Chapter 10
Machinability Study of Polymeric Parts Fabricated by Additive Manufacturing Under a Dry Milling Process

P. Arnés-Urgellés, J. Bayas, E. A. Ramírez, F. Maldonado, C. G. Helguero, and J. L. Amaya

Abstract Additive manufacturing (3D printing) is rapidly becoming a viable substitute into material subtraction processes due to the design flexibility it offers for complex parts fabrication. Being a relative novelty, meeting specific applications' requirements, such as dimensional tolerances and surface roughness, implicate an aggressive increase in fabrication costs. Machining of 3D printed parts is proposed by the authors as a method to attain these requirements. This study focuses on the influence of cutting parameters on the machinability of pieces produced by two different AM technologies: MultiJet Printing (MJP) and fused deposition modelling (FDM). All tests were performed on acrylonitrile butadiene styrene (commonly referred to as ABS), measuring improvement of surfaces' roughness as a machinability indicator and comparing it to injection moulded polyoxymethylene copolymer (POM) for reference purposes. With cutting speed, feed rate and cut depth as the process parameters, 13 terns were formed. Milling processes were executed on 30 x 30 x 10 mm block-shaped 3D prints and surface roughness values were obtained via a portable roughness tester. It was found that the most influential parameter was feed rate, consistently with previous studies conducted in metallic elements. Parts fabricated by FDM presented a higher machinability ratio when compared to MJP, with a value of 1.27. This is interpreted as a high machinability with respect to the reference material, proving that the surface of a 3D printed ABS part could be improved with post-fabrication machining.

Keywords Additive manufacturing · Post-process machining · Surface roughness · Machinability · Milling

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10.1 Introduction

Additive manufacturing (AM) of polymeric parts, commonly referred to as 3D printing, is considered a suitable prototyping tool given its low production time and geometrical restrictions when compared to traditional manufacturing technologies; nowadays, the development of this process has enabled applications to go beyond prototyping and into direct service (Levy et al. 2003). Unfortunately, the steep correlation between investment in AM equipment and mechanical finishing acts as a limitation factor when considering employing this manufacturing alternative for certain applications with restrictive dimensional and roughness requirements, for example, when printing parts for a mechanical coupling. To overcome this, the possibility of incorporating subsequent machining to the AM process of polymers was explored by the authors.

The combination of AM and traditional machining operations has been studied for metallic materials (Olivier et al. 2011; Kruth et al. 2005; Isaev et al. 2016; Konstantinos et al. 2015) which has gained special interest given that additive manufacturing technology has now further uses than prototyping (Olivier et al. 2011). This arrangement implies a cutback in waste material when compared to operations based solely on material removal. This results in a decrease in manufacturing time, energy consumption and feedstock, positively impacting environmental care and overall processes (Jeremy et al. 2015).

To establish the compatibility of both processes, it is necessary to consider the 3D printed polymeric parts' machinability. This term refers to the relative ease of a material to be machined under the appropriate tools and cutting conditions. The factors that have an impact on machining performance are the material's properties, the tool's geometry and the cutting parameters. There are different perspectives from which to analyse machinability, these being the amount of cutting force exerted, the wearing of the tool, or the surface's quality (Kalpakjian and Schmid 2014; Mills 2012; Seker and Hasirci 2006); but most published literature refers only to metals (Sikdar 2007; Thiele 1990; Nourredine et al. 2003), whose response to cutting conditions may not translate very well into polymers due to the properties differences. Prior studies conducted in metallic elements established that among the tested cutting parameters, feed rate was the most influential one (Gaitonde et al. 2008). For this purpose, the following study focuses on the influence of cutting parameters on 3D printed pieces, *i.e.* feed rate, spindle rotations and depth of cut, aiming to obtain the highest decrease on surface roughness.

To the authors knowledge, the only machinability index that refers to polymers was proposed by Davim & Mata for glass fibre reinforced plastic (Paulo Davim et al. 2008), which considers the specific cutting pressure and surface roughness, each with a weighing factor. However, due to the unavailability of referential work regarding machining of additive manufactured polymeric parts, the authors opted for a simplified approach that would allow the determination of a tendency or behaviour to be recognized in the present exploratory study. The proposed index considers a benchmark approach. The method consists in determining the machinability index

MI as the ratio between the surface roughness *Ra* of the base or reference material and the test material, as presented in Eq. (10.1). Values of *MI* greater than the unit refer to an increase of surface quality, and thus, an ease of the tested material to be machined. Accordingly, *MI* below the unit corresponds to materials that are more difficult to machine.

$$MI_{\text{test material}} = \frac{Ra_{\text{base material}}}{Ra_{\text{test material}}} \tag{10.1}$$

10.2 Materials and Methods

This section details the methodology followed to establish the machinability of 3D printed parts and consequently find the cutting parameters that provide an improvement to surface finish.

10.2.1 Equipment and Materials Set-Up

Among the different AM technologies, this study focuses on fused deposition modelling (FDM) and MultiJet Printing (MJP). Regarding the employed equipment, FDM processes were carried on in a 3DSystems Cube 3D printer and MJP process on a 3DSystems ProJet 3510 SD. Milling machining operations were carried on a ROLAND MDx-40A, 3-axis CNC milling machine, using a high-speed steel (HSS) end mill of 6 mm in diameter.

Even though a wide range of polymeric materials are used in additive manufacturing, acrylonitrile butadiene styrene (commonly referred to as ABS) was selected due to its commercial availability and compatibility with a wide range of 3D printers. Process parameters considered a layer thickness of 200 μm and 30–32 μm, for FDM and MJP, respectively. Due to the process characteristics, MJP pieces are considered solid (100% infill percentage), while FDM specimens were printed with a honeycomb internal pattern, resulting in a 10% infill percentage.

Since the chosen definition of machinability involves a base material as a reference, injection moulded polyoxymethylene copolymer (POM) was selected due to its machinability ease, similarity in hardness and applications to ABS, and commercial availability.

10.2.2 Optimal Conditions Determination

Given that thermoplastics are being subjected to machining, it is important to consider their low thermal conductivity, low elasticity modulus and the loss of rigidity with heat application; this translates into a need to use sharp cutting tools with positive attack angles to reduce the exerted forces, along with large relief angles, low feed rates and cutting depths and high rotational speeds (Kalpakjian and Schmid 2014).

10.2.2.1 Surface Roughness Measurement

Surface roughness values, both prior and post machining, were determined by a Phase-II SRG-4500 portable roughness tester. In accordance with the employed surface roughness instrument's measuring range, 30 x 30 x 10 mm block-shaped samples were designed; post-process cleaning was conducted, and dimensions were verified after the printing processes.

The workpiece was prepared by marking different reference points for testing; measurements were taken in three different points of each piece to obtain an average value. Roughness was measured in a cross and longitudinal route, relative to the cut feed direction; for each tern of cutting conditions, a replica was made for error calculation. Only specimens with errors below 10% were considered for further testing. Additionally, measurements of non-machined pieces were obtained for reference purposes.

10.2.2.2 Cutting Parameters Variation

Maximum values for feed rate, spindle speed and cutting depth were 2500 mm/min, 15,000 rpm and 0.175 mm, respectively. These conditions correspond to the milling equipment's limitations and the available literature on finishing processes (Benardos and Vosniakos 2003) given that the aim of this study was to reduce roughness. Decrements of 500 mm/min of feed rate were tested, as well as decrements of 2500 rpm for the spindle rotation and 0.025 mm for the depth of cut. Minimum considered values were 500 mm/min, 5000 rpm and 0.075 mm, for feed rate, spindle rotation and depth of cut, correspondingly.

Initially, feed rate was varied, setting rotational speed at the highest value and cut depth at its minimum, according to common cutting conditions in finishing operations. For each feed rate value, surface roughness was measured and plotted, aiming to identify a tendency and determining the value that would yield in the lowest roughness. Using said value, a second test considered a variation in spindle rotation, while maintaining a constant value of depth of cut and feed rate; similarly, resulting in the determination of an optimal rotational value (minimum roughness). Lastly, cut depth was varied and the prime value found following the same steps.

10.2.3 Machinability Index Development

To develop the machinability index, the base material's original roughness was measured, and the workpiece was machined using the determined optimal cutting conditions. With all the roughness values obtained, Eq. (1) was used and comparisons were made.

10.3 Results and Discussion

Prior to machining, it was found that the workpieces average surface roughness was 0.685 μm longitudinal and 3.325 μm cross-directional for MJP specimens. For the elements fabricated with FDM, the roughness tester presented an "out of range" warning, therefore the maximum measurable value of the instrument was assumed, this being 40 μm. For the control element of the base material Polytec 1000, values of 1.273 μm longitudinal and 1.524 μm cross-directional were obtained.

For the first phase of testing, the maximum rotation speed value (15,000 rpm) and the minimum depth of cut (0.075 mm) were set, as feed rate was varied from 500 to 2500 mm/min. As shown in Fig. 10.1a, the best surface roughness for longitudinal direction measurements was obtained for a feed rate value of 1000 mm/min in the FDM case, while for MJP the lowest surfaced roughness was obtained to the lowest feed rate value. In the cross-direction (Fig. 10.1b), both technologies were consistent with their results; the best surface finish was attained with the lowest feed rate value of 500 mm/min.

In the FDM case, there was a stagnation region between minimal and maximum tested values, from both longitudinal and cross-directional perspective; even though for the latter it was less perceivable. On the other hand, surface roughness on MJP is overall smaller than in FDM, especially for the cross-direction, which is attributed to the manufacturing process and technology accuracy; *i.e.* MJP has lower printing

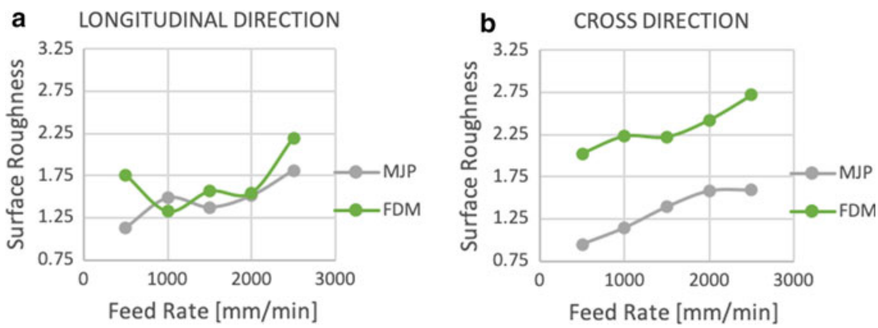

Fig. 10.1 Average roughness curve (Ra) versus feed rate for each 3D printing technology. **a** Longitudinal direction data. **b** Cross-direction data

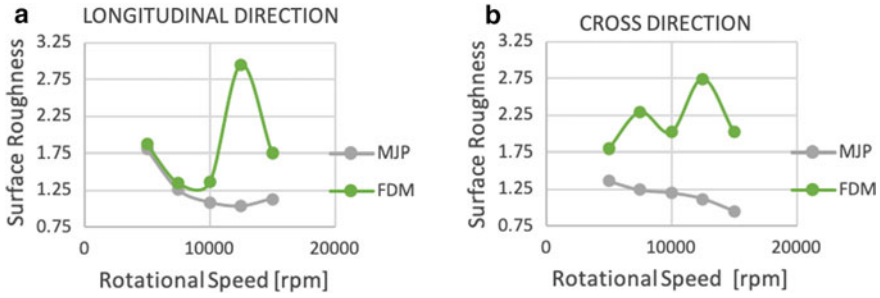

Fig. 10.2 Average roughness curve (Ra) versus rotational speed for each 3D printing technology. **a** Longitudinal direction data. **b** Cross-direction data

tolerances and delivers a solid workpiece, whereas FDM's plastic filaments are observable.

For the second phase of the test, a feed value 500 mm/min and a depth of cut 0.075 mm were set, while spindle speed was varied. In Fig. 10.2a, MJP showed steady variations, and even though the lowest surface roughness corresponds to 12,500 rpm, the relative variation with the 15,000 rpm test is of 8.85%; additional data need to be collected to determine if there is a stagnation region or if roughness will decrease even further. As Fig. 10.2b depicts, for MJP the highest rotation speed value of 15,000 rpm yielded an optimal surface roughness. However, FDM technology evidenced optimal surface roughness at the lowest tested rotational speed, 5000 rpm, even though the exposed behaviour was not consistent enough to predict the response to other values.

In the third phase of the test, the depth parameter was varied, and the feed rate and spindle values were constant. Here, deviations were made with respect to the initially established methodology; the original range for depth was of 0.075 to 0.175 mm, but upon noticing the forming tendency the authors decided to move said range to 0.050–0.150 mm in an attempt to see if surface roughness would decrease even further.

As presented in Fig. 10.3a, for the data obtained in a longitudinal direction relative to the feed route, for both technologies the lowest surface roughness corresponds to the lowest depth tested. For cross-directional data (Fig. 10.3b), however, MJP showed that for the smaller depth (0.05 mm) a certain surface roughness value (1.122 µm) was obtained; then, as depth was augmented, roughness decreased to a minimum and subsequently commenced a gradual increase which sustained for the rest of the tested depths. For the case of printing by FDM, it was not possible to observe a strictly increasing behaviour, albeit it was determined that the best surface finish occurred at the lowest depth, being consistent with longitudinal data.

For the testing of the Polytec 1000 base material, the combination of cutting parameters that generated the best surface roughness for each 3D printing technology tested was used. Table 10.1 shows the lowest roughness values obtained for MJP and FDM along with the base material's results obtained when machined with

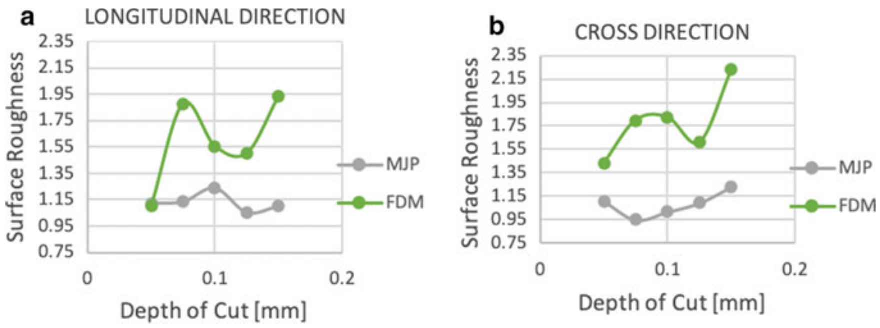

Fig. 10.3 Average roughness curve (Ra) versus Depth of cut for each 3D printing technology. **a** Longitudinal direction data. **b** Cross-direction data

Table 10.1 Average roughness (Ra) of materials under optimal cutting conditions

	Longitudinal direction (μm)	Cross-direction (μm)	Average (μm)
MJP	1.123	0.949	1.0362
POM under MJP cutting conditions	0.565	0.831	0.6980
FDM	1.099	1.432	1.2653
POM under FDM cutting conditions	1.792	1.416	1.6040

the respective optimal cutting conditions. An average is calculated among longitudinal and cross-direction in an attempt to obtain a more accurate representation of the workpiece's topology. It is possible to notice that MJP's average roughness is surpassed by FDM's, but the contrary is true for their correspondingly machined base material; POM under MJP cutting conditions' average roughness is lower than the case for FDM.

Using Eq. (1), a milling machinability index of 0.67 and 1.27 was obtained for MJP and FDM printing technology, respectively. According to what was established, this would translate into MJP workpieces having a higher roughness than the base material when machined under the same conditions, *i.e.* worse output with the same input, while FDM specimens presented a better response than the base material to the same cutting conditions.

It is important to notice that even after machining, MJP produced pieces maintained a lower surface roughness than FDM ones, however, the difference among these two was greatly reduced; initially FDM surface values could not be measured for they exceeded the instrument's range; therefore, the maximum was assumed which is 40 μm while MJP's was 2.005 μm; after milling, there was a relative variation of 18% among the two. FDM pieces had a greater improvement (38.7347) than MJP ones (0.9688), surpassing MJP's initial roughness when milled.

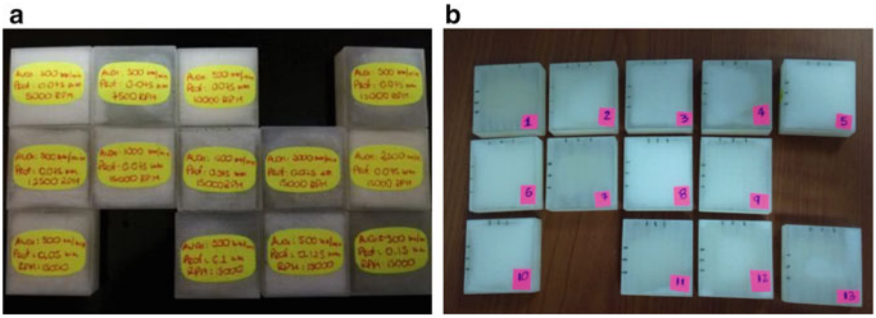

Fig. 10.4 MJP produced workpieces. **a** Before milling **b** After milling

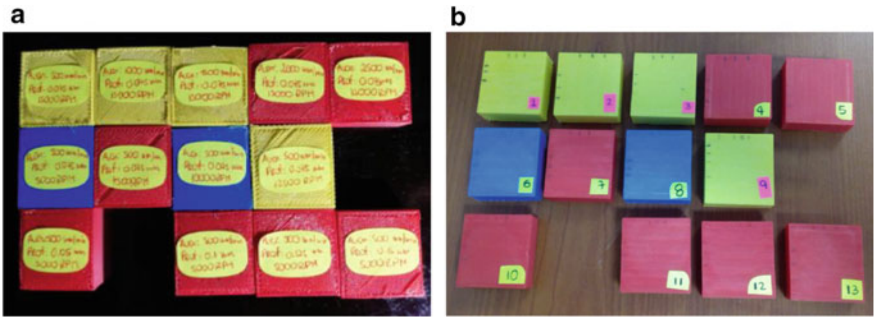

Fig. 10.5 FDM produced workpieces. **a** Before milling **b** After milling

Figure 10.4a and b shows the block-shaped workpieces prior and post-machining for MJP produced specimens, respectively. For every combination of parameters tested, a workpiece was marked accordingly. Visible changes were not perceived after performing the milling operations.

Figure 10.5a and b depicts the before and after machining workpieces produced by FDM printing technology. It is observable that the recently printed FDM workpieces had uneven surfaces, visible filaments clearly showing the printing direction, while after machining, the filament's orientation is less perceivable, and surfaces have an even finish.

10.4 Conclusions

In this exploratory study, it was possible to observe additive manufactured workpieces' responses when subjected to milling, a traditional machining operation. The tests were conducted in ABS blocks which were manufactured via two different technologies: MultiJet Printing (MJP) and fused deposition modelling (FDM). Both technologies showed compatibility with the milling process, since the workpiece's surface roughness was enhanced; however, FDM results yielded into bigger improvement, reducing over 38 μm in roughness, with the assumed initial roughness, given it exceeded the instrument's range. This was obtained by using a feed rate of 500 mm/min, 5000 rpm for spindle speed and a cutting depth of 0.05 mm; minimum feed rate, spindle speed and cutting depth tested. For MJP, the best surface roughness was obtain for a feed rate of 500 mm/min, a spindle speed of 15,000 rpm and a cutting depth of 0.075 mm; the variation achieved for this printing technology was of 0.9688 μm.

For the FDM, it is advised to measure roughness in more than one orientation given that the sensor-stylus radius is smaller than the plastic filament thickness, measuring in the same direction could result into the probe collecting skewed data, whereas a cross-sectional approach relative to the printing trajectory would ensure the probe's path not to be constrained by said pattern.

Among the considered cutting parameters, it was found that feed rate was the most influential one, consistently with previous studies conducted in metallic elements. This was concluded from the variability of the data; for spindle speed and depth of cut, the variation was relatively smaller than the response obtained for feed rate variations.

The milling machinability index obtained for MJP and FDM produced pieces was of 0.67 and 1.27, respectively. Recalling that the base material was assigned the unit as a reference value, this would indicate that MJP was less machinable than the POM, resulting in a higher surface roughness when exposed to the same cutting conditions. By contrast, FDM presented a better response than the base material, to the same parameters' arrangement.

The results would encourage an FDM workpiece to be machined if the implementation requires so, since the final FDM workpiece roughness even surpassed non-machined MJP pieces, this being 1.2653 μm and 2.005 μm, respectively. It would not be advisable to machine MJP workpieces for the improvement obtained is not considered relevant for the majority of applications. Functions such as mechanical couplings, assemblies, and elements subject to force transmission, according to material properties, would greatly benefit from the reduction of surface roughness using FDM technology.

As future work, the authors aim to obtain additional data in an attempt to develop equations that would describe a tendency so that behaviour of 3D printed polymers subjected to milling operations can be predicted. A more in-depth roughness analysis is also on the horizon for future works, incorporating surface roughness profiles and the workpieces integrity.

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