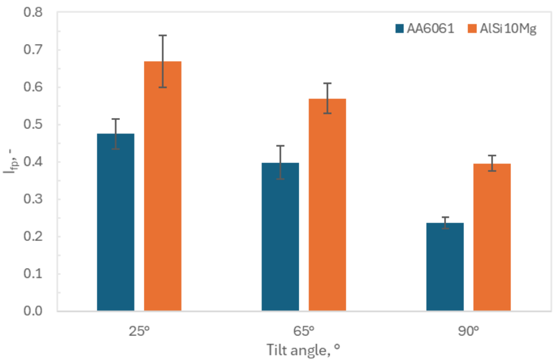

Figure 2. Surface finishing parameter I_{fp} as a function of the specimen tilt angle for AlSi10Mg and AA6061 alloys.

4. Conclusions

Rotation-assisted Fluidized Bed Finishing (R-FBF) of specimens manufactured by the Laser-Powder Bed Fusion (L-PBF) AM technology has been investigated under a variety of operating conditions. Two different specimens materials were considered, AlSi10Mg and AA6061. The effectiveness of R-FBF has been assessed, as a function of the nature of the abrasive material and of the tilt angle of the specimen with respect to the prevailing motion of the fluidized particles, at fixed mean relative tangential speed of 2 m/s between the surface and the abrasives.

Results confirm R-FBF is an effective treatment aimed at improving the surface texture parameters of metal parts made through AM. In particular, for both the specimen materials and regardless of the initial values of texture parameters, surface finishing depends on the orientation of the specimen with respect to the prevailing flow of the fluidized particles. Surface finishing is maximized when plain shear flow of fluidized particles is established close to and past the specimen. In fact, for tilt angle equal to 25° a surface roughness reduction of 67% and 47% was achieved for AlSi10Mg and AA6061 materials, respectively.

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