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Rotation-assisted Abrasive Fluidised Bed Machining of AlSi10Mg parts made through Selective Laser Melting Technology

Andrea El Hassanin[a,]*, Maurizio Troiano[a], Fabio Scherillo[a], Alessia Teresa Silvestri[a,b], Vincenzo Contaldi[a,c], Roberto Solimene[d], Fabrizio Scala[a], Antonino Squillace[a], Piero Salatino[a]

[a]Dept. of Chemical, Materials and Industrial Production Engineering (DICMAPI), University of Naples Federico II, Piazzale Vincenzo Tecchio 80, 80125, Naples, Italy
[b]University of Bergamo, Bergamo, Italy
[c]MBDA Italia S.p.A,, Via Carlo Calosi 1, 80070, Naples, Italy
[d]Combustion Research Institute (IRC), National Research Council (CNR), Naples, Italy

* Corresponding author. Tel.: +39-339-1464823. *E-mail address:* andrea.elhassanin@unina.it

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Abstract

Poor surface quality represents one of the most critical drawbacks of metal parts produced by powder bed-based Additive Manufacturing (AM) technologies, such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM). Among the several post-process surface finishing treatments, Fluidised Bed Machining (FBM) could represent an intriguing and cost effective option for the treatment of complex AM metal parts. This work illustrates the results of the preliminary tests carried out by means of the FBM technology in which an external contribution of rotational speed of the samples was introduced. Rotation of the samples was considered in order to increase the relative speed and energy dissipation between the parts and the fluidised abrasive particles, with the aim to increase the process efficiency in terms of surface roughness reduction. For the experiments, AlSi10Mg alloy square flat samples were built in vertical direction by means of SLM technology and dipped into an abrasive fluidized bed of silica sand. The preliminary tests were carried out by adopting a minimum fluidization regime of the abrasives and establishing, through the rotation of the samples, two values of mean superficial tangential speed of 1 m/s and 2 m/s. The effect of the latter was investigated in combination with different impact angles, considering a process time of 30 min. The surfaces were characterized quantitatively by means of confocal microscopy and weight loss measurements, while SEM images were acquired in order to observe the real morphology evolution after the treatment. The experimental results suggested a slight surface modification and roughness reduction for the investigated FBM process conditions, due to a low energy transfer from the abrasives to the surfaces. On the other hand, the results shown also that a greater surface smoothing effect was achieved when increasing the tangential speed and adopting low impact angles.

Keywords: Selective Laser Melting, AlSi10Mg, Fluidised Bed Machining, Roughness analysis, Surface finishing

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1. Introduction

It is well established nowadays that Additive Manufacturing (AM) represents one of the most intriguing manufacturing processes family on the actual market [1]. Given the high design flexibility, the wiser usage of materials and the very tunable physical and mechanical properties, AM could represent the starting point for a remarkable change in the traditional manufacturing contexts based mainly on material subtraction processes [2]. Although AM technologies belong to the near net shape processes family, a consistent series of pre and post-process operations are required to meet the desired final product specifications [3,4]. In this context, the post-process surface finishing step represents a fundamental operation that is needed to achieve a satisfactory surface quality [5], representing very often also a high cost operation when

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carried out manually and leading to a not reliable and repeatable output. All these considerations are particularly true when considering metal AM processes, among which the ones based on powder feedstock as the raw material, i.e. Selective Laser Melting (SLM) and Electron Beam Melting (EBM) technologies, are the most sensitive to the mentioned surface quality issues [6]. More specifically, the phenomena that contributes to the high surface roughness of the parts are two: the *stair-step effect* and the *balling effect* [7]. Therefore, the resulting surface is characterized by a random texture, caused by the sintering of loose particles, that is unacceptable for most of the applications of the final parts. Among the several techniques that are currently available [8], Fluidised Bed Machining (FBM) represents a very intriguing option for the treatment of complex parts [9, 10]. Moreover, according to some process considerations and experimental results reported elsewhere [11,14], the process efficiency could be increased when a rotation of the part is introduced, allowing at the same time the adoption of less turbulent fluidisation regimes - that would lead otherwise to the need for more complex reactors - as well as the reduction of the process time. With this premise, in this work are reported the results of the preliminary FBM experiments in which the combined effect of sample rotation and impact angle were considered as the main process variables. More specifically, the influence of two values of average tangential speed of the abrasive particles was investigated, the latter represented by silica sand particles with high hardness and low density.

2. Materials and Methods

2.1. AlSi10Mg samples and FBM experimental setup

In order to investigate more easily the effects of the process variables considered, the FBM experiments were carried out on 20 x 20 x 2 mm^3 square flat samples (fig. 1), made by means of SLM technology and using one of the most widespread materials: the AlSi10Mg aluminum alloy. The samples were manufactured in collaboration with MBDA Italy S.p.A. by means of an EOS EOSINT M280 SLM machine. The samples were built in the vertical direction with respect to the building platform, using the process parameters provided by EOS GmbH for the considered material (*EOS Part Property Profile AlSi10Mg Speed 30 μm*) employed in other experiments reported elsewhere [15]. The SLM process for the production of the samples was carried out starting from the AlSi10Mg powders feedstock provided by EOS GmbH, with an average particle size of 30 μm. After the SLM process, the samples were stress relieved at 300 °C for 2 hours. Subsequently, the manufactured samples were treated by means of the FBM process, using the Plexiglas reactor illustrated in fig. 2. The latter was composed by two modules, with a total height of 1440 mm and an inner diameter of 206 mm, and equipped with a purposely made samples fixture that allowed to fix the impact angle at any desired value as well as to rotate around the horizontal axis. The rotation of the clamping system was provided by means of an electrical motor regulated by an inverter. In the lower module, the carrier gas flow rate (air) is homogenized by means of ceramic rings, before passing to the upper module through a bubble caps metal distributor. The latter has the function to hold the abrasive particles in stationary conditions as well as to allow their fluidisation when the superficial gas speed acting on them is increased.

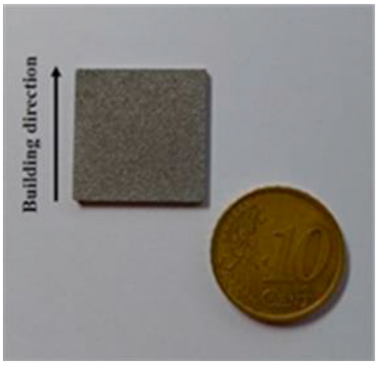


Fig. 1. AlSi10Mg sample made through SLM used for the FBM experiments.

Fig. 2. Plexiglas reactor used for the FBM experiments, with a detailed image of the samples clamping system placed inside (abrasives not present).

For the experiments, irregular shaped silica sand particles were used as the abrasive (avg. size: 570 μm, Vickers Hardness: 900 HV, apparent density: 2,57 Kg/dm^3), kept in the minimum fluidisation regime by means of a superficial gas speed acting on the particles of 0,2 m/s. As stated before, the experiments were carried out considering the introduction of a rotation of the sample inside the fluidised bed, whose impact speed component is prevalent with respect to the value provided by the fluidisation itself. The sample rotation determines a specific sample/abrasive interaction, distinguished by a prevalent sliding of the abrasives on the surface, promoting the material removal through superficial shear stresses [11]. On the other hand, the tangential speed of the particles on the surface is a function of the punctual distance of the sample from the rotation axis as well as of the specific impact angle considered (in this work, 25°, 65° and 90° with respect to the horizontal position were considered). Therefore, based on the eq. 1 that correlates the tangential speed (v) with the distance from rotation axis (b) and the rotation speed provided by the electrical motor (ω), two values of average tangential speed were considered, i.e. 1-2 m/s. In table 1 are reported the process parameters adopted to establish these two values, considering a process time of 30 min for each experiment.

$$v = \frac{2\pi \cdot \omega \cdot b}{60} \tag{1}$$

Table 1. Rotation-related process parameters used for the FBM experiments.

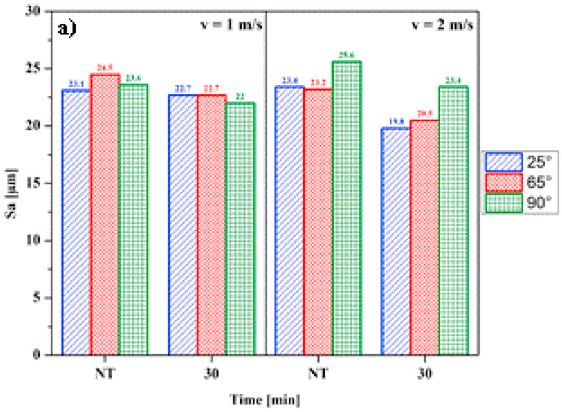
Impact angle [°]	b [mm]	ω [rpm]	
		v = 1 m/s	v = 2 m/s
25	43 ± 4,2	222	444
65	37 ± 9,1	258	516
90	32 ± 10	299	597

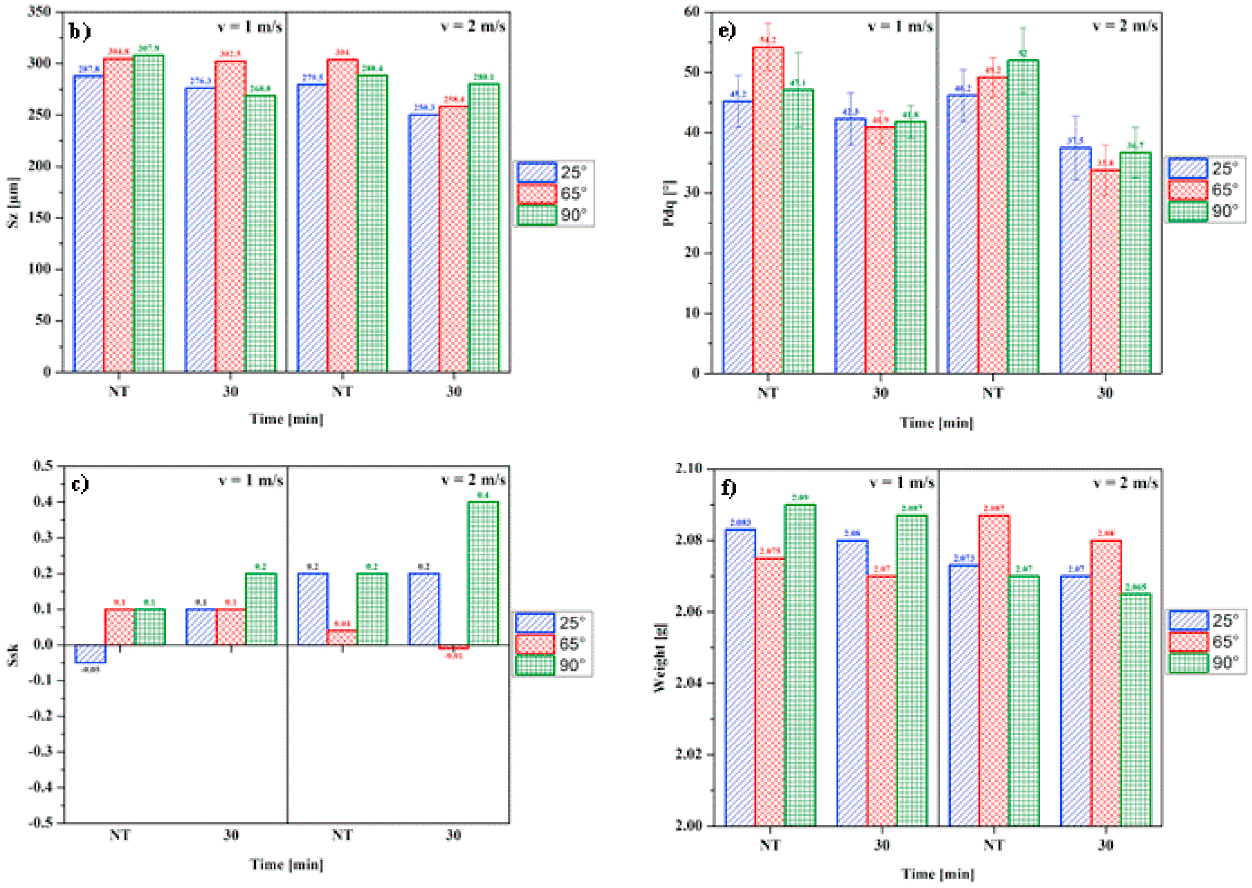
2.2. Characterization tests

Before and after the FBM treatment, the samples were characterized in terms of quantitative and qualitative surface modification analyses, as well as in terms of weight loss. Before any characterization test, an accurate cleaning of the samples was carried out by means of an ultrasonic bath in ethanol, followed by drying at 80 °C for 1h. Surface analyses have been carried out by means of Scanning Electron Microscopy (Hitachi TM3000 SEM) and Confocal Microscopy (Leica DCM3D confocal microscope). SEM images were acquired from the surface exposed to the treatment to perform a qualitative morphological evolution analysis. Confocal Microscopy was employed for a quantitative analysis of the surface modifications, by means of the extraction of different surface texture parameters. From the center of each sample, an 8x8 mm^2 acquisition area was considered for the analyses, on which tilt correction and fill of missing points operations were performed. Regarding the surface texture parameters, S_a (mean areal roughness), S_z (maximum areal peak-valley distance), S_{sk} (areal skewness) and S_{ku} (areal kurtosis) were investigated according to ISO 25178-2 standard [16]. In this context, S_a and S_z represents the more common texture parameters for the evaluation of surface quality, whereas S_{sk} and S_{ku} parameters are very useful to determine the symmetry degree of the surfaces and the sharpness of the peaks/valleys respectively. Moreover, P_{dq} (primary profile root mean square slope) was considered according to the ISO 4287 standard [17]. Based on the average and standard deviation values acquired from ten profiles, five for each of the two directions that identifies the sample geometry, this parameter represents a useful indicator that could be related to the removal of the sintered powders that characterizes the SLM processed surface, since lower values indicates a greater smoothness and brilliance of the examined surface.

3. Results and Discussions

In fig. 3a-f are reported the time evolutions of the chosen surface texture parameters and the weight loss, as a function of the impact angle of the abrasives on the surface and average tangential speed mentioned in the previous section. From the observation of the evolution of S_a and S_z it can be observed that, generally speaking, the roughness reduction induced by the treatment is limited. Moreover, based on this observation, the reliability of the quantification of the benefits induced by the FBM process is hampered by the different starting roughness values of the samples, caused by the sintering of powders with different sizes on the surface. On the other hand, it can be observed also that the increase of the average tangential speed from 1 m/s to 2 m/s leads to more appreciable results, a process condition in which a clear influence of the impact angle emerge, suggesting the 25° impact angle as the best case. For the latter, the reductions of S_a and S_z are of 4 μm and 30 μm respectively. The evolution of S_{sk} suggests that the symmetry of the surface is poorly altered by the treatment, whose variation is never greater than 0,2 points regardless of the specific impact angle or the tangential speed value, whereas S_{ku} presents a slight trend of increase of the values after the treatment. Finally, P_{dq} shows a more clear trend of reduction for all the investigated process conditions and, according to similar considerations done for S_a and S_z, the major reductions (approx. 13°) were observed again for the 25° impact angle. However, all these results could be justified considering the low impact energy transferred to the surface in the investigated process conditions. More specifically, whether if the relative speed between the surface and the abrasives is achieved through the fluidisation of the abrasives or the rotation of the sample, the low density of the abrasives used does not provide a sufficient impact energy transfer to the surface. Consequently, the desired surface modification is slightly promoted, with a poorer surface roughness reduction. Referring to the impact angle, the best case of 25° could be justified by the major shear stresses experienced by the surface impinged by the particles, due to a longer sliding path compared to the other impact angles investigated. This premise leads to an enhanced surface modification, as observed for the more consistent reduction of S_a and S_z. On the other hand, the increase of the impact angle towards 90° enhances the contribution of normal impacts of the abrasive particles on the surface that, combined with the low impact energy possessed by the latter due to the low density and the minimum fluidisation regime, leads to poorer surface modifications.





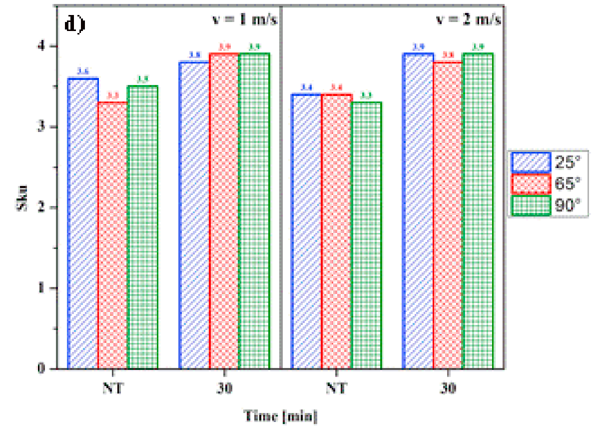


Fig. 3. Evolution of the surface texture parameters and the weight loss, used to quantify the surface modifications induced after the FBM treatment as a function of the average tangential speed and the impact angle. (a) Sa, (b) Sz, (c) Ssk, (d) Sku, (e) Pdq, (f) weight loss. (NT = not treated).

The results obtained by the quantitative analysis carried out by means of confocal microscopy were also in agreement with qualitative morphology evolution analysis conducted by means of SEM. In fig. 4 are reported in comparison the SEM images that illustrates the typical morphology of an untreated sample and the resulting actual surfaces after the treatment, considering the different impact angles and an average tangential speed of 1 m/s. With the same comparison aim but for the higher tangential speed value of 2 m/s, in fig. 5 are also reported the SEM images before and after the treatment. The morphology evolutions suggests that the impinging particles under the different process conditions promoted a slight removal of the sintered particles on the surface of the samples, supporting the considerations done before about the low impact energy transferred to the surface by the abrasive particles. The results are also in agreement with the previous observations about the influence of the tangential speed and the impact angle discussed before, as well as with the weight loss trends observed in fig. 3f, suggesting a very slight reduction that indicates a narrow material removal rate.

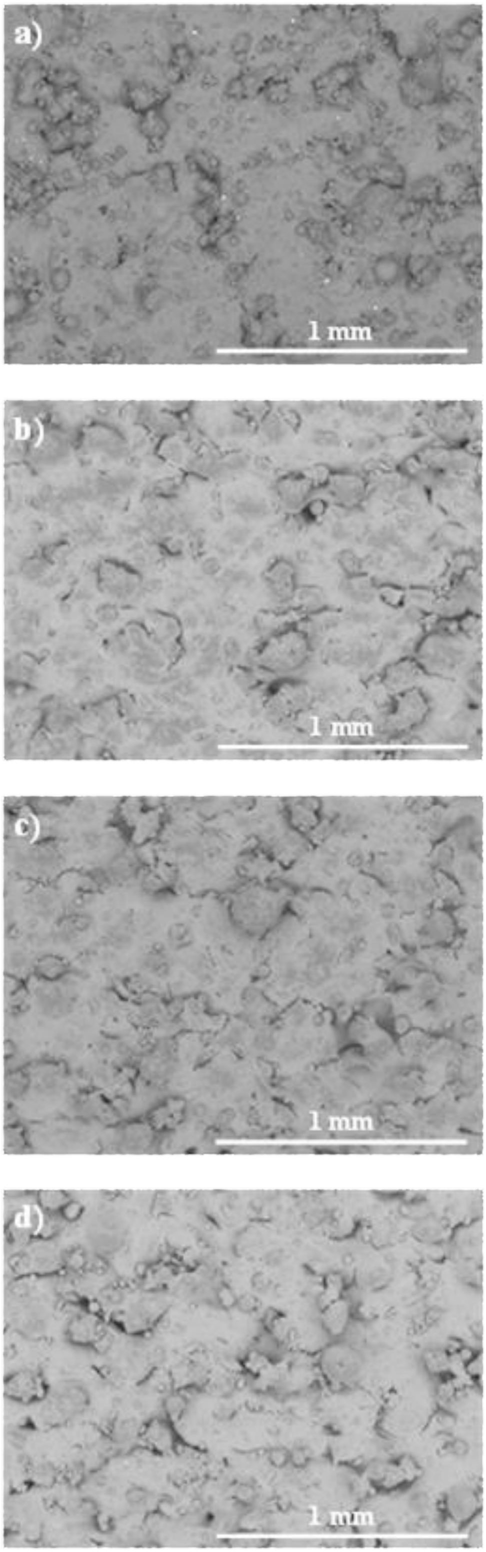


Fig. 4. Comparison between SEM images before and after the FBM treatment with an average tangential speed of 1 m/s. (a) untreated sample, (b) 25°, (c) 65 °, (d) 90°.

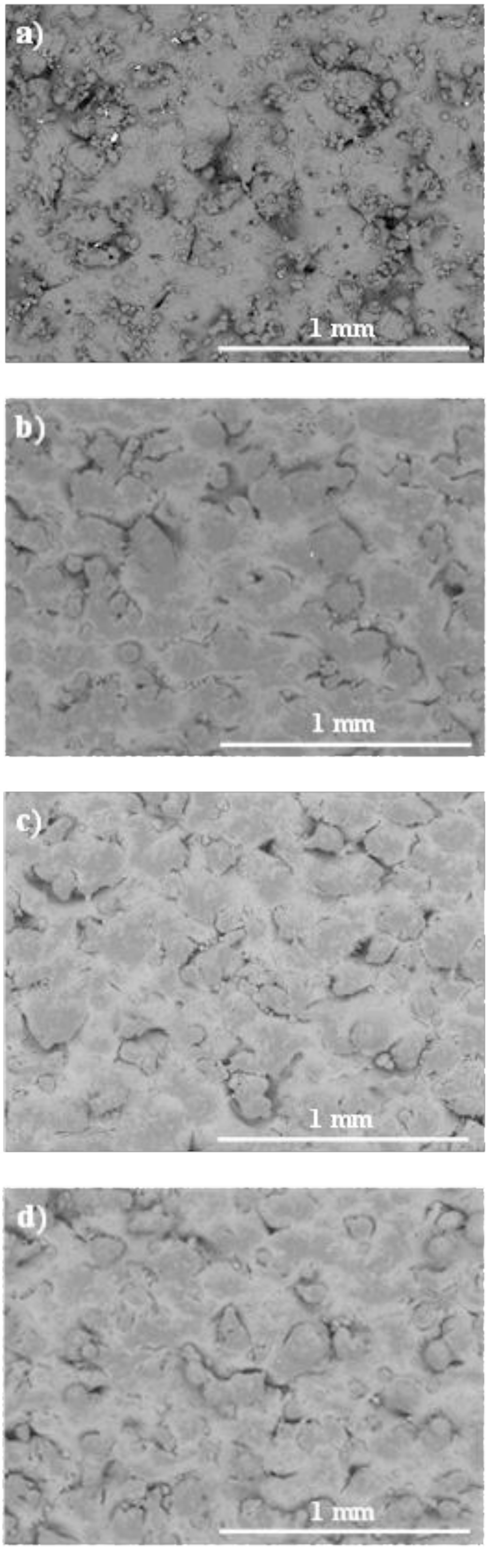


Fig. 5. Comparison between SEM images before and after the FBM treatment with an average tangential speed of 2 m/s. (a) untreated sample, (b) 25°, (c) 65 °, (d) 90°.

Moreover, according to the previous observations, it can be noted that the surface morphology laying underneath the sintered powders (not completely removed) remains unaltered, representing a further proof of the low impact energy transferred to the surface in the investigated process conditions. More specifically, the latter aspect indicates that the plastic deformation of the sample under the effect of the impinging particles is negligible, as observable from the slight peening effect experienced by the residual sintered powders on the surface. Furthermore, the surface is also characterized by the presence of several craters and undercuts caused by the build up of the sintered powders due to the balling effect, that represents a further contribution that leads to a more difficult evaluation of the real surface texture by means of the investigated parameters.

4. Conclusions

Based on the experimental results obtained from the rotation-assisted abrasive FBM of AlSi10Mg parts made through SLM technology, the following conclusions can be drawn:

- In relation to the process parameters fixed and investigated, an appreciable but limited reduction of the surface roughness was provided (approx. 20% for the best case). This result, observed mainly by the evolution of S_a and S_z, could be ascribable to the low density of the silica sand abrasive particles used for the experiments that leads, regardless of the other process parameters, a low impact energy transfer to the surface under treatment. The latter point implies a slight surface modification by means of material removal and plastic deformation of the surface, as observed by the SEM analysis and mainly represented by a partial removal of the sintered powders present on the sample due to the balling effect. Moreover, the high hardness ratio between the AlSi10Mg aluminum alloy and the abrasive particles seems not to play a crucial role in relation to the aim of the surface treatment;
- The rotation of the sample inside the fluidized bed, that provides an increase of the relative speed with the impinging particles, enhances the process efficiency. More specifically, an appreciable increase of the surface roughness reduction was observed when the average tangential speed of the particles acting on the surface was increased from 1 m/s to 2 m/s. However, the surface roughness improvements are still slight taking into consideration the previous point;
- The impact angle of the abrasives on the sample, determined by the inclination of the latter with respect to the horizontal direction, represents a significant process variable, although its influence on the treatment efficiency is minor compared to the one mentioned in the previous point for the investigated process conditions. More specifically, the 25° value was found to be the most effective in relation to the major shear stresses experienced by the surface under treatment, due to the longer sliding path of the abrasive particles interacting with the surface. On the other hand, the 65° and 90° impact angles promotes a major contribution of normal impacts of the abrasive particles, whose contribution to the surface roughness improvements are low in consideration of the first point discussed in this section. Therefore, an important experimental outcome is represented by the greater process efficiency when shear is the prevalent interaction mechanism between the abrasives and the surface, established when low impact angles are adopted;
- The slight surface modification provided by the treatment under the different process conditions was also in agreement with the evolution of the other surface texture parameters investigated. More specifically, the slight variation of S_{sk} and S_{ku} as well as the reduction of P_{dq} are in agreement with the removal of the smallest sintered powders on the surface, leaving unaltered the surface morphology laying underneath. This result was also justified by the poor weight loss measured during the experiments.
- Based on all the previous points, in order to promote more consistent surface quality improvements, further investigations are needed with respect to some critical process variables: for instance, the choice of abrasives characterized by higher density than silica sand might lead to better results due to a more appreciable impact energy transfer, considering all the other process parameters fixed. Another option could be represented by the adoption of longer process times, for which it could be expected to reach very high surface quality.

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