Post-processing treatments to enhance additively manufactured polymeric parts: A review

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Abstract

The potential of additive manufacturing to produce optimized and customized polymeric parts is often impaired by poor surface finish, low mechanical properties, and insufficient dimensional accuracy. Post-processing treatments are usually adopted to address these issues. Scientific community and industrial actors are engaged in the development and use of post-processing to enhance the performance and widen the range of application of polymeric components manufactured by additive technologies.

The present work aims to provide an exhaustive classification and discussion of the post-processing treatments, as well as an extensive literature review of the approaches proposed within the scientific community. A holistic view of post-processing is provided, including a discussion of the benefits associated with each technique as well as its side effects. This work is intended to support the selection of the most appropriate post-processing by considering multiple aspects such as the material, part geometry, processing time, costs, and treatment specificity.

Keywords: additive manufacturing, polymers, post-processing treatments.

1 Introduction

Post-processing treatments are defined as the steps taken after the completion of an additive manufacturing (AM) build cycle to achieve the desired properties in the final product (ISO 2015). Their role is considered to be of primary importance to address the main issues derived from AM processes, such as a roughness, dimensional discrepancies between designed and manufactured parts, porosity, and anisotropy that represent a limitation for demanding applications (Ngo et al. 2018; Tofail et al. 2018; Turner and Gold 2015; Singh, Ramakrishna, and Singh 2017). These issues can be partially addressed by following two distinct strategies: optimizing the various process parameters or using post-processing techniques. Indeed, the research community highlights the importance of post-processing to improve the characteristics and broaden the application range of additively manufactured parts (Lee, Nagalingam, and Yeo 2020).

This work aims to categorize and discuss the existing post-processing techniques adopted to improve AM polymeric parts, analyzing their potential and limitations. Although a variety of materials are used for AM applications, such as metal powders, ceramic powders, polymer/composite feedstock filaments (Singh, Ramakrishna, and Singh 2017; Lee, An, and Chua 2017; Lee et al. 2016), polymeric parts represent approximately 50% of all AM components (Wohlers 2020) and the potentialities connected to their enhancement are of great interest.

Many papers in the scientific literature describe the use of post-processing. However, a clear and comprehensive review has not been provided, and each study is limited to a specific issue, technology, or treatment typology (Kumbhar and Mulay 2018; Chohan and Singh 2017; Wickramasinghe, Do, and Tran 2020). An integrated and holistic view of post-processing techniques is currently lacking. One of the main efforts of this review is to provide an in-depth analysis of the benefits associated with each post-processing treatment, as well as highlighting any potential side effects.

2 Critical issues

Several AM techniques are currently available for the 3D printing of polymeric or hybrid materials. ISO/ASTM 52900:2015 divides these technologies into seven process categories: Binder Jetting (BJ), Directed Energy Deposition (DED), Material Extrusion (ME), Material Jetting (MJ), Powder Bed Fusion (PBF), Sheet Lamination (SHL) and Vat Photopolymerization (VAT). However, the most commonly used for polymers and specifically developed for this class of materials are: BJ, ME, MJ, PBF and VAT. Each AM technology is characterized by specific peculiarities that give rise to numerous critical issues, the relevance of which may differ depending on to the specific technology. This section describes and categorizes these issues for additively manufactured polymers. Three categories were identified and analyzed: surface characteristics, mechanical properties, and dimensional accuracy.

2.1 Issues affecting surface characteristics

Surface characteristics are mainly affected by the layer-by-layer appearance, also known as stair stepping or staircase effect (Ngo et al. 2018; Leuteritz and Lachmayer 2018). The layer-by-layer appearance is caused by the intrinsic nature of AM, which involves slicing the geometry into different layers according to the selected layer thickness. The layer-by-layer appearance is amplified when parts with inclined or curved surfaces are printed, and it depends on the layer thickness and surface angle with respect to the build platform (sloping angle). The effect increases with increasing layer thickness and decreases with increasing sloping angle. The influencing factor when curved surfaces are printed is the curvature radius (Fig. 1-a). Roughness is further affected by the nature of the material processing adopted by the specific AM technology (Fig. 1-b). In general, ME is characterized by a higher roughness with respect to VAT (Chohan and Singh 2017). The ME printing resolution is strictly related to the nozzle’s diameter, usually in the range of 0.25–0.8 mm. The VAT printing resolution is greater than that of ME since related to the laser spot or pixel size (often less than 0.1 mm). In MJ, the resolution is related to the size of the deposited droplets and therefore to the size of the nozzles installed on the printing head (approximately 0.05 mm, depending on the specific 3D printer). Moreover, MJ can print thinner layers (i.e., 16 μm) than ME and VAT, which significantly reduces the layer-by-layer appearance (Kumar and Kumar 2015; Cazon, Morer, and Matey 2014). Parts manufactured by PBF are also not significantly affected by the layer-by-layer appearance. When PBF parts are printed, the presence on their surfaces of partially melted powder particles often covers the layer stratification thus impairing the visualization of the layer-by-layer appearance. However, with respect to MJ, the presence of partially melted particles can increase roughness (Crane et al. 2017). A similar effect can be observed for BJ, where some particles surrounding the processed region on the slice are glued by the deposited binder (Ziaee and Crane 2019; Ngo et al. 2018). The surface characteristics of the post-treated parts are mainly assessed using the following measurement methods and instruments: atomic force microscopy, scanning electron microscopy, chromatic confocal microscopy and rugosimeters.

2.2 Issues affecting mechanical properties

Polymeric 3D printed parts are increasingly required to withstand operating mechanical loads. For this reason, the enhancement of mechanical properties as tensile and compressive strength, modulus of elasticity, yield stress, deformation beyond yield point, fracture toughness, ductility, is a crucial task.

Mechanical properties can be affected by porosity (Fig. 1-c), moisture absorption (Fig. 1-d), and anisotropy (Fig. 1-e) (Ngo et al. 2018; Dizon et al. 2018).

Porosity is common to different AM technologies, but its extent depends on the specific technology. It is mainly caused by the formation of voids between consecutive layers, but sometimes also by the presence of impurities (especially for PBF, BJ, and VAT). In ME, the formation of voids is quite common and is considered one of the main drawbacks affecting mechanical properties owing to the reduced interfacial bonding between consecutive layers (Ngo et al. 2018; Zareiyan and Khoshnevis 2017). Void formation and porosity in ME are particularly influenced by the layer thickness, layer width, raster pattern angle, and extrusion temperature (Eiliat and Urbanic 2018). In PBF the porosity, rather, is affected by aspects such as the purity of the material, sphericity, size and distribution of the particles (known as particle size distribution (PSD)), layer thickness, and energy density (Schmid, Amado, and Wegener 2014; Beal et al. 2009). Porosities for VAT and MJ are influenced by the presence of air bubbles and nozzle clogging, respectively, and are generally lower than those of the other technologies, as these circumstances rarely occur. When it happens, it is mainly because reinforced and filled materials (for VAT) or high volatility inks (for MJ) are used (Medellin et al. 2019; Shen and Naguib 2019).

Moisture absorption is caused by both the hygroscopicity of the pure polymer and the porosity of the printed parts. Porosity may indeed increase the ability to retain water with respect to the pure material (Ngo et al.

2018). Moisture absorption significantly affects the end-use mechanical properties of the printed parts due to a plasticizing effect that increase ductility reducing strength and stiffness (Barone et al. 2020a). Parts manufactured by ME, PBF, and BJ can be significantly affected by this issue, as they are characterized by a high level of porosity.

Mechanical properties are also affected by anisotropy. The layer-by-layer approach introduces directional dependencies of the mechanical behavior of the printed parts, which may exhibit lower tensile strength along the Z-direction (build direction) than the X–Y direction (in plane), as shown in Fig. 1-e. The fracture occurs in correspondence to the layer interface, which represents the weak point due to the layer-to-layer bond (Torrado et al. 2015). For ME, anisotropy is one of the most significant factors in comparison to the other AM technologies, and it is influenced by the building direction, layer thickness, layer width, airgap, raster pattern, and angle (Dizon et al. 2018). For VAT, anisotropy is typically very low (approximately 1%), and it is influenced by layer thickness, post-curing carried out at various wavelengths, and thermal treatments carried out at different temperatures and durations (Dizon et al. 2018). The anisotropy for PBF is relatively low (approximately 10%), and it is influenced by energy density, laser beam speed, part orientation, layer thickness, bed temperature, and hatch pattern. The control of polymer powder in terms of shape, size, and distribution also plays a crucial role (Caulfield, McHugh, and Lohfeld 2007). The anisotropy of BJ can be ascribed to the same factors that affect PBF, but its significance can be increased by the higher porosity and hygroscopicity. The anisotropy for MJ (approximately 2%) is similar to that observed for VAT. This can be ascribed to the high homogeneity of parts produced by MJ and VAT, which show low porosity.

The control of mechanical properties can be particularly significant when lattice structures are 3D printed. These structures represent a growing trend for vibration isolation (Syam et al. 2018), lightweight design (Leonardi et al. 2019), heat dissipation and so on (Pan, Han, and Lu 2020), and their mechanical behavior is impaired by surface defects which can lower properties such as strength and toughness.

The mechanical properties of the post-treated parts are mainly evaluated using the following characterization methods: tests for tensile strength, compression strength, flexural strength, impact resistance, fracture toughness and fatigue.

2.3 *Issues affecting dimensional accuracy*

The low accuracy typical of certain AM technologies can limit their application when detailed and small part dimensions are required (Conner et al. 2014). A remarkable impact on dimensional accuracy is determined by superficial defects and thermal phenomena such as shrinkage or warping (Fig. 1-f). However, process parameters such as layer thickness, part orientation, extrusion and bed temperatures, raster angle, and width have a significant influence, and their optimization is required to limit dimensional deviations.

The dimensional accuracy of VAT is affected by curl distortion and volume shrinkage. The shrinkage phenomenon deteriorates the accuracy of SLA models, especially along the building direction. The use of supporting structures, which separate the part from the printing platform, can mitigate this issue. However, their removal after the printing process may damage the final part. A significant impact on dimensional accuracy is associated with process parameters such as layer thickness, hatch spacing, energy density, and cure depth, and several studies in the technical literature have focused on their optimization (Cotabarren et al. 2019; Khorasani and Baseri 2013).

The dimensional accuracy of PBF can be impaired by the surface characteristics, the stress introduced by the sintering process, which causes a deformation, the building direction, and the substrate temperature, which may cause part warping during the process (Chung and Das 2006). In addition, the use of a mixture of new and recycled powders is recommended because of the high cost of new powder and waste minimization. However, this approach can increase the roughness, and dimensional accuracy can be affected after a certain number of powder recycling cycles (Nsengimana et al. 2019).

The dimensional accuracy of BJ is influenced by the same factors as that of PBF, i.e., high roughness, building direction, and quality and size of the powder mixture. Layer thickness and binder saturation also have a significant impact (Vaezi and Chua 2011). For the same layer thickness, specimens with a lower binder saturation have a more uniform surface and, thus, higher dimensional accuracy. For the same binder saturation, specimens with a lower layer thickness have a less uniform surface and lower dimensional accuracy.

MJ is characterized by good dimensional accuracy and repeatability, and it is often preferred over the other technologies in the 3D printing of anatomical details, medical devices, and dental appliances (Salmi et al. 2013; Camardella, Vilella, and Breuning 2017). The dimensional accuracy of the post-treated parts is mainly assessed using the following instruments: calipers, micrometers and optical 3D scanning. Table 1 qualitatively summarizes the significance level of the described critical issues related to each AM technology.

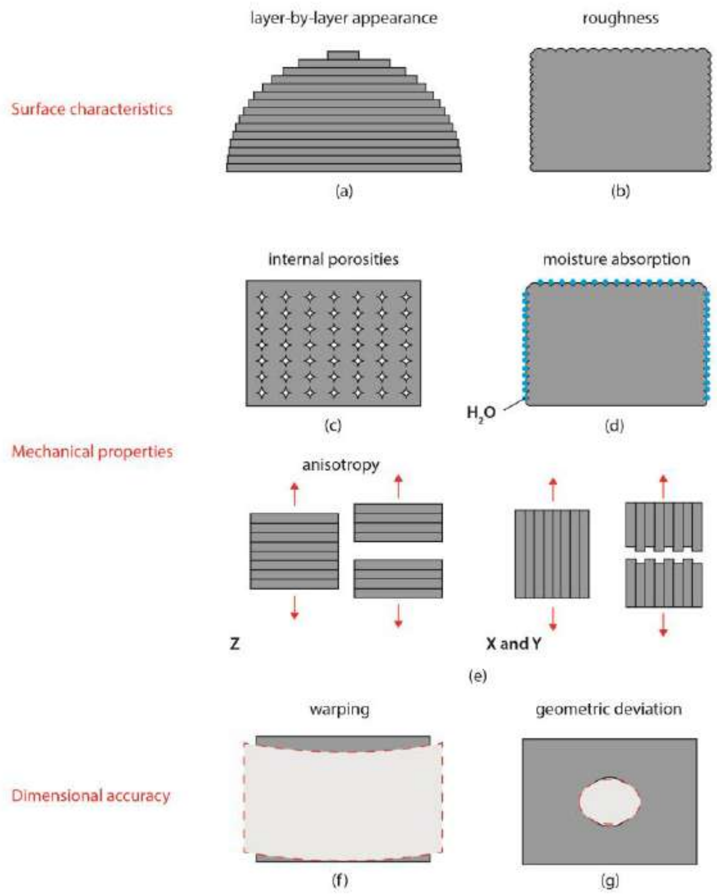


Figure 1. Critical issues for AM polymers.

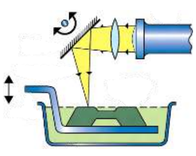
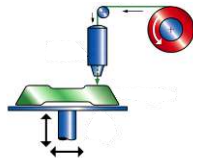
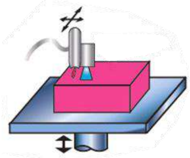
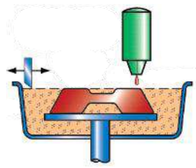
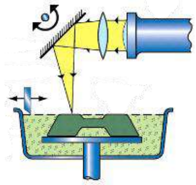
		AM technologies				
		VAT Photopolymerization	**Material Extrusion (ME)**	**Material Jetting (MJ)**	**Binder Jetting (BJ)**	**Powder Bed Fusion (PBF)**
	ISSUE					
Significance level	***Layer-by-layer appearance***	medium	high	low	medium	medium
	Roughness	low	high	low	high	high
	Internal porosities	low	medium	low	high	medium
	Anisotropy	low	high	low	high	medium
	Shrinkage	medium	medium	low	medium	medium
	Warping	medium	high	low	low	high

Table 1. Significance level of critical issues associated with each AM technology.

3 Post-processing treatments

Drawbacks stemming from the issues described in the previous section significantly undermine the potential of AM in the production of functional parts. In recent years, a wide variety of post-processing treatments have been developed to address these issues, thus enhancing the effectiveness of AM polymers. An interesting perspective for the classification of post-processing treatments is provided in (Leuteritz and Lachmayer 2018), although it is restricted to surface finishing methods for reflective optics. Two different principles were used: the physical principle adopted to modify the printed parts, thus distinguishing among optical, chemical, thermal, and mechanical post-processing, and the principle adopted to modify the component surface, thus distinguishing among subtractive, additive, and transformative techniques.

In the present review, both approaches are used to discuss and categorize post-processing treatments. Specifically, four treatment categories were identified and adopted based on the physical principle: mechanical, chemical, irradiation, and thermal. Moreover, each treatment was also classified as subtractive, additive, or transformative according to the typology of the process undergone by the printed part.

3.1 Mechanical treatments

Mechanical treatments include all the techniques based on the use of abrasive media and/or mechanical tools.

In both cases, the process mainly results in material removal due to the impact of abrasive media or the cutting action of a tool.

Three different categories were identified and discussed: abrasive treatments, cutting tool-based treatments, and pressure-based treatments.

3.1.1 Abrasive treatments

3.1.1.1 Manual finishing or sanding

Manual finishing or *sanding* is probably the most conventional method to enhance edge definition and improve surface finishing. It is usually based on the use of abrasive sandpaper with different grit sizes (Fig. 2). Manual finishing is suitable for prototypes or small series, because its repeatability is very low and strictly related to the skills of the operator. However, it remains widely used to reduce layer-by-layer appearance and is often used as a reference method to assess more advanced and innovative techniques (Nsengimana et al. 2019). Abrasive action can also be achieved by exploiting machining processes (e.g., rotating wheels). In this case, a coolant is used to prevent the polymer heating, which may cause warping.

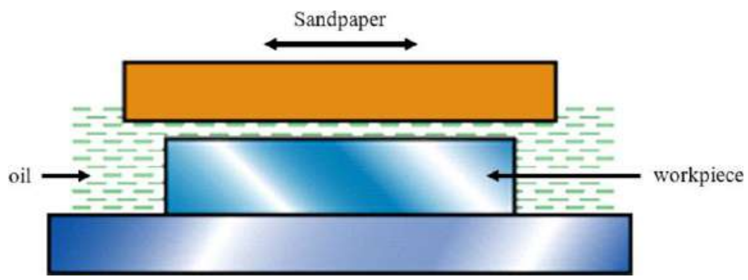


Figure 2. Process schematic of manual finishing.

3.1.1.2 Mass finishing

Mass finishing processes are defined as those capable of simultaneously treating a large number of relatively small parts. The two most important mass finishing processes are *vibratory bowl finishing* (VBF, also known as *vibratory grinding*) and *barrel finishing* (BF, also known as *barrel tumbling*). Both involve the use of a cyclic action to create grinding contact on the part’s surfaces by abrasive action media composed of specially shaped pallets, fine abrasive compounds, and water. The material removal rates depend on the processing time, media size and shape, and adopted compound.

VBF uses a vibratory bowl to house the parts to be treated and the finishing medium. Vibratory actions cause the parts and the medium to grind against each other. In (Schmid, Simon, and Levy 2009) vibratory grinding was investigated in the finishing process of SLS parts, and the roles of the shape and typology of ceramic abrasive media and processing time were discussed. The treatment effectiveness was demonstrated on noncomplex shapes with a variation in the average roughness (R_a) from 11 to 2 μm.

BF consists of loading parts within a rotating barrel charged with abrasive media, water, and a compounding agent (Fig. 3). A proper rotation speed must be selected, in accordance with the characteristics of the charge and the part to be treated, to obtain the desired results. The barrel rotation causes relative motion between the media mass and the parts that tumble on each other. This produces a cutting action, which results in rapid and effective deburring of the parts. BF is widely used because of the large range of materials that can be processed. Over the past few years, it has been investigated with ME polymers (Boschetto and Bottini 2015a, 2015b; Singh and Trivedi 2017; Fischer and Schöppner 2013). The deposition angle was experimentally demonstrated to strongly affect the BF removal rate and alter the nominal dimension of FDM parts (Boschetto and Bottini 2015b). A theoretical model was developed by the same authors (Boschetto and Bottini 2015a) to investigate the coupled interactions between FDM and BF. The model allows the roughness prediction as a function of the FDM parameters, layer thickness and deposition angle, and the quantity of BF material removal. In (Singh and Trivedi 2017) three parameters of the FDM process (geometry, layer density, and orientation) and three parameters of the BF process (media shape, media weight, and finishing cycle time) were studied to determine their effects on roughness and dimensional accuracy. It was found that BF is suitable to improve surface finishing, removing the stair-case effect, with negligible dimensional deviations, and that the resulting R_a is significantly affected by the media shape. In (Fischer and Schöppner 2013) BF was investigated for the surface finishing of Ultem® 9085-FDM parts. The effect of varying the grinding process time and the use of different-shaped ceramic abrasive media was detailed. Reductions in roughness of up to 52% were reported with triangular-shaped media. Rotational speed, processing time, and media shape and size were the most critical parameters for controlling the material removal rate. A similar study was carried out in (Delfs, Li, and Schmid 2015) for SLS parts.

VBF and BF, though similar, are characterized by certain differences. VBF tends to produce smoother surfaces because the abrasive action occurs at each vibration pulse, resembling a filing process. In BF, higher cutting forces are exerted because the parts tumble against each other, rather than gently rubbing together, and thus it is suitable for tougher materials. However, VBF machines are usually more complex and expensive than BF systems.

Mass finishing techniques are characterized by a high degree of automation. Moreover, no tooling is required because parts do not need to be clamped, and no specialized operators are required. However, they are quite inconsistent in imparting uniform finishing on the whole surface of the treated parts (Chohan and Singh 2017). The grinding effectiveness for parts exhibiting indentations, cavities, and holes is a critical issue. Better finishing results are achievable for open-ended grooves rather than for grooves closed at both ends. The ability of the abrasive media to enter cavities depends on their relative sizes, and eventual media entrapment may further reduce finishing results (Schmid, Simon, and Levy 2009; Fischer and Schöppner 2013). Another issue to consider when mass finishing is adopted is the rounding effect on edges and corners, which may be significant with increasing finishing times and/or with the use of aggressive abrasive media (Fischer and Schöppner 2013).

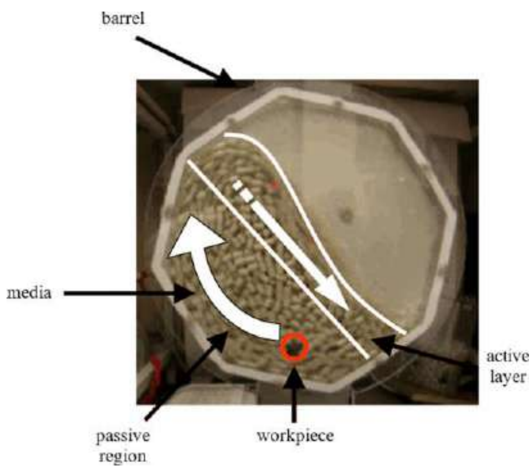


Figure 3. Barrel finishing, (Boschetto and Bottini 2015b).

3.1.1.3 Abrasive flow finishing

Abrasive flow finishing (AFF) (also known as *abrasive flow machining* or *abrasive blasting*) is an advanced process that uses an abrasive-laden elastic medium for surface finishing, deburring, and edge contouring at the micro/nano level. AFF has similarities with mass finishing, except for the use of a flow to accelerate the wear action. Its use is quite common for metal post-processing (Mali and Manna 2009), but it has also been applied to AM polymers (Williams and Melton 1998; Mali et al. 2018). AFF operates by flowing a viscoelastic compound charged with abrasive particles and additives through a restrictive passage composed of a workpiece/tooling combination (Fig. 4-a). The compound viscosity temporarily rises during this step and decreases after its passage through the restricted area. The abrasive particles act as a tool to remove peaks from the surface of the component. In (Mali et al. 2018) a sustainable polymer abrasive gel-based medium was used to finish FDM parts. In (Williams and Melton 1998) the use of AFF was investigated to finish the surfaces of SLA prototypes. The media properties play a crucial role because they should result in nonsticky, viscoelastic fluids. The number of cycles, extrusion pressure, grit composition and size, workpiece material properties, and fixture design are the parameters with the highest impact on the surface quality (Mali et al. 2018). The equipment required for this technique is more advanced and expensive than that for BF.

Abrasive jet deburring (AJD) is based on the use of a high-velocity stream of abrasive particles, which is directed onto the part surface through a nozzle (Fig. 4-b). The most used particles are miniaturized glass beads, crushed steel shots, aluminum oxide, silicon carbide, or nut shells. Although the abrasive is generally propelled by air, water can also be used. This technique was used in (Leong et al. 1998) to polish SLA jewels, showing a 70% improvement in roughness by using dry air and glass beads. Among all the parameters involved in the process (abrasive type, nozzle diameter and angle, air pressure, blasting distance, and time), it was found that the air pressure and blasting time were the two most critical factors affecting the deburring process. The study concluded that dimensional variations caused by deburring were small and well within those encountered in the jewelry industry.

A magnetic field is used in *magnetic-field-assisted finishing* (MFAF) to control and manipulate a magnetic abrasive medium for the material removal process. The magnetic polishing medium is employed as a flexible tool capable of accessing complex geometries. MFAF must be considered as a secondary finishing technique because primary finishing of the part is usually required to reduce the roughness values to approximately 1–2 μm. In (Guo et al. 2018), MFAF following a precision grinding process was used to improve the surface quality of polyamide (PA)-SLS parts. The results showed that R_a was reduced from 15 to 2.85 μm by means of primary finishing and further to 0.89 μm by MFAF. *Ball-end magnetorheological finishing* (BEMRF) is a recently developed MFAF process that uses a tool to flow pressurized magnetorheological fluid, containing abrasive particles (e.g., iron particles), through the center of a spindle surrounded by an electromagnetic coil (Fig. 4-c). A magnetic flux density gradient occurs between the workpiece and the tool tip when the electromagnet is energized, and the fluid stiffens into the form of a magnetically controlled ball-end shape at the spindle tip. This process forms a polishing spot with a controlled size and shape, which is used as a finishing tool on the part's surface. BEMRF is an unconventional technique that imparts a good surface finish on magnetic as well as nonmagnetic parts, which can have either flat or freeform shapes (Singh, Jha, and Pandey 2011, 2013). This process was tested with good results in (Kumar et al. 2019) for poly (lactic acid) (PLA)-FDM parts. An R_a of 81 nm was obtained after 75 min of treatment. In general, this process is suitable when high-quality surfaces are required. However, the higher equipment cost with respect to traditional processes, the strict control requirements for process parameters (e.g., spindle speed, feed, and gap between tool tip and workpiece), and the composition of the magnetorheological fluid are factors to be considered.

AFF techniques represent an appropriate choice when high-quality and smooth surfaces are required. However, they may be too severe for certain polymers due to the heat generated by friction, which can exceed the glass transition temperature. The major limitation of all the flow finishing techniques is related to the poor control of the pressure distribution of the abrasive stream, which may cause uneven material removal from the part surface. All the reviewed studies showed a better response for flat surfaces, whereas the process was highly random and aggressive for edges and corners. Moreover, intricate details and blind holes can hardly be treated in most cases.

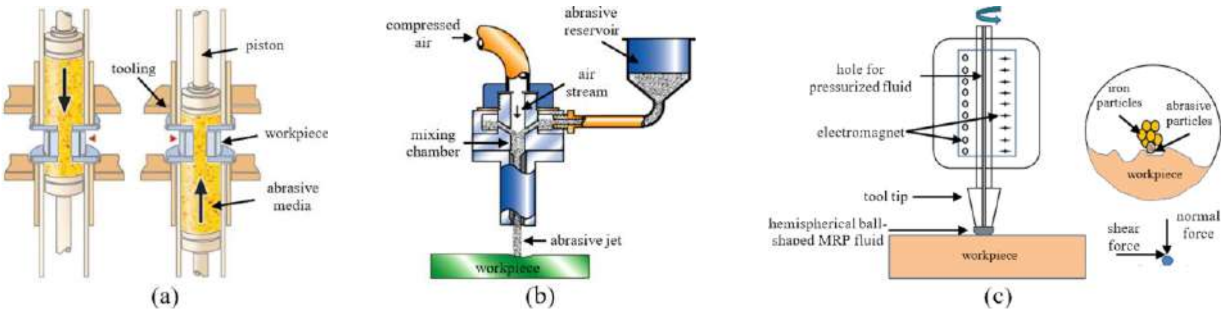


Figure 4. Process schematics of three AFF techniques: a) abrasive flow finishing, b) abrasive jet deburring, and c) ball-end magnetorheological finishing, (Kumar et al. 2019).

3.1.2 Cutting tool-based machining

Cutting tool-based machining includes all the techniques based on controlled material removal processes, through chip formation, by using cutting tools. The *computer numerical control* (*CNC*) *machining* process (also known as *CNC grinding*) uses a tool head to remove material. The process works similarly to FDM in terms of the tool head control. This analogy has prompted the investigation of CNC machining as a secondary process to remove cusps produced by layer stratification, thus reducing the layer-by-layer appearance (Boschetto, Bottini, and Veniali 2016; Kulkarni and Dutta 2000). In (Boschetto, Bottini, and Veniali 2016) tests on acrylonitrile butadiene styrene (ABS)-FDM parts were carried out to determine the relation between cutting depth and sloping angle. A variable cutting depth was then considered to avoid internal defect generation during post-processing. A significant reduction in R_a and a reliable uniformity of the finished surfaces was observed. In (Kulkarni and Dutta 2000), a material removal finishing process integrated with layered manufacturing was proposed. The AM part was machined with a ball-end milling tool using the same manufacturing setup, thus avoiding the problem of fixturing the part for finishing after the layered manufacturing process. The work aimed at defining a better CNC cutter path algorithm, but intricate details were inaccessible to the ball-end milling cutter after the part was completely layered.

A material removal process for ME parts, named *hot cutter machining* (HCM), which combines thermal and mechanical principles, was proposed in (Pandey, Reddy, and Dhande 2003; Pandey, Venkata Reddy, and Dhande 2006). The technique is based on machining the workpiece when it is still attached to the build platform (Fig. 5-a). Thermoplastic polymers soften with increasing temperature. For this reason, heated machining tools are used to lower the cutting forces with respect to room-temperature machining, thus preserving the part integrity. R_a values close to 0.3 μm were obtained with HCM for ABS parts. HCM requires highly controlled mutual placement between the cutting tool and the workpiece, and it was only tested on flat surfaces because the blade-like cutter cannot be used on freeform surfaces with intricate geometric features.

A similar approach, using a heated tool, was introduced in (Taufik and Jain 2016) to improve the surface finish of ABS-FDM parts. The use of a CNC-assisted selective melting tool was proposed to add, instead of cut, semi-solidified material to profile valleys, thus reducing the peak-to-valley heights (Fig. 5-b). A heated tool was used to melt the profile peaks and fill the neighboring valleys with the softened material. The results showed a significant improvement in the surface finish.

Generally, cutting tool-based machining requires highly controlled mutual placements between the 3D printed part and the tool head. The tool must indeed be accurately calibrated to effectively reduce the layer-by-layer appearance without modifying the part geometry. The identification of the optimal cutting parameters is also difficult, because of the highly anisotropic surface morphology of AM parts (Boschetto, Bottini, and Veniali 2016). Moreover, cutting tool-based machining may be unable to access internal features and complex geometries, and the method may require a long processing time because of the machining setup and generation of the CNC code. This issue generally makes the process expensive (Nsengimana et al. 2019).

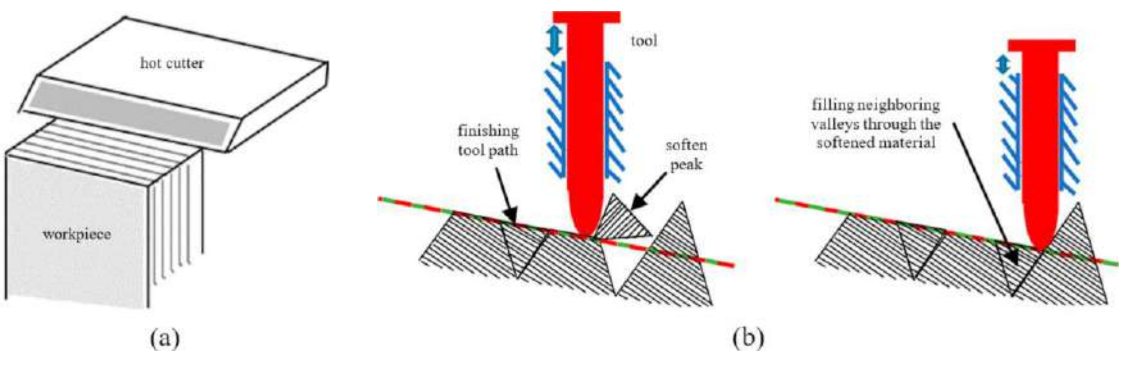


Figure 5. Process schematic of HCM: a) (Pandey, Reddy, and Dhande 2003), b) (Taufik and Jain 2016).

3.1.3 Pressure-based finishing

Pressure-based techniques are characterized by a pressing action on the surface profile peaks with the aim of filling the valleys. Among them, *loading* was used in (Chen, Wang, and Tsai 2019) to enhance the optical reflectivity of different FDM polymers. The printed specimens were placed on a glass sheet, which was positioned on a heated plate, and pressure was applied from above (Fig. 6-a). The simultaneous application of mechanical and thermal principles reformed the parts surface. The study demonstrated that the reflectivity of the treated parts was significantly higher than that of nontreated specimens, particularly when elevated temperatures were used. However, higher dimensional deviations were observed with increasing temperatures. This technique is suitable and effective when highly controlled optical properties are required. Nevertheless, its application is restricted to the treatment of planar surfaces or, in any case, surfaces characterized by a regular geometry.

Burnishing is a cold working finishing process, which induces a surface plastic deformation by sliding contact with a proper tool. A hardened sphere, which is pressed onto/across the surface part, is typically used as a burnishing tool (Fig. 6-b). The loading action presses the asperities to fill the profile valleys. *Ball burnishing* was used in (Vinitha, Rao, and Mallik 2012) for the surface finishing of ABS-FDM parts. An improvement in the roughness and hardness was observed.

Ultrasound treatments, which are based on the application of ultrasonic vibrations, are maybe the most recently investigated technique for the post-processing of AM polymers. The combined application of pressure and ultrasonic vibrations (through the use of an ultrasonic horn) minimized the external defects and internal porosity of AM polymers, thus enhancing the mechanical properties (Wickramasinghe, Do, and Tran 2020). Ultrasound vibrations are used for the homogenization of internal regions through material melting, which fills internal pores. Melting is caused by the transformation of ultrasound into friction energy, which is then converted into heat. An ultrasonic horn, kept in contact with the printed specimen, was used to strengthen the ABS-FDM parts in (Li et al. 2018; Wu et al. 2018). Both studies demonstrated an improvement in the mechanical behavior in terms of bending, tensile strength, and Young’s modulus, which was always greater than 10% compared to the as-printed samples.

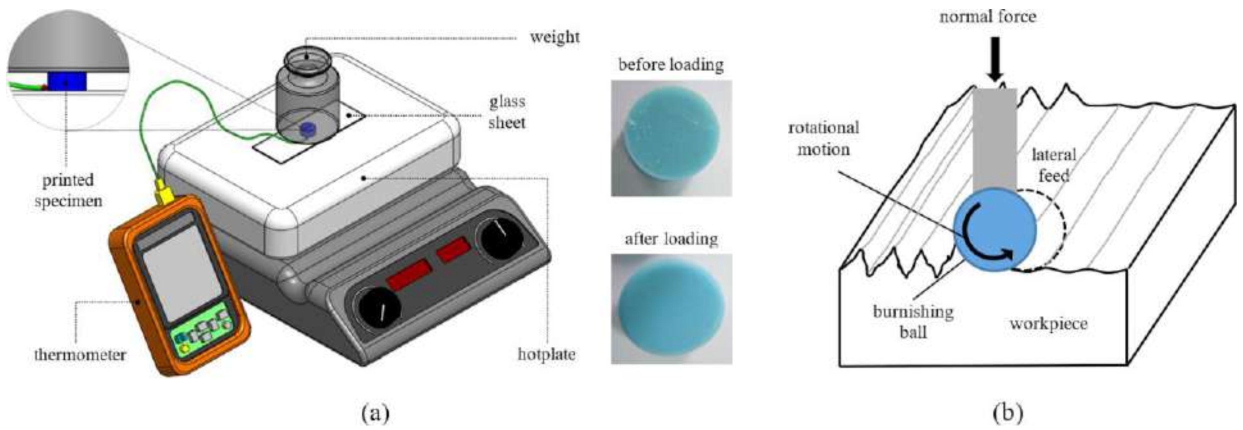


Figure 6. Process schematics of two pressure-based finishing techniques: a) loading (Chen, Wang, and Tsai 2019), b) ball burnishing.

Table 2 reports a summary of the analyzed mechanical post-processing techniques in terms of main process parameters, advantages, limitations, and relevant references. Furthermore, for each reported reference, the AM technology adopted, and the most significant results achieved are documented.

Technique	Most significant process parameters	Advantages	Limitations	References	AM tech.	Investigated properties	Reported results
Manual finishing or sanding	Paper grit type and size, applied pressure and velocity	Suitable for prototypes or small series	High processing time, low repeatability	(Nsengimana et al. 2019)	ME	Dimensional deviations	Significant dimensional deviations
				(Ahn, Lee, and Jeong 2004)	ME	Roughness	Optical transmissivity $\uparrow$ (up to 16%)
Vibratory bowl finishing	Cycle time, vibratory frequency, abrasive media size and shape, adopted compound	High degree of automation, good repeatability	Complex equipment, small holes and cavities can be an issue, non-uniform finishing	(Schmid, Simon, and Levy 2009)	PBF	Roughness	$R_a \downarrow$ (up to 2 μm)
Barrel finishing	Cycle time, revolutions per minute, abrasive media size and shape, adopted compound	High degree of automation, low-cost equipment, good repeatability	Long processing time, brittle materials should not be treated, small holes and cavities can be an issue, non-uniform finishing	(Fischer and Schöppner 2013)	ME	Roughness, shape deviations	$R_z \downarrow$, rounding of edges and corners
				(Singh and Trivedi 2017)	ME	Roughness, dim. deviations (Δd)	$R_a \downarrow$ (up to 3 μm), Δd (up to 0.18 mm)
				(Boschetto and Bottini 2015b)	ME	Roughness, dim. deviations	$R_a \downarrow$ (up to 4 μm)
				(Boschetto and Bottini 2015a)	ME	Roughness	Model to predict roughness after BF
				(Nsengimana et al. 2019)	ME, PBF	Shape deviations	Rounding of sharp corners
Abrasive flow finishing	Extrusion pressure, grit composition and size, media viscoelastic properties, fixture design	Suitable for internal channels' finishing	High-cost and advanced equipment	(Mali et al. 2018)	ME	Roughness	ΔR_a = 21.37 μm (on ext. surf.) ΔR_a = 6.27 μm (on int. surf.)
				(Williams and Melton 1998)	VAT	Roughness	$R_a \downarrow$
Abrasive jet deburring	Abrasive type, nozzle diameter and angle, air pressure, blasting distance and time	Flexible due to the variety of blasting media, little or no heat generation	Slow material removal rate, dust collection system required to avoid air pollution	(Leong et al. 1998)	VAT	Roughness, dimensional deviations	$R_a \downarrow$ (up to 70%) Thickness $\downarrow$ (up to 5.85%)
Magnetic-field assisted finishing	Magnet's rotational speed, abrasive composition, polishing force	Complex geometries can be treated	Primary finishing process required	(Guo et al. 2018)	PBF	Roughness, surface hardness	$R_a \downarrow$ (up to 0.89 μm) Hardness $\downarrow$ (from 50.5 to 49.3 HBR)
Ball-end magnetorheologic al finishing	Spindle speed, gap between tool tip and workpiece, fluid composition	Suitable to obtain high-quality surfaces	High-cost equipment, high control of process parameters required	(Kumar et al. 2019)	ME	Roughness	$R_a \downarrow$ (up to 81 nm)
CNC machining	Cutting speed, feed rate, cut depth	High degree of automation, high repeatability	Long processing time, demanding in term of path algorithm	(Boschetto, Bottini, and Veniali 2016)	ME	Roughness	$R_a \downarrow$ (up to 1.4 μm)

			generation, internal complex surfaces can be inaccessible	(Lavecchia et al. 2018)	ME	Roughness	R_a ↓ (up to 2 μm)
Hot cutter machining	Cutting speed, feed rate, cut depth, cutting tool temperature	Lower cutting forces than CNC machining, high repeatability	Complex surfaces cannot be easily treated	(Pandey, Reddy, and Dhande 2003)	ME	Roughness	R_a ↓ (up to 0.5 μm)
				(Pandey, Venkata Reddy, and Dhande 2006)	ME	Roughness	R_a ↓ (up to 2.2 μm)
				(Taufik and Jain 2016)	ME	Roughness	R_a ↓
Loading	Pressure and temperature of the loading tool	Suitable to obtain high-quality surfaces	Restricted to simple and planar geometries	(Chen, Wang, and Tsai 2019)	ME	Surface reflectivity, roughness, shrinkage	Enhancement of surface reflectivity (up to 13%) (R_a ↓ up to 0.42 μm) Shrinkage ↑ (up to 12%)
Ball burnishing	Feed rate, pressure	Low-cost process, non-chip machining	Internal surfaces cannot be treated	(Vinitha, Rao, and Mallik 2012)	ME	Roughness, surface hardness	R_a ↓ (up to 0.11 μm) Surface hardness ↑
Ultrasound	Ultrasound frequency and amplitude	Internal volumes can be treated, no chemical reactions are caused	Hollow parts cannot be treated, depth limited by the ultrasound vibrational energy	(Li et al. 2018)	ME	Tensile and flexural strength	Tensile strength ↑ (up to 22.8 %) Young's modulus ↑ (up to 20.6%) Bending strength ↑ (up to 49%)
				(Wu et al. 2018)	ME	Flexural strength	Bending strength ↑ (up to 10.8%) Bending modulus ↑ (up to 12.5%)

Table 2. Taxonomy of the analyzed mechanical post-processing treatments and main reviewed papers. Cell colors refer to the issues discussed in the corresponding papers (blue: dimensional accuracy, red: surface characteristics, green: mechanical properties).

3.2 Chemical treatments

Chemical treatments include all the techniques that use solvents, sealants, coatings, and infiltrates.

Mechanical contact is replaced with chemical contact between the workpiece and substances in different forms (vapor, spray, bath). Five different treatments have been identified and discussed: chemical bath finishing (CBF), vapor smoothing (VS), infiltration, coating, and plating.

3.2.1 Chemical-bath finishing

CBF is based on the immersion of a part in a chemical bath containing solvents such as dichloroethane, dimethyl ketone (acetone, $(CH_3)_2CO$), or ester and chloride solvents. This treatment was found to efficiently reduce the roughness by dissolving the external part of the treated surfaces (Jayanth, Senthil, and Prakash 2018). CBF has been widely used for ME parts and, in particular, for polymers such as ABS (Galantucci, Lavecchia, and Percoco 2010; Jayanth, Senthil, and Prakash 2018; Percoco, Lavecchia, and Galantucci 2012a; Galantucci, Lavecchia, and Percoco 2009; Fernandez et al. 2016; Hambali, Cheong, and Azizan 2017) and PLA (Valerga et al. 2019). ABS is an amorphous polymer with a low reticulation degree, including nitrile functionality with a mild interaction with polar solvents such as acetone, ester, and chloride solvents (Galantucci, Lavecchia, and Percoco 2009). Acetone is the most used solvent, owing to its low cost, low toxicity, and high diffusion rate. In (Galantucci, Lavecchia, and Percoco 2009, 2010; Percoco, Lavecchia, and Galantucci 2012a; Hambali, Cheong, and Azizan 2017), the post-treatment consisted of immersing the ABS specimens into a bath of 90% acetone and 10% water by volume for 300 s. The treatment proved to greatly improve the surface finish of ABS prototypes. The chemical bath dissolves single layers and rasters, which subsequently join together, reducing the roughness and increasing the structure compactness (Galantucci, Lavecchia, and Percoco 2010). However, variations in the mechanical properties should also be considered, as chemical agents can modify the material microstructure and its thermal properties. For example, several studies observed a decrease in the tensile strength and an increase in the ductility of ABS samples by increasing the immersion time (Galantucci, Lavecchia, and Percoco 2010; Jayanth, Senthil, and Prakash 2018; Hambali, Cheong, and Azizan 2017). Moreover, bending tests carried out in (Galantucci, Lavecchia, and Percoco 2010) revealed a general improvement in the flexural strength. For both tensile and bending tests, the raster angle showed a loss of influence on the mechanical properties, probably owing to an improved isotropy after the treatment (Galantucci, Lavecchia, and Percoco 2010). In (Percoco, Lavecchia, and Galantucci 2012a), experimental investigations revealed an increment in the compressive strength. In (Jayanth, Senthil, and Prakash 2018), dichloroethane was also utilized to treat ABS-FDM samples, which were immersed into acetone (99%) and dichloroethane (98%) solution for times ranging between 3 and 7 min and then dried at room temperature for 1 h. The effect of immersion time on the ultimate tensile strength and surface finish for acetone-treated, dichloroethane-treated, and untreated samples was evaluated. The tensile strength obtained for acetone-treated samples was higher than of dichloroethane-treated samples. Moreover, a better surface finish was obtained using dichloroethane because it dissolves the ABS material at a higher rate compared to acetone. In (Fernandez et al. 2016) a chemical treatment involving dipping in an acetone bath for 20 s was carried out to improve the surface finishing of an ABS-FDM centrifugal pump impeller. R_a of the open blades side decreased from 21 μm to 0.45 μm.

In (Valerga et al. 2019), the immersion of PLA-FDM samples in different organic solvents was experimented to improve the surface quality and structure. The samples were immersed in four solvents: ethyl acetate ($C_4H_8O_2$), tetrahydrofuran (C_4H_8O), dichloromethane (CH_2Cl_2), and chloroform ($CHCl_3$). Structural and thermal variations and crystallinity properties were analyzed according to the applied treatments. A partial and relatively homogeneous crystallization of the material was observed, resulting in changes in thermal resistance and mechanical behavior. In addition, an improvement in the roughness up to 97% was observed.

CBF represents an easy, fast, and economical technique because it requires minimal human intervention and provide a significant improvement in the surface finish at the expense of a negligible change in the workpiece sizes (Jayanth, Senthil, and Prakash 2018). Moreover, any geometry can be treated, regardless of its complexity. Possible drawbacks include the large amount of solution required for the complete immersion of large parts and, in some cases, limited stability of chemical agents dissolved in the solution. It is also worth noting that a risk of excessively eroding small features exists, especially for undiluted solutions. However, the use of diluted solutions considerably increases immersion times.

3.2.2 Vapor smoothing

VS is a finishing process developed by Stratasys, Ltd., based on the reaction of the external surface of the manufactured part with chemical vapors in a controlled environment, which re-flow the material (Fig. 7). The process is usually carried out by multiple sequential cycles. Any interaction between chemical vapors and the substrate creates a sort of "*slurry*" (chemical agent–polymer). Therefore, after a VS cycle, a cleaning stage is required before repeating the successive cycle. Two forms of VS can be distinguished: hot vapor smoothing (HVS) (Chohan et al. 2017; Gao et al. 2017; Chohan, Singh, and Boparai 2016; Lalehpour, Janeteas, and Barari 2018; Kuo, Chen, and Chang 2017; Singh, Singh, and Singh 2016) and cold vapor smoothing (CVS) (Wjesundera, Schutte, and Potgieter 2017; Neff, Trapuzzano, and Crane 2018; Singh et al. 2017; Gao et al. 2017; Garg, Bhattacharya, and Batish 2017, 2016; Colpani, Fiorentino, and Ceretti 2019; Colpani, Fiorentino, and Ceretti 2020; Jin et al. 2017). In HVS, the apparatus is composed of two chambers: a smoothing chamber and a cooling chamber. The smoothing chamber is heated, thus allowing vaporization of the chemical agent. The cooling chamber is instead used for the fixation of the re-flowed material, thus shortening the process. In CVS, the treatment is carried out at room temperature, resulting in a more gradual process. Highly volatile substances, such as acetone (Singh et al. 2017; Neff, Trapuzzano, and Crane 2018; Garg, Bhattacharya, and Batish 2016, 2017; Wjesundera, Schutte, and Potgieter 2017; Kuo, Chen, and Chang 2017; Zhang, Han, and Kang 2017; Colpani, Fiorentino, and Ceretti 2019; Colpani, Fiorentino, and

Ceretti 2020; Lalehpour, Janeteas, and Barari 2018; Xu, Xi, and Liu 2019; Coppola et al. 2019; Gao et al. 2017), dichloromethane (Jin et al. 2017), or smoothing fluids composed of mixtures of decafluoropentane and trans-dichloroethylene (Chohan et al. 2017; Chohan, Singh, and Boparai 2016; Singh, Singh, and Singh 2016), are usually adopted. Acetone is the most frequently used solvent, because it is colorless and has a low a boiling temperature (56 °C).

The literature mostly describes VS treatments on ABS-FDM parts (Neff, Trapuzzano, and Crane 2018; Wjesundera, Schutte, and Potgieter 2017; Singh et al. 2017; Chohan et al. 2017; Kuo, Chen, and Chang 2017; Gao et al. 2017; Garg, Bhattacharya, and Batish 2017, 2016; Singh, Singh, and Singh 2016; Chohan, Singh, and Boparai 2016; Lalehpour, Janeteas, and Barari 2018; Colpani, Fiorentino, and Ceretti 2019; Colpani, Fiorentino, and Ceretti 2020; Zhang, Han, and Kang 2017) and PLA-FDM parts (Coppola et al. 2019; Jin et al. 2017). Several studies demonstrated the effectiveness of VS in reducing roughness (Lalehpour, Janeteas, and Barari 2018; Colpani, Fiorentino, and Ceretti 2019; Singh et al. 2017; Garg, Bhattacharya, and Batish 2016; Kuo, Chen, and Chang 2017; Colpani, Fiorentino, and Ceretti 2020) with the potential of maintaining dimensional accuracy and preserving part geometry (Singh, Singh, and Singh 2016; Singh et al. 2017; Chohan et al. 2017; Garg, Bhattacharya, and Batish 2016; Kuo, Chen, and Chang 2017).

In (Lalehpour, Janeteas, and Barari 2018), the influence of number and duration of smoothing cycles on the roughness of ABS-FDM parts was investigated. Cycle duration demonstrated a more significant effect on roughness with respect to the number of cycles. Cycle repetition was required because long treatment periods resulted in a substantial amount of material removal. The best smoothing protocol was found to be three cycles of 15 s. In (Colpani, Fiorentino, and Ceretti 2019), a characterization of cold acetone VS on the surface finish of ABS-FDM parts, in terms of roughness, uniformity, and treatment time, was carried out. The results showed a reduction in the roughness of up to 98%. Moreover, a model to correlate the achievable surface finish with the initial roughness and treatment time was proposed. The same authors experimented with cold acetone VS to enhance the surface finishing of customized tracheal stents produced by biocompatible silicone casting with ABS-FDM molds (Colpani, Fiorentino, and Ceretti 2020).

Dimensional deviations, however, must be addressed if high-end applications are required. In (Singh et al.

2017), the Stratasys Inc. vapor smoothing station (VSS) was used to treat ABS-FDM parts. Acetone was selected as an alternative smoothing fluid to that provided by the Stratasys VSS. The results highlighted the capability of the VSS to improve the surface finish up to the nano-level with negligible dimensional deviations. A hip implant replica manufacturing process was proposed in (Chohan et al. 2017; Chohan, Singh, and Boparai 2016) by combining FDM and VS. A highly volatile solvent (43 °C boiling point), composed of decafluoropentane (30%) and trans-dichloroethylene (70%), was used. The optimization of various FDM and VS parameters was investigated in (Chohan et al. 2017) with the aim of achieving minimal dimensional variations, as required for mass production. Shrinkage in both linear and radial dimensions was observed. Similar conclusions were also reported in (Singh, Singh, and Singh 2016). In (Garg, Bhattacharya, and Batish 2016), cold acetone VS on ABS-FDM samples shown to reduce roughness with minimal dimensional variations up to an exposure time of 40 min. However, corners and sharp edges were rounded off at longer exposure times (90 min).

Many authors have also focused on studying the influence of acetone VS on the mechanical properties of ABS-FDM parts (Neff, Trapuzzano, and Crane 2018; Wjesundera, Schutte, and Potgieter 2017; Gao et al. 2017; Garg, Bhattacharya, and Batish 2017; Chohan, Singh, and Boparai 2016; Zhang, Han, and Kang 2017) In (Wjesundera, Schutte, and Potgieter 2017), interlayer bonding was investigated. The study concluded that acetone alters the polymer chain structure of the ABS material, which results in a more brittle structure with lower ductility. An inverse proportional relationship between the ultimate tensile stress and amount of vapor exposure was also observed. In (Neff, Trapuzzano, and Crane 2018), a slight impact on mechanical properties, including stiffness, strength, and elongation at break, was observed. A marginal reduction in tensile and flexural strengths was also observed in (Garg, Bhattacharya, and Batish 2017), whereas in (Zhang, Han, and Kang 2017) VS was found to weaken thermal stability. In (Chohan, Singh, and Boparai 2016), an optimization of FDM and VS process parameters was aimed at improving the hardness of ABS hip implant replicas. The results suggested that short treatment times (30 s) and repeated cycles slightly increased the hardness (~10%). In (Jin et al. 2017), dichloromethane vapors (99% concentration) were used to treat the PLA-FDM parts. Dichloromethane vapors, rather than dichloromethane dipping, were considered because the control of the chemical reaction between pure dichloromethane and PLA is difficult, and aggressive interactions could occur. Tensile tests showed a strength reduction of 63% and an improvement in the elongation at break of 50%.

In addition, some studies have focused on the design and development of alternative experimental apparatus for the implementation of VS processes (Coppola et al. 2019; Xu, Xi, and Liu 2019; Kuo, Chen, and Chang 2017). These approaches arise from the need to increase heating efficiency (Xu, Xi, and Liu 2019) and have VSS allowing an adjustment of both the speed and concentration of the solvent as well as the treatment temperature (Coppola et al. 2019).

A novel automated solution for the post-processing of polymeric AM parts is the Postpro3D, developed by Additive Manufacturing Technologies (AMT Ltd, Sheffield, UK), and based on the proprietary PUSh™ physical-chemical process exclusively licensed to AMT by the University of Sheffield (Ellis, Brown, and Hopkinson 2015; Crane et al. 2017). The machine is based on a physical-chemical process and allows a reduction of the working time and highly detailed texture surfaces if compared to the other vapor smoothing stations. Moreover, this process can be used with a wide variety of polymers, such as PLA, Nylon-12, Nylon-11, Nylon-6, TPU and ULTEM 9085 (Syam et al. 2019).

Reviewed literature has revealed that VS represents one of the most widely used techniques for the post-processing of ABS-FDM parts. CVS requires longer treatment time than CBF, but is also less invasive. Moreover, it is safer with respect to HVS, because it does not involve heat treatment. HVS may result in a faster smoothing effect with respect to CVS, but also in inferior process control, which can cause nonuniform surface treatments. Vapor treatments, in general, are less aggressive than chemical bath treatments, where the concentration of chemical agents and the immersion time must be accurately tuned to avoid undesired effects on the treated parts.

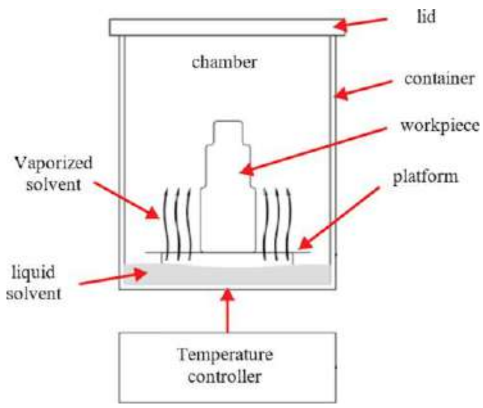


Figure 7. Process schematic of VS.

3.2.3 *Infiltration*

Infiltration is based on the infiltration of a low-viscosity liquid material into parts characterized by a porous structure (Jo et al. 2016; Impens and Urbanic 2016) (Fig. 8). Capillary force, pressure, or vacuum (Mireles et al. 2011) can be used for liquid diffusion through the pores of the parts. The liquid material is then transformed into a solid state by means of light or heat. Infiltration is commonly carried out by immersing the part in a liquid bath. Infiltrates are usually composed of thermosetting resins, such as polyurethane, cyanoacrylate, and epoxy. Processing procedures, in terms of mixture ratios and immersion times, can differ widely depending on the specific infiltrate used. Resin viscosity has a remarkable influence on aspects such as infiltration time and coating thickness (Jo et al. 2016). Resin infiltration within a porous part can modify the mechanical properties (Impens and Urbanic 2016; Suwanprateeb 2006; Impens and Urbanic 2015; Zarringhalam and Hopkinson 2003) and the ultimate strength and tightness are often increased (Jo et al. 2016; Mireles et al. 2011). Moisture absorption can also be prevented (Barone et al. 2020b). A double infiltration method, using a heat-cured dental acrylate, was adopted in (Suwanprateeb 2006) to increase the flexural properties of a natural polymer structure fabricated by BJ using a water-based binder. In (Zarringhalam and Hopkinson 2003), tensile and impact tests were carried out on SLS parts made of Duraform™ powder and subjected to post-processing, including thermal treatment and infiltration with polymeric infiltrates. In (Impens and Urbanic 2016), a comprehensive assessment of the impact of using various commonly recommended infiltrates on the mechanical properties of BJ parts is presented.

In general, the nature and mechanical properties of the infiltrating materials are the means to modify the mechanical behavior of the final part. In (Feng et al. 2018) a methacrylate/cellulose nanocrystal mixture was used as an infiltrate for ABS-ME specimens. The approach was inspired by the microstructure of wood. The results showed that the mechanical properties and thermal stability improved considerably after infiltration. Infiltration also improves the roughness owing to the resin coated on the surface of the part (Jo et al. 2016). In some cases, infiltrates are also used to obtain different optical properties for AM parts. In (Suwanprateeb and Suwanpreuk 2009), for example, samples made by BJ using polymethyl methacrylate (PMMA) powders, mixed with maltodextrin binders, were infiltrated with heat-cured acrylate resin. The results showed increases in flexural properties and optical transmittance, thus approaching the values of PMMA sheet and SLA samples. In (Ayres et al. 2019), a vacuum infiltration of epoxy and cyanoacrylate resins was tested and compared for BJ polymers. The mechanical properties and heat deflection temperatures were evaluated. Vacuum infiltration was found to be highly effective for all the tested resins. However, epoxy demonstrated the highest strength and excellent heat deflection temperature performance.

Infiltration is one of the most effective post-processing techniques to enhance the properties of porous parts. For this reason, it is mainly used for BJ, PBF, and, to a lesser extent, for ME. The removal of excess resin is a critical issue to guarantee dimensional accuracy, and it is related to the resin viscosity and surface tension. In particular, resin accumulation in corners and edges should be avoided. The excess resin on the surface of the infiltrated specimens can be wiped with a tissue paper (Suwanprateeb and Suwanpreuk 2009) or by using a roller (Barone et al. 2020a).

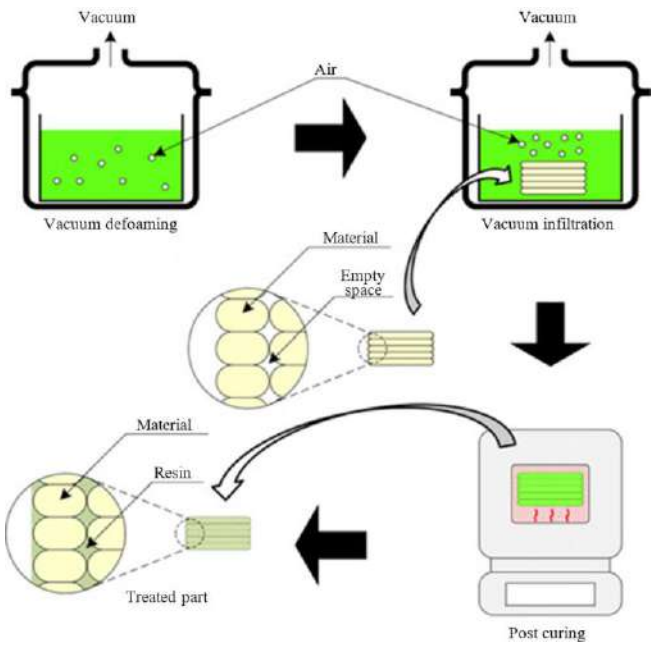


Figure 8. Process schematic of infiltration technique, (Jo et al. 2016).

3.2.4 Coating

Coating involves the application of a thin film of a coating material on the external surface of the part (Fig. 9). This process exhibits certain similarities with respect to infiltration, but it is mainly aimed at providing a superficial layer to cover the part rather than filling its internal pores. One of the most commonly used coating techniques is *dip coating*, which involves immersing and removing the part into and from a tank containing the coating product according to pre-determined immersion and withdrawal speeds (Zhu et al. 2015; de Campos et al. 2011; Lee et al. 2019; Schmid, Simon, and Levy 2009). Further approaches include depositing the coating by simple immersion in a tank, or by *manual brushing* or *spraying* (Leite et al. 2018; Vicente et al. 2019; Miguel et al. 2019; Barone et al. 2020a). Manual methods can be effective in saving processing times and costs when a limited number of parts must be treated. However, nonuniform coatings are obtained, and repeatability is difficult to achieve (Chohan and Singh 2017). Manual brushing and spraying processes are generally characterized by significant dimensional deviations between treated and untreated parts (Nsengimana et al. 2019). The coating thickness cannot be accurately controlled by setting objective parameters, such as in the dip coating process, but mainly depends on the skills of the operator.

In general, the coating thickness and surface profile are highly influenced by coating material properties, such as viscosity and surface tension. However, process parameters also play a significant role, such as immersion and withdrawal speeds in the case of the dip coating technique.

Coating can be used to provide smoother surfaces, as in (Zhu et al. 2015), where water-based polyurethane coatings were applied on ABS-FDM parts. Coating products mainly consist of thermosetting resins, which can be charged with specific fillers to obtain advanced functionalities such as low wettability, heat resistance, and wear resistance (Lee et al. 2019; de Campos et al. 2011).

Also, coatings can be used as sealants to maintain or increase mechanical properties and/or reduce water absorption (Leite et al. 2018; Miguel et al. 2019; Vicente et al. 2019; Barone et al. 2020a). In (Leite et al. 2018), for example, the effects of different sealing treatments (i.e., aqueous acetone solutions, polyurethane wood sealer, and aqueous acrylic-based varnish) on the water absorption of ABS-FDM parts were investigated. Mechanical characterization was also carried out by compressive and tensile tests. Acrylic-based varnish treatment was found to preserve the dimensional stability of the samples, reduce the porosity, and maintain the compressive and tensile properties. In (Miguel et al. 2019), the effects of two different polymeric coatings, polyurethane elastomer and silicone, on the water absorption and mechanical properties of PA-FDM parts were evaluated. In (Barone et al. 2020a), two different coatings, a photosensitive UV resin and an acrylic varnish, were tested for short carbon fiber-reinforced PA-FDM parts. The coating effects were evaluated by comparing the Young’s modulus, yield stress, and ultimate stress of the coated and uncoated specimens by means of tensile tests. In (Vicente et al. 2019), the authors investigated acrylic and polyurethane varnishes as protective coatings to reduce water absorption and improve the mechanical properties of PLA-FDM parts. The polyurethane coating showed the best performance, reducing water absorption by 38%, which also indicated an increase in the tensile strength and ductility up to 24%.

Coating treatments are well suited for all AM technologies. However, their impact on certain aspects such as mechanical properties or surface quality may be more significant for those characterized by high roughness and pronounced layer-by-layer appearance.

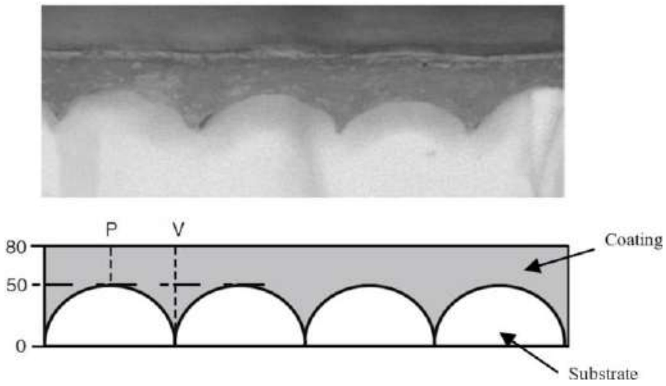


Figure 9. Coating; micrography and process schematic (Zhu et al. 2015).

3.2.5 Plating

Plating consists of rendering conductive a nonconductive material, by depositing a thin conductive layer on its surface. Plating can be carried out either by using electrical or chemical energy, in processes known as electroplating (EP) or electroless plating, respectively. Plating is used to enhance the strength and structural integrity as well as to improve the durability and thermal resistance of polymeric materials (Olivera et al. 2016). When electroless plating is used, the metallic layer is deposited through the chemical reduction of metal ions in an aqueous solution and the subsequent deposition of metal without using electrical energy (Equbal and Sood 2014a; Equbal and Sood 2014b). Surface preparation prior to the plating process is essential to guarantee proper adhesion of the metallic layer on the polymeric substrate (Dixit, Srivastava, and Narain 2019).

Electroplating involves the deposition of a thin metallic coating by combining chemical and electrical principles (Fig. 10). The part, which acts as a cathode, is immersed in an ionized electrolytic solution with a metallizing source material, which acts as an anode. A direct electrical current induces the metallic ions to migrate from the source material to the workpiece. Although electroplating is mainly used to treat metallic parts, it can also be used for polymers if they have been previously prepared with conductive layers (e.g., by an electroless process or by solution spray) (Akhouri, Banerjee, and Mishra 2020). Coatings made of copper, nickel, or chrome have been tested for ABS (Kannan and Senthilkumaran 2014b; Khan et al. 2018; Kannan and Senthilkumaran 2014a) and PLA (Angel et al. 2018; Arun et al. 2018) -FDM parts, as well as for SLA and SLS (Saleh et al. 2004) parts. ABS is the most frequently electroplated plastic, and it has found the widest acceptance in the plating industry (Olivera et al. 2016).

In electroless treatments, deposition occurs spontaneously without requiring any external electrical potential. For this reason, electroless plating, unlike electroplating, does not suffer from uneven current density, which may be caused by the electrical resistance of the bath or the substrate geometry. However, it is worth noting that film thickness and uniformity are not easy to control in electroless procedures (Dixit, Srivastava, and Narain 2019). In addition, they represent a multistep procedure that often requires long deposition times and complex chemical solutions, some of which can also be costly and environmentally hazardous.

Plating treatments can be used to enhance corrosion resistance (Arun et al. 2018), hardness, impact, and tensile strength (Kannan and Senthilkumaran 2014b, 2014a; Arun et al. 2018; Saleh et al. 2004) or to incorporate high-conductivity materials onto 3D printed structures (Angel et al. 2018), but can also enhance light reflectance and surface smoothing (Olivera et al. 2016; Khan et al. 2018). Both electroless and electroplating treatments demonstrated to improve surface roughness. In (Dixit, Srivastava, and Narain 2019), copper electroless plating of ABS-FDM parts evidenced an improvement of the average surface roughness with respect to the as-printed condition (R_a from 8 μm to 5 μm). In (Kannan and Senthilkumaran 2014b), a decrease of the average surface roughness was evidenced in ABS-FDM parts with the increase of the coating thickness (from 3.3 μm for non-treated parts to R_a = 2.2 μm, 1.43 μm and 0.7 μm for plating thickness values of 60 μm, 70 μm and 80 μm, respectively). Among the electroplating parameters, voltage is the one that has shown to have the greatest influence on thickness and then on surface roughness (Akhouri, Banerjee, and Mishra 2020).

Electroplating is suitable when a small number of workpieces must be treated because it is a demanding process in terms of time and cost. Moreover, geometric variations due to the film thickness must be considered.

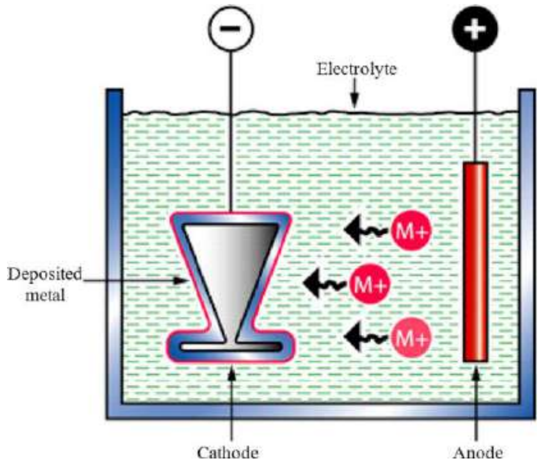


Figure 10. Process schematic of electroplating.

Table 3 reports a summary of the analyzed chemical post-processing techniques in terms of main process parameters, advantages, limitations, and relevant references. Furthermore, for each reported reference, the AM technology adopted, and the most significant results achieved are documented.

Technique	Most significant process parameters	Advantages	Limitations	References	AM tech.	Investigated properties	Reported results
Chemical bath	Nature of chemical agents, immersion time, temperature	Fast and low-cost technique, complex geometries and internal channels can be treated	Large amount of chemical solution required, small features can be excessively eroded, diluted solutions considerably increase immersion times, results highly related to the interaction chemical agent – treated material	(Valerga et al. 2019)	ME	Roughness, thermal resistance	Roughness ↓ (up to 97%) Thermal resistance ↑ (up to 50° C)
				(Fernandez et al. 2016)	ME	Roughness	R_a ↓ (from 21 μm to 0.45 μm)
				(Galantucci, Lavecchia, and Percoco 2009)	ME	Roughness, dimensional deviations	R_a ↓ (up to 2.2 μm) Negligible dimensional deviations
				(Galantucci, Lavecchia, and Percoco 2010)	ME	Roughness, tensile and flexural strength	R_a ↓ (up to 1.88 μm) Tensile strength ↓ (slightly) Flexural strength ↑ (slightly)
				(Hambali, Cheong, and Azizan 2017)	ME	Roughness, tensile strength	R_a ↓ (up to 97.2%) Tensile strength ↓ (up to 42.58%)
				(Jayanth, Senthil, and Prakash 2018)	ME	Roughness, dimensional deviations, tensile strength	R_a ↓ (up to 0.84 μm with dichloroethane) Negligible dimensional deviations, Tensile strength ↓ (from 36.75 to 18.89 MPa with dichloroethane)
				(Percoco, Lavecchia, and Galantucci 2012a)	ME	Compressive properties	Compressive strength ↑ (slightly)
Vapor smoothing	Nature of chemical agents, temperature, number and duration of smoothing cycles	Short processing time, minor dimensional deviations wrt chemical bath	Low process control, non-uniform finishing, results highly related to the interaction chemical agent – treated material	(Chohan, Singh, and Boparai 2016)	ME	Roughness, hardness	R_a ↓ (up to 93%, R_a = 0.21 μm) Hardness ↑ (slightly)
				(Singh, Singh, and Singh 2016)	ME	Dimensional deviations	Optimization of VS parameters to minimize linear and radial dimensional deviations
				(Singh et al. 2017)	ME	Roughness, dimensional deviations	R_a ↓ (up to 0.07 μm) Negligible dimensional deviations
				(Chohan et al. 2017)	ME	Roughness, dimensional deviations	R_a ↓ Dim. deviations 0.17% ÷ 0.44%
				(Lalehpour, Janeteas, and Barari 2018)	ME	Roughness, dimensional deviations	R_a ↓ (up to 95%) Dim. deviations up to 0.082 mm

				(Kuo, Chen, and Chang 2017)	ME	Roughness, dimensional deviations	R_a ↓ (up to 98%) Dim. deviations up to 0.18%
				(Garg, Bhattacharya, and Batish 2016)	ME	Roughness, dimensional deviations	R_a ↓ (up to 0.02 µm) Negligible dimensional deviations
				(Colpani, Fiorentino, and Ceretti 2019)	ME	Roughness, dimensional deviations	R_a ↓ (up to 98%) Negligible dimensional deviations
				(Neff, Trapuzzano, and Crane 2018)	ME	Roughness, dimensional deviations, tensile strength	R_a ↓ (up to 72%) Negligible dim. deviations (< 1%) Young's modulus Elongation at break ↑ (slightly)
				(Garg, Bhattacharya, and Batish 2017)	ME	Roughness, tensile and flexural strength	R_a ↓ (up to 0.135 µm) Marginal reduction of mechanical strength
				(Ellis, Brown, and Hopkinson 2015)	PBF	Roughness, tensile strength	R_a ↓ Tensile strength ↓ (slightly) Elongation at break ↑
				(Crane et al. 2017)	PBF	Roughness, tensile and flexural strength	R_a ↓ (up to 5 µm) Flexural strength not affected Elongation at break ↑ (slightly)
				(Jin et al. 2017)	ME	Tensile strength, toughness	Tensile strength ↓ (up to 63%) Elongation at break ↑ (up to 50%) Toughness ↑
Infiltration	Infiltrate viscosity, immersion time, temperature	Low-cost equipment, internal volumes can be treated	Limited to porous parts, removal of excess infiltrate from the external surface	(Jo et al. 2016)	ME	Roughness, tightness, shrinkage, tensile strength	Tensile strength ↑ Tightness ↑
				(Suwanprateeb and Suwanpreuk 2009)	BJ	Light transmittance, flexural properties	Light transmittance ↑ Flexural strength ↑ (from 0.2 to 81.3 MPa)
				(Impens and Urbanic 2016)	BJ	Tensile, compressive, and flexural strength	Enhancement of mechanical properties by using different infiltrates
				(Barone et al. 2020a)	ME	Tensile strength, porosity, water absorption	Water absorption and porosity ↓ Tensile strength ↑
				(Feng et al. 2018)	ME	Tensile strength, thermal stability	Specific tensile strength ↑ Thermal stability ↑
				(Ayres et al. 2019)	BJ	Tensile, compressive, and flexural strength	Mechanical strength ↑ (up to 10%)
				(Zaldivar et al. 2017)	ME	Flexural strength	Flexural strength ↑ (up to 90%)
Coating	Immersion time, withdrawal speed, number of dipping cycles, coating product composition, temperature, viscosity	Minimal equipment required, fast processing time, complex surfaces can be treated	Non-uniform surface finishing, substrate wettability can be an issue, impurity complications	(Zhu et al. 2015)	ME	Roughness, surface sealing	Roughness ↓ Surface sealing ↑
				(Nguyen and Lee 2018)	ME	Roughness, heat absorption, dimensional deviations	R_a ↓ (up to 2.06 µm) Heat absorption ↓ Dim. variations up to 0.11 mm
				(Leite et al. 2018)	ME	Surface sealing, water absorption, compressive and tensile strength	Water absorption ↓ Mechanical properties not affected
				(Miguel et al. 2019)	ME	Surface sealing, water absorption, compressive and tensile strength	Water absorption ↓ Mechanical properties slightly affected
				(Lee et al. 2019)	ME	Hydrophobicity, tensile strength	Superhydrophobic surfaces are obtained Tensile strength ↓ (slightly)
				(Barone et al. 2020a)	ME	Tensile strength, porosity, water absorption	Water absorption and porosity ↓ Tensile strength ↑
				(Vicente et al. 2019),	ME	Water absorption, tensile strength	Water absorption ↓ (up to 38%) Tensile strength ↑ (up to 24%)
				(de Campos et al. 2011)	SLS	Thermal properties	Thermal stability ↑
Plating	Current density, solution flow rate and temperature, solution chemical composition, processing time	Surface metallization is obtained, durability and thermal resistance are improved	Suitable for prototypes or small series, surface preparation required, non-uniform surface finishing (electroless), demanding in terms of time and costs	(Equbal and Sood 2014a)	ME	Surface metallization	Electrical conductivity is obtained
				(Khan et al. 2018)	ME	Roughness, plating thickness	Optimization of process parameters to decrease roughness and increase plating thickness

	(Saleh et al. 2004)	VAT, PBF	Roughness, dimensional deviations, tensile strength	Roughness ↓ and tensile strength ↑ by increasing plating thickness Dim. deviations within 10 μm
	(Kannan and Senthilkumaran 2014a-b)	ME	Roughness, hardness, tensile strength, impact resistance	Roughness ↓ and tensile strength ↑ by increasing plating thickness Impact strength and hardness ↑

Table 3. Taxonomy of the analyzed chemical post-processing treatments and main reviewed papers. Cell colors refer to the issues discussed in the corresponding papers (blue: dimensional accuracy, red: surface characteristics, green: mechanical properties).

3.3 *Irradiation treatments*

Irradiation treatments include techniques that use radiation derived from different sources (laser or light) and with different wavelengths. Irradiation treatments are contactless, and the only interaction occurring is between the energy sources and the treated surface.

Three different treatments have been identified and discussed: laser polishing, ionizing radiation, and UV light.

3.3.1 Laser polishing

Laser polishing is based on scanning the part's surface with a laser beam (Fig. 11). Originally developed to improve the surface quality of metallic parts, this treatment has recently been investigated for PLA-FDM (Chai et al. 2018; Dewey and Ulutan 2017; Chen, Zhang, and Gan 2020), fiber-reinforced PLA-FDM (Chen et al. 2020) and ABS-FDM (Kumbhar and Mulay 2016; Chai et al. 2018; Taufik and Jain 2017) parts. A carbon dioxide (CO_2) laser source is usually adopted (Chai et al. 2018; Kumbhar and Mulay 2016; Taufik and Jain 2017; Dewey and Ulutan 2017), but infrared or visible laser sources can be also used (Chen, Zhang, and Gan 2020; Chen et al. 2020). The material transformation involves both thermal and chemical processes, depending on how the laser interacts with the material substrate. A primary effect of the laser irradiation is the melting of the superficial polymer material, which then rapidly re-solidifies to form a new surface profile. The molten material is usually flattened by gravity and surface tension (Chai et al. 2018). A secondary effect is that chemical bonds are broken, and their fragments are ejected in the plasma plume. When rapid heating and melting of the material is induced by the laser, the photochemical ablation process sublimates the polymer, directly producing the gaseous phase typical of gas/plasma plume. Laser polishing has been tested for ME parts, yielding good results in terms of roughness reduction. In (Chai et al. 2018), a CO_2 laser scanning technique was used to improve the surface quality of PLA- and ABS-FDM parts. The study demonstrated that laser treatment was more effective in the improvement of PLA surfaces (roughness reduction of up to 68%, from 14.42 μm to 4.64 μm) than ABS surfaces (roughness reduction of up to 5%, from 11.75 μm to 11.2 μm). In (Taufik and Jain 2017), a conventional CO_2 laser engraving machine (Epilog) was used to improve the surface finish of ABS-FDM parts. Only planar surfaces were processed because samples were required to be maintained at the same z-height during the treatment. A similar study was also carried out in (Kumbhar and Mulay 2016). In (Dewey and Ulutan 2017), a CO_2 laser was used to post-process PLA-FDM parts. A reduction of up to 97% (R_a = 2 μm) was achieved by varying both the laser speed and power. In (Chen, Zhang, and Gan 2020), the effects of pulsed fiber laser (1070 nm wavelength) polishing on the surface quality and mechanical properties of PLA-FDM parts were experimentally studied by controlling the laser power and beam diameter. The roughness, surface morphology, dynamic mechanical analysis (DMA), and tensile properties were studied. The results showed that a lower laser power and greater beam diameter can facilitate the formation of smoother surfaces. The roughness was reduced by up to 90% by selecting the optimal parameters. The mechanical testing showed an increase of Young's modulus and tensile strength (13.2 and 9.8% compared with those of as-printed specimens, respectively) and a slight ductility decrease. Different samples were tested, and the maximum decrease in strain was around 1%. In general, however, the results of laser polishing treatments are highly dependent on specific polymer properties, such as the glass transition temperature or surface tension (Chai et al. 2018). Moreover, it is to highlight that the results of laser polishing are also influenced by the characteristics of the adopted laser source. Most laser beams, indeed, are characterized by a Gaussian irradiance profile. This means that the irradiance profile decreases by moving away from the center of the laser beam cross-section. The Gaussian irradiance profile is a factor that can affect laser polishing, heating up and vaporizing the polymer non-uniformly during the laser exposure. Flat-top laser beams, instead, have a constant irradiance profile and they can be a good option to overcome this issue and uniformly heat up and melt the polymer (Metel et al. 2018). Finally, one of the main interesting aspects of laser polishing is the possibility of finishing objects of small dimensions by using a very fine laser diameter. However, when large parts must be post-processed, this technique can be time-consuming.

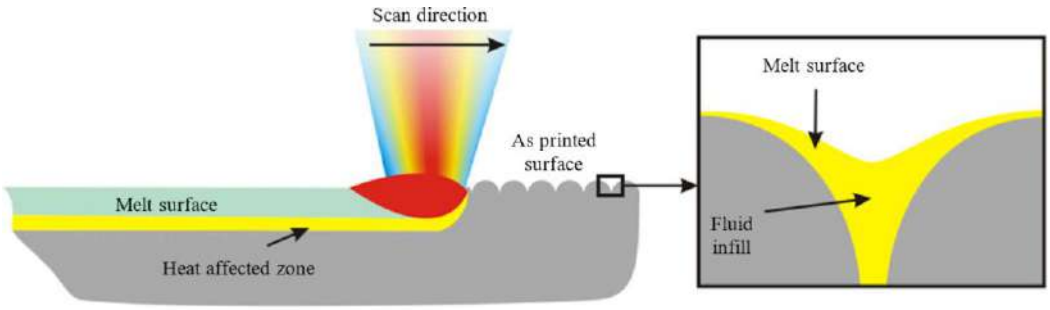


Figure 11. Process schematic of laser polishing, (Chai et al. 2018).

3.3.2 Ionizing radiation

Ionizing radiation is often used in the medical manufacturing industry as a reliable method for sterilizing products. Ionizing radiation has been applied to different polymers such as polyacrylates, polyurethanes, and others (Rankouhi et al. 2018; West et al. 2019; Wady et al. 2020; Gupta and Anjum 2003). When polymers are subjected to gamma radiation, their molecular structures change due to chain scission and crosslinking. In (Rankouhi et al. 2018), the effects of a cobalt-60 gamma source on ABS filaments and ABS-FDM samples were investigated. Tests revealed that the ultimate stress and elastic modulus increased for ABS samples subjected to gamma radiation after manufacturing. More severe degradation was observed for samples manufactured with irradiated filaments, owing to the oxidation that occurs during ME. In (West et al. 2019), the effects of gamma radiation on the mechanical behavior of PLA-FDM specimens were assessed. For ionizing radiation doses up to 50 kGy, the mechanical performance of the polymer was unaffected, which is beneficial for aerospace and medical applications. At larger doses, degradation of the mechanical properties occurred owing to an over-crosslinking condition. In (Wady et al. 2020), FDM samples made using PLA, thermoplastic polyurethane (TPU), chlorinated polyethylene (CPE), PA, ABS, and polycarbonate (PC) were exposed to gamma-ray doses. PA showed the best mechanical properties, with no changes in the ultimate tensile strength and an increase in stiffness.

Another approach relies on the use of ionizing radiation on polymers blended with specific radiation sensitizers, such as trimethylolpropane triacrylate (TMPTA) and triallyisocyanurate (TAIC). In this case, ionizing radiation creates crosslinks between polymer chains of the blended polymer. The effect is an improvement in mechanical properties such as toughness, ductility, and ultimate tensile strength. In (Shaffer et al. 2014), for example, sensitized PLA-FDM parts were treated with gamma rays to improve interlayer adhesion and reduce anisotropy. The results showed a significant enhancement of toughness, ductility, and ultimate tensile strength of PLA samples blended with TAIC and exposed to ionizing radiation at 60 °C. However, worse results were obtained at 20 °C, highlighting that temperatures below the glass transition hinder chain mobility, thus preventing a high degree of crosslinking.

Ionizing radiation is demonstrated to have great potential for the enhancement of polymer properties by introducing high degrees of interlayer crosslinking for ME thermoplastic polymers.

3.3.3 UV light

UV light post-processing is based on the use of UV radiation to increase the crosslinking degree of photosensitive polymers. This treatment is mostly adopted for the post-processing of VAT parts. In (Yang, Li, and Zhao 2019), mathematical models were developed to estimate the tensile strength and hardness of SLA parts based on the curing degree. The models showed high accuracy in tensile strength (88–90%) and hardness (95–98%) prediction. Moreover, the study demonstrated experimentally that UV post-curing significantly enhanced the analyzed mechanical properties in comparison to the as-printed parts. In (Bonada et al. 2017), tensile and bending tests were carried out on DLP manufactured samples to study the influence of UV exposure time on the mechanical properties and photocuring conversion ratios. The Young's modulus, tensile strength, and flexural strength notably increased with the increase in UV exposure time, whereas the percentage of elongation decreased. The use of UV sources for other purposes has also been documented in technical literature. In (Oskui et al. 2016), exposure to UV light was investigated to mitigate the toxicity of ME and VAT parts. In (Graf et al. 2018), instead, the ME and an aerosol-jet printing (AJP) system were combined with a UV flash lamp with the aim of functionalizing the surface of 3D printed parts. The results showed an improvement of up to 94% in terms of the roughness and demonstrated the feasibility of realizing conductive tracks on PLA-parts.

Table 4 reports a summary of the analyzed irradiation post-processing techniques in terms of main process parameters, advantages, limitations, and relevant references. Furthermore, for each reported reference, the AM technology adopted, and the most significant results achieved are documented.

Technique	Most significant process parameters	Advantages	Limitations	References	AM Tech.	Investigated properties	Reported results
Laser polishing	Laser type (Gaussian, flat-top), laser speed and power, scanning path	Finishing of parts with small dimensions by using a very fine laser diameter, very high repeatability	Time-consuming when large parts or a large number of parts must be post-processed, mainly suitable for planar surfaces	(Chai et al. 2018),	ME	Roughness	R_a ↓ (up to 68%, PLA, R_a = 4.64 μm) R_a ↓ (up to 5%, ABS, R_a = 11.2 μm)
				(Dewey and Ulutan 2017)	ME	Roughness	R_a ↓ (up to 97%, R_a = 2.02 μm)
				(Kumbhar and Mulay 2016)	ME	Roughness	R_a ↓ (up to 0.228 μm)
				(Taufik and Jain 2017)	ME	Roughness	Analysis of distinct surface profile features (R_a ↓)
				(Chen, Zhang, and Gan 2020)	ME	Roughness, dynamic and tensile properties	R_a ↓ (up to 90.4%, R_a = 1.02 μm) Tensile strength ↑ (up to 13.2%, 67.9 MPa) Young's modulus ↑ (9.8%, 864 MPa) Storage modulus ↑ (up to 58%)
				(Chen et al. 2020)	ME	Roughness, dynamic and tensile properties	R_a ↓ (up to 93.9%, R_a =0.41 μm) Tensile strength ↑ (up to 25.6%, 52.98 MPa) Young's modulus ↑ (34.1%, 1048.21 MPa) Storage modulus ↑
Ionizing radiation	Radiation dose, radiation sensitizers, temperature	Ideal for sterilizing parts, great potential to enhance polymer properties combined with sensitizers, internal volumes can be treated	Advanced and high-cost technique, specialized operators required, safety issues	(Shaffer et al. 2014)	ME	Dynamic and tensile properties	Toughness ↑ (up to 70%)
				(Rankouhi et al. 2018)	ME	Tensile and flexural properties	Tensile strength ↑ Young's Modulus ↑
				(West et al. 2019)	ME	Tensile and flexural properties	Tensile modulus ↑ linearly with radiation dose
				(Wady et al. 2020)	ME	Tensile properties	Tensile strength not affected for nylon Young's modulus ↓ (up to 50% for PLA)
UV light	UV wavelength, exposure time, UV irradiance	Low-cost treatment, processing time not dependent from the surface size, mitigate toxicity of parts	Restricted to photopolymers, blind parts cannot be treated	(Graf et al. 2018)	ME	Roughness	R_a ↓ (up to 90%, R_a = 0.351 μm)
				(Yang, Li, and Zhao 2019)	VAT	Tensile and hardness properties	Models to predict tensile strength and hardness based on UV light exposure
				(Bonada et al. 2017)	VAT	Tensile and flexural properties	Tensile strength ↑ Young's modulus ↑ Elongation at break ↓

Table 4. Taxonomy of the analyzed irradiation post-processing treatments and main reviewed papers. Cell colors refer to the issues discussed in the corresponding papers (blue: dimensional accuracy, red: surface characteristics, green: mechanical properties).

3.4 Thermal treatments

Thermal treatments include all the techniques that rely on the use of heat sources. Softening of thermoplastic polymers, hardening of thermosetting polymers, or curing of unreacted monomer can indeed be obtained by heating.

Two different treatments have been identified and discussed: local surface heating and annealing.

3.4.1 Local surface heating

Local surface heating uses hot air jets or light sources to locally melt the polymer surface. In (Neff et al. 2019), ABS-FDM for printed electronics was thermally treated using a high-intensity visible light projector. The roughness typical of ME reduces electrical conductivity and can introduce anisotropy, especially in radio frequency devices. Thermal heating, induced by the light projector, caused a local surface reflowing, thus allowing self-smoothing due to the surface tension. Heat was monitored during the process using an infrared camera (Fig. 12-a). The same study compared the results of thermal smoothing with those obtained using an acetone VS. The smoothing processes significantly reduced the roughness of extruded components by 80% and 90% for thermal smoothing and VS, respectively.

In (Adel et al. 2018), a hot air jet was tested and the influence of air jet temperature, air jet velocity, and nozzle translational speed was evaluated for PLA-FDM samples (Fig. 12-b). An 88% reduction (R_a = 0.85 μm) with respect to the as-printed parts was observed. A key issue of this treatment is related to the forces generated by the hot air flow, which contribute, together with the surface tension, to the self-smoothing of the treated surface. A hot air jet can be a suitable solution when a low-cost polishing treatment is needed. However, the temperature and velocity of the air jet, as well as the nozzle speed, represent critical parameters to avoid overheating and surface degradation of the parts.

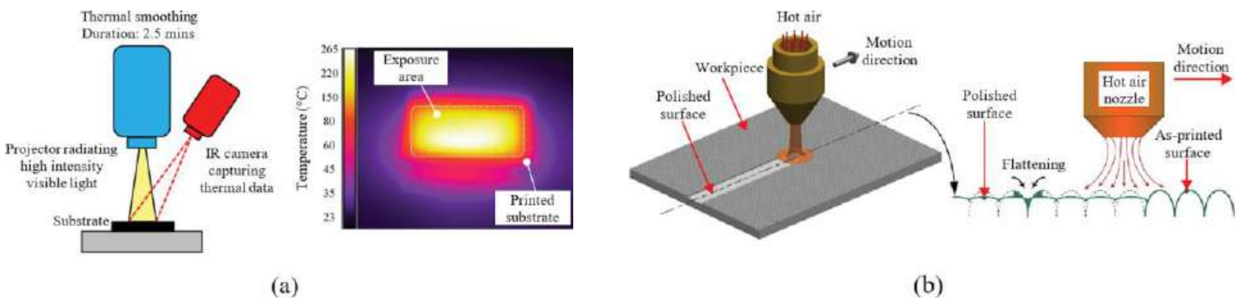


Figure 12. a) Thermal smoothing by visible light projection, (Neff et al. 2019), b) process schematic of hot air jet, (Adel et al. 2018).

3.4.2 Annealing

Annealing is the process of heating a part to a specific temperature, holding the temperature constant for a certain amount of time, and then slowly cooling the part to room temperature. This treatment is used to enhance the mechanical and thermal conductivity properties of 3D printed parts because temperatures above the glass transition allow the material to reflow, thus filling porosities and interlayer gaps to a significant extent (Hart et al. 2018; Prajapati et al. 2019; Singh et al. 2019). In (Hart et al. 2018), an improvement of around 2700% in fracture toughness was reported on ABS-FDM samples because of thermal annealing at 135 °C for 168 h. In (Prajapati et al. 2019), a similar post-process carried out at the same temperature for 96 h produced a 150% increase in thermal conductivity, thus restoring the part's thermal conductivity to nearly that of the underlying material.

Heat can reduce the UV exposure time of photopolymers if thermal initiators are used, thus ensuring the complete polymerization of internal regions, which would otherwise be compromised by photoabsorption (Uzcategui et al. 2018). Heat treatment of polymers can promote rearrangement of the polymer chains, a higher degree of crystallinity, and thus better mechanical properties (Wagner, Mount, and Giles 2014). In (Wang et al. 2017), heat treatments were investigated for MJ with VeroClear material, supplied by Stratasys, Ltd. The results showed that heat treatment carried out at 150 °C increased the tensile strength, strain at peak stress, and tensile modulus by 20.11%, 38.83%, and 33.46%, respectively, with respect to the as-printed specimens. In (Torres et al. 2015), thermal post-processing was used for PLA-FDM parts. Annealing treatments at 100 °C were performed using different annealing times. The results indicated that heat treatments can be particularly beneficial to increase the strength of low-infill components. However, long annealing times were accompanied by a significant loss in ductility and an increase in the variance of material properties. In (Bhandari, Lopez-Anido, and Gardner 2019), annealing was used to improve the interlayer tensile strength of short carbon fiber (SCF)-reinforced polyethylene terephthalate glycol (PETG)-FDM and PLA-FDM composites. Appropriate temperature ranges were investigated to carry out effective treatments. The interlayer tensile strengths of the SCF-PETG-FDM and SCF-PLA-FDM composites increased by factors of three and two, respectively, after annealing at a suitable temperature. In (Singh et al. 2019), different annealing temperatures and times were used to improve the overall performance (roughness, hardness, dimensional accuracy, tensile strength, flexural strength, and impact strength) of ABS-FDM parts. It was found that the part density and annealing temperature had statistically significant effects on the selected output responses, whereas annealing time, in the range of 20–30 min, was not significant.

Microwave heating was studied in (Wang et al. 2019) to increase the mechanical properties of SiC/PLA-FDM composites. SiC absorbed microwave radiation and gained heat in the microwave field, enabling improved temperature increase characteristics and temperature distribution. The heating process enabled the re-melting of the PLA rasters, thus increasing their interface bonding. The microwave-heated SiC/PLA composite samples (with a SiC mass fraction of 5%) showed increases of 51% in tensile strength and 42% in tensile modulus with respect to pure PLA.

Table 5 reports a summary of the analyzed thermal post-processing techniques in terms of main process parameters, advantages, limitations, and relevant references. Furthermore, for each reported reference, the AM technology adopted, and the most significant results achieved are documented.

Technique	Most significant process parameters	Advantages	Limitations	Reference	AM Tech.	Investigated properties	Reported results
Local surface heating	Air jet velocity, temperature, nozzle speed, distance from the workpiece	Low-cost treatment, flexible tool	Local overheating can be an issue, internal channels cannot be treated	(Neff et al. 2019)	ME	Roughness	Ra ↓ (up to 80%, R_a = 1 μm)
				(Adel et al. 2018)	ME	Roughness	Ra ↓ (up to 88%, R_a = 0.85 μm)
Annealing	Temperature, time	Low-cost and simple equipment required, internal volumes can be treated, many properties can be affected at the same time	Warping issues, highly dependent upon the polymer properties, high processing time due to polymer low conductivity	(Singh et al. 2019)	ME	Roughness, hardness, dimensional accuracy, tensile flexural and impact strength	Ra ↓ at the increase of annealing T Δd ↑ at the increase of annealing T Tensile strength ↑ for annealing T ↑ Flexural strength ↑ for annealing T ↑
				(Wang et al. 2017),	MJ	Tensile strength, tensile modulus	Tensile strength ↑ (up to 37.59%) Tensile modulus ↑ (up to 43.71%)
				(Wang et al. 2019)	ME	Tensile strength, tensile modulus	Tensile strength ↑ (up to 51%) Tensile modulus ↑ (up to 42%)
				(Bhandari, Lopez-Anido, and Gardner 2019)	ME	Interlayer tensile strength	Interlayer tensile strength ↑ by 3 times for PETG-CF and 2 times for PLA-CF
				(Torres et al. 2015)	ME	Shear strength, ductility	Shear strength ↑ Ductility ↓
				(Hart et al. 2018)	ME	Fracture toughness	Interlaminar toughness ↑ (up to 2700%)
				(Prajapati et al. 2019)	ME	Thermal properties	Thermal conductivity ↑ (up to 150%)

Table 5. Taxonomy of the analyzed thermal post-processing treatments and main reviewed papers. Cell colors refer to the issues discussed in the corresponding papers (blue: dimensional accuracy, red: surface characteristics, green: mechanical properties).

3.5 *Approaches combining different treatments*

Certain attempts have been reported in the scientific literature to simultaneously or sequentially combine different techniques to enhance post-processing effectiveness with respect to a specific issue.

In (Lavecchia et al. 2018), the authors compared the effects of CNC grinding and micro-sandblasting on the roughness of ABS-FDM parts. They also experimented with a combined approach, in which both CNC grinding and micro-sandblasting were supplemented with physical vapor deposition (PVD) to apply a thin metal film over the surface of ABS parts. The CNC grinding process yielded better results than micro-sandblasting for the enhancement of surface finishing. Moreover, PVD showed a further reduction in the roughness value of 89.6% with respect to simple CNC grinding.

A combined post-processing method for ABS-FDM parts was also investigated in (Nguyen and Lee 2018). The post-processing consisted of acetone VS, drying, and aluminum coating by a cold spraying method. The roughness slightly increased after the aluminum coating, but the treatment resulted in an improvement in thermal properties because the aluminum layer was found to reflect heat radiation, thus decreasing heat absorption. Moreover, the treated parts were analyzed from a dimensional point of view and a maximum dimensional variation of 0.11 mm after the treatment was measured.

In (Ahn, Lee, and Jeong 2004), a post-processing treatment was proposed that consisted of sequential applications of 180 °C heating, acrylic resin infiltration, and surface sanding. The approach was investigated to increase the optical transmissivity of ABS-FDM parts to 16%. Simple ABS heating increases optical transmissivity, but temperatures above 180 °C cannot be reached because of warping and dimensional changes. For this reason, an approach combining different techniques is preferred to further enhance optical transmissivity without introducing temperature issues.

In (Zaldivar et al. 2017), a vacuum plasma treatment followed by epoxy resin infiltration was tested on ABS-FDM parts. Plasma treatment was used as a preparatory phase to improve the wettability of the polymeric substrate and promote chemical bonding between ABS and infiltrated epoxy. The mechanical characterization showed a 130% increase in flexural strength with respect to the as-printed material.

In (Uzcategui et al. 2018), a dual-cured method for an acrylate resin manufactured through SLA was developed. The approach was based on a dual-initiation system in which photoinitiated printing is followed by a thermal post-cure to achieve uniform curing of the printed part. Complete curing throughout the whole part volume cannot be achieved when photosensitive resins are used, owing to the presence of photoabsorbers. To overcome this issue, and improve the mechanical properties, the authors introduced a thermal initiator that did not show polymerization at the selected wavelength (405 nm) during UV curing. The combination of photo and thermal curing enhanced the mechanical properties of AM photopolymers.

A combined treatment process to enable the fabrication of ABS-FDM biomedical microdevices was presented in (McCullough and Yadavalli 2013). An acetone-based soaking method was proposed to seal part surfaces. A UV light irradiation treatment was then proposed for poly (ethylene glycol) methacrylate (PEGMA) grafted onto the ABS surface. The increase in hydrophilicity and biocompatibility was finally evaluated for microfluidic devices.

4 Discussion

Currently, AM represents a powerful tool for designing and producing high-performance parts, whose characteristics often exceed those achievable by conventional manufacturing techniques. However, AM is not free from critical issues, which can be more pronounced (e.g., anisotropy, porosities) than or even additional (e.g., layer-by-layer appearance) to those typical of traditional manufacturing methods. Several treatments have been investigated by researchers to address these issues. Hence, there is a need to provide a clear and comprehensive overview to select the most appropriate treatment in relation to the specific issues to be addressed.

Although the authors are aware of the difficulties associated with grouping the wide range of existing treatments into well-defined categories, an attempt has been made, as schematized Fig. 13. Treatments have been categorized according to their physical principle (mechanical, chemical, irradiation, and thermal) and to the modification occurring at the surface level (subtractive, additive, and transformative). Figure 13 also highlights the correlations between post-processing techniques and treated critical issues. Reviewed research papers document that almost all the treatments were used to enhance surface characteristics, and all the chemical, irradiation, and thermal treatments, except for local surface heating, were used to enhance the mechanical properties. Moreover, dimensional accuracy was discussed for all the chemical treatments and some of the mechanical treatments. It is worth noting that certain techniques were investigated to address two or more different issues and to enhance different characteristics. An improvement in surface characteristics, for example, generally has a positive effect on mechanical properties, such as fatigue behavior or ductility (Chen, Zhang, and Gan 2020; Galantucci, Lavecchia, and Percoco 2010; Jayanth, Senthil, and Prakash 2018).

Mechanical techniques represent the most traditional post-processing treatments, as they are derived from conventional metal finishing techniques, although their use on polymeric parts is impaired by greater limitations when compared to metals (e.g., lower temperature resistance, lower hardness, and lower strength). Mechanical treatments can be applied largely without regard for material properties, because they are based on abrasive, cutting, or pressure actions. The effectiveness of these actions is influenced by the hardness and wear properties, which do not significantly differ among AM polymers. These techniques are suitable for improving the surface characteristics of AM polymers, because they reduce the layer-by-layer appearance as well as material roughness. Mechanical post-processing treatments have also been used to enhance mechanical properties (Li et al. 2018; Wu et al. 2018) and the influence on dimensional accuracy has been considered (Nsengimana et al. 2019; Singh and Trivedi 2017; Fischer and Schöppner 2013). Indeed, the mechanical behavior of AM parts benefits from obtaining a more homogeneous surface characterized by fewer defects (Nsengimana et al. 2019; Cazon, Morer, and Matey 2014). Essentially, these treatments are subtractive in nature (Boschetto and Bottini 2015b; Mali et al. 2018), but in a few cases, they can also be classified as transformative (Chen, Wang, and Tsai 2019). Pressure-based post-processing encompasses all the mechanical techniques that are based on a transformative action instead of a subtractive action. Among pressure-based techniques, ultrasound is the only mechanical post-processing method that primarily acts on mechanical properties, without necessarily affecting surface characteristics (Li et al. 2018; Wu et al. 2018; Wickramasinghe, Do, and Tran 2020). Mechanical treatments may damage weak features (e.g., thin walls, strut-and-node-based structures) and are less effective than chemical treatments in processing complex shapes and areas that are difficult to access. These geometric features are indeed more accessible for vapor or a liquid bath than for an abrasive medium or for cutting tools.

Chemical action can modify polymeric AM parts, affecting their characteristics under different transversal aspects. Currently, they are mainly used to increase mechanical, thermal, or optical properties, surface finishing, or tightness. However, chemical treatments are characterized by a high specificity, meaning that a solvent, in the form of vapor or bath, can effectively work for a specific polymer without giving appreciable results for others. This aspect is also confirmed by the existence of many studies regarding chemical treatments on ABS parts (Jayanth, Senthil, and Prakash 2018; Wjesundera, Schutte, and Potgieter 2017; Galantucci, Lavecchia, and Percoco 2010; Percoco, Lavecchia, and Galantucci 2012b; Singh et al. 2017). Chemical treatments are the most investigated techniques, and various treatments are available. Among these, infiltration, coating, and plating are based on material addition to improve surface characteristics, reducing the layer-by-layer appearance, or by filling the voids and the internal porosities created by layer stratification. For these reasons, according to the nature of the coating or infiltrate products, these treatments can also improve the mechanical properties (Leite et al. 2018; Suwanprateeb 2006; Barone et al. 2020a; Zarringhalam and Hopkinson 2003; Barone et al. 2020b; Ayres et al. 2019; Vicente et al. 2019; Zaldivar et al. 2017). Plating, which can be considered a hybrid process combining chemical and electrical physical principles, is largely used for metals but is also promising for AM polymers. Chemical bath finishing and vapor smoothing are transformative processes, because the solvent–part interaction causes material reflowing, which results in a surface flattening with the reduction of the layer-by-layer appearance. The improvement of surface characteristics with chemical bath and vapor smoothing is significant (Galantucci, Lavecchia, and Percoco 2010; Nguyen and Lee 2018; Singh et al. 2017), although the mechanical properties can be negatively affected by chemical agents (Jayanth, Senthil, and Prakash 2018; Wjesundera, Schutte, and Potgieter 2017).

Irradiation treatments are transformative in nature, as they are commonly used to change the physical state of treated parts, from solid to molten and/or from solid to plasma, such as in laser polishing or to generate crosslinking between different layers in ionizing radiation treatments (in the presence of specific radiation sensitizers) (Shaffer et al. 2014). Irradiation treatments are less frequently reported in the literature than mechanical and chemical treatments, and are mostly used to improve surface characteristics, mechanical properties, or even to reduce toxicity of AM parts (Chai et al. 2018; Shaffer et al. 2014; Oskui et al. 2016). These treatments are characterized by high specificity and should be accurately defined and customized for each specific polymer in terms of the adopted wavelengths and treatment times.

Thermal treatments can be considered transformative because they act by modifying physical and chemical material properties. They are mostly used to improve surface finishing (Neff et al. 2019; Adel et al. 2018; Singh et al. 2019), enhance mechanical properties (Wang et al. 2017; Bhandari, Lopez-Anido, and Gardner 2019; Torres et al. 2015) and relieve residual stresses originating during resin polymerization and finishing processes (Bhandari, Lopez-Anido, and Gardner 2019). When surface characteristics must be improved, polymer heating to a semi-molten state induces a material softening and reflowing process, which minimizes the layer-by-layer appearance. When the mechanical properties must be enhanced, heat is used to promote rearrangement of polymer chains (crystalline vs. amorphous), for thermoplastic polymers, or to promote a higher crosslinking degree, for thermosetting polymers (Adel et al. 2018; Torres et al. 2015). The increase in crystallinity and crosslinking degree are key factors in improving mechanical properties, particularly close to the glass transition temperature (Ashby 2018; Callister and Rethwisch 2018). Whereas surface heating is suited to locally reflow the material, thus improving the surface characteristics, annealing also influences the mechanical properties because the entire part volume is heated. In general, an effective thermal treatment can only be carried out with appropriate knowledge of the material’s thermal properties, such as glass transition, thermal expansion coefficient, and thermal distortion resistance (Callister and Rethwisch 2018). Thermal distortion, indeed, may affect the dimensional stability to a greater extent with respect to other material classes (e.g., metals or ceramics).

A further classification of the reviewed papers with respect to AM technologies evidences that most of the scientific papers investigated the use of post-processing on ME parts (about 80%), some focused on post-processing carried out for VAT and PBF parts (each less than 10%), while very few reported results on BJ, and almost none on MJ. In the authors’ opinion, this finding reflects the wider diffusion of ME at research centers and universities, owing to its low cost of purchase and maintenance and the availability of a wide range of materials. Furthermore, ME is one of the most adversely affected AM technologies by the critical issues described in this review whereas MJ, as also shown in Tab. 1, is one of the least affected.

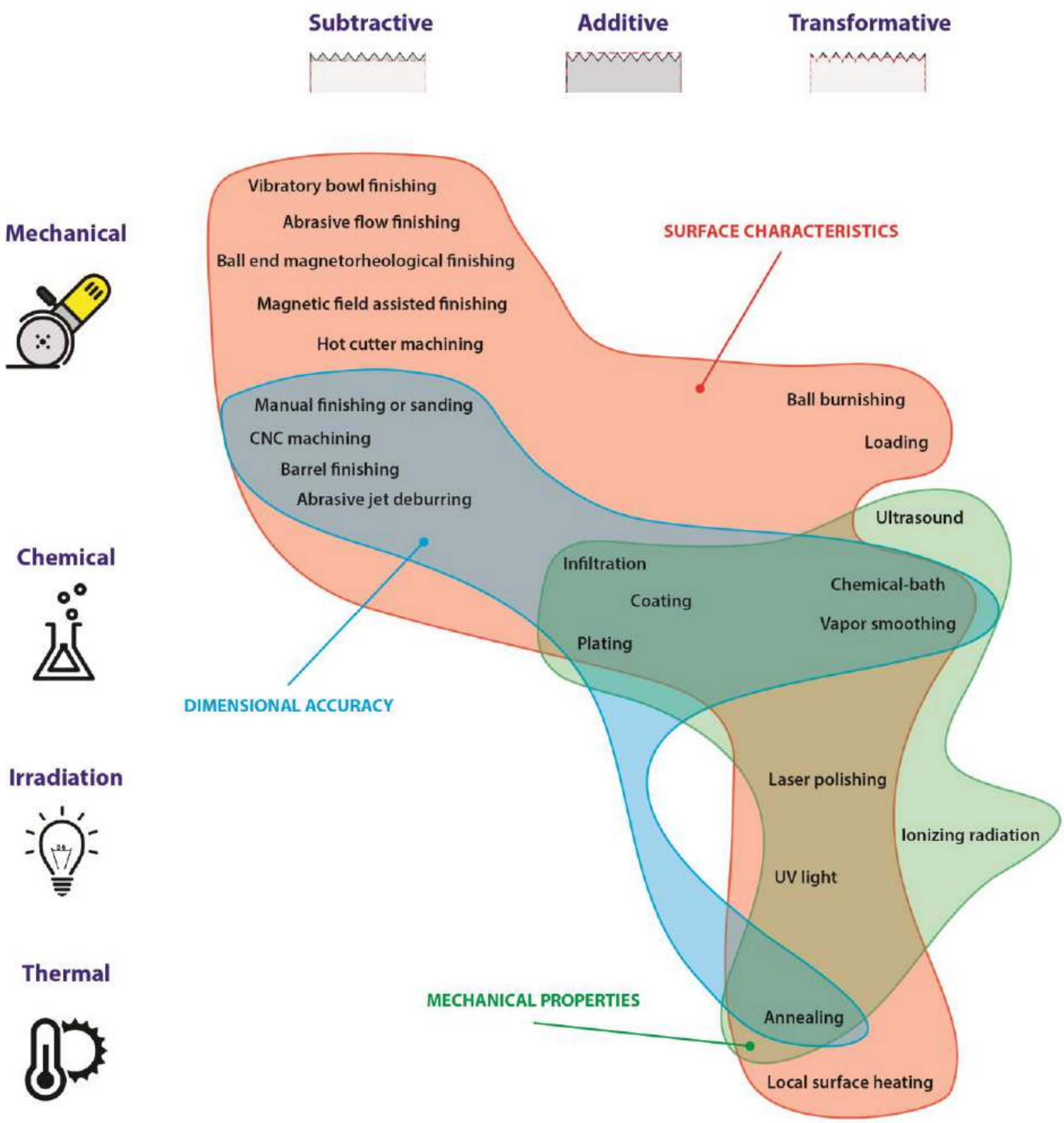


Figure 13. Treatments categorization according to their physical principle and to the modification occurring at the surface level. Correlations between post-processing techniques and treated critical issues are also highlighted by different colors (blue: dimensional accuracy, red: surface characteristics, green: mechanical properties).

6 Future trends

One of the most significant conclusions that can be drawn is that each treatment can improve a specific aspect but may have a negative impact on others, thus affecting its overall effectiveness. For this reason, a possibility that has only been marginally explored by the scientific community relies on a combined action of two or more treatments. This approach would certainly increase the post-processing time and costs which, however, would not represent a significant limitation for the manufacturing of value-added products for advanced and challenging applications. On the other hand, the application of post-treatments in the industrial field cannot ignore considerations regarding post-processing time, which can represent the real critical bottleneck. Each AM technology requires its post-processing treatments, and every possible effort should be oriented toward a sustainable automatization to enable viable use in production contexts. Also, scaling remains a challenge, and investments should be oriented towards eliminating laborious manual workflows, which increase costs and lead time of 3D printed parts.

A final consideration regards lattice and/or auxetic structures and in general cellular materials. Scientific literature has only marginally explored post-processing treatments on these types of structures. Lattice and auxetic structures represent a growing trend in AM for vibration isolation, lightweight design, heat dissipation, metamaterial mechanisms and so on. They can be characterized by multiple and different mechanical behaviors, e.g. high stiffness and strength or high deformations, energy adsorption, ductility and damping. However, as already discussed in the present work, mechanical properties can be affected by the poor surface quality, which could greatly benefit from post-processing treatments. In particular, lattice structures which commonly consist of thin features as basic elements (the strut), can significantly suffer meager surface characteristics (i. e., inhomogeneity and the presence of defects, layer stratification, etc.). The quality of lattice's surface can affect mechanical properties resulting in brittle fractures, low strength, low ductility and toughness. For this reason, post-processing treatments aimed to repair the external surfaces and increase their quality could be of utmost importance in the enhancement of lattice structures and to widen their range of industrial applications.

7 Conclusions

The huge potential of AM polymers in terms of producing parts characterized by high shape optimization and customization is impaired by critical issues such as surface characteristics, low mechanical properties, and dimensional accuracy. For this reason, post-processing treatments are fundamentally necessary to obtain parts with enhanced performance and reliability. In this paper, an in-depth classification and literature review of existing techniques was presented with the aim of providing valid support in selecting the most appropriate treatment in relation to the specific problems to be addressed. The detailed description and discussion of each individual treatment was also aimed at providing a holistic view of the post-processing of polymeric AM parts, which is currently lacking in the scientific literature, and to correlate, where possible, AM technologies, critical issues, and the most appropriate post-processing techniques. The proposed work allows the identification of current deficiencies and opportunities for future developments, which could consist of optimizing the most promising treatments and/or combining multiple approaches to obtain polymeric AM parts characterized by advanced and/or unique performances.

References

Adel, M., O. Abdelaal, A. Gad, A. B. Nasr, and A. Khalil. 2018. "Polishing of fused deposition modeling products by hot air jet: Evaluation of surface roughness." *Journal of Materials Processing Technology* 251:73-82. doi: 10.1016/j.jmatprotec.2017.07.019.

Ahn, S. H., C. S. Lee, and W. Jeong. 2004. "Development of translucent FDM parts by post-processing." *Rapid Prototyping Journal* 10 (4):218-24. doi: 10.1108/13552540410551333.

Akhouri, D., D. Banerjee, and S. B. Mishra. 2020. "A review report on the plating process of fused deposition modelling (FDM) built parts." *Materials Today-Proceedings* 26:2140-2. doi: 10.1016/j.matpr.2020.02.461.

Angel, K., H. H. Tsang, S. S. Bedair, G. L. Smith, and N. Lazarus. 2018. "Selective electroplating of 3D printed parts." *Additive Manufacturing* 20:164-72. doi: 10.1016/j.addma.2018.01.006.

Arun, K., K. Aravindh, K. Raja, P. A. Jeeva, and S. Karthikeyan. 2018. "Metallization of PLA plastics prepared by FDM-RP process and evaluation of corrosion and hardness characteristics." *Materials Today-Proceedings* 5 (5):13107-10. doi: DOI 10.1016/j.matpr.2018.02.299.

Ashby, Michael F., Hugh Shercliff, and David Cebon. 2018. *Materials: engineering, science, processing and design*.

Ayres, T. J., S. R. Sama, S. B. Joshi, and G. P. Manogharan. 2019. "Influence of resin infiltrants on mechanical and thermal performance in plaster binder jetting additive manufacturing." *Additive Manufacturing* 30. doi: 10.1016/J.Addma.2019.100885.

Barone, S., P. Neri, S. Orsi, A. Paoli, A. V. Razionale, and F. Tamburrino. 2020a. "Two coatings that enhance mechanical properties of fused filament-fabricated carbon-fiber reinforced composites." *Additive Manufacturing* 32:101105. doi: https://doi.org/10.1016/j.addma.2020.101105.

Barone, Sandro, Paolo Neri, Sara Orsi, Alessandro Paoli, Armando V. Razionale, and Francesco Tamburrino. 2020b. Properties Enhancement of Carbon PA 3D-Printed Parts by Post-processing Coating-Based Treatments. Paper presented at the Design Tools and Methods in Industrial Engineering, Cham, 2020.

Beal, V. E., R. A. Paggi, G. V. Salmoria, and A. Lago. 2009. "Statistical Evaluation of Laser Energy Density Effect on Mechanical Properties of Polyamide Parts Manufactured by Selective Laser Sintering." *Journal of Applied Polymer Science* 113 (5):2910-9. doi: 10.1002/app.30329.

Bhandari, S., R. A. Lopez-Anido, and D. J. Gardner. 2019. "Enhancing the interlayer tensile strength of 3D printed short carbon fiber reinforced PETG and PLA composites via annealing." *Additive Manufacturing* 30. doi: 10.1016/J.Addma.2019.100922.

Bonada, J., A. Muguruza, X. Fernandez-Francos, and X. Ramis. 2017. "Influence of exposure time on mechanical properties and photocuring conversion ratios for photosensitive materials used in Additive Manufacturing." *Manufacturing Engineering Society International Conference 2017 (Mesic 2017)* 13:762-9. doi: 10.1016/j.promfg.2017.09.182.

Boschetto, A., and L. Bottini. 2015a. "Roughness prediction in coupled operations of fused deposition modeling and barrel finishing." *Journal of Materials Processing Technology* 219:181-92. doi: 10.1016/j.jmatprotec.2014.12.021.

Boschetto, A., and L. Bottini. 2015b. "Surface improvement of fused deposition modeling parts by barrel finishing." *Rapid Prototyping Journal* 21 (6):686-96. doi: 10.1108/Rpj-10-2013-0105.

Boschetto, A., L. Bottini, and F. Veniali. 2016. "Finishing of Fused Deposition Modeling parts by CNC machining." *Robotics and Computer-Integrated Manufacturing* 41:92-101. doi: 10.1016/j.rcim.2016.03.004.

Callister, W. D., and D. G. Rethwisch. 2018. *Materials Science and Engineering: An Introduction, 10th Edition*: Wiley.

Camardella, L. T., O. D. V. Vilella, and H. Breuning. 2017. "Accuracy of printed dental models made with 2 prototype technologies and different designs of model bases." *American Journal of Orthodontics and Dentofacial Orthopedics* 151 (6):1178-87. doi: 10.1016/j.ajodo.2017.03.012.

Caulfield, B., P. E. McHugh, and S. Lohfeld. 2007. "Dependence of mechanical properties of polyamide components on build parameters in the SLS process." *Journal of Materials Processing Technology* 182 (1-3):477-88. doi: 10.1016/j.jmatprotec.2006.09.007.

Cazon, A., P. Morer, and L. Matey. 2014. "PolyJet technology for product prototyping: Tensile strength and surface roughness properties." *Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture* 228 (12):1664-75. doi: 10.1177/0954405413518515.

Chai, Y., R. W. Li, D. M. Perriman, S. Chen, Q. H. Qin, and P. N. Smith. 2018. "Laser polishing of thermoplastics fabricated using fused deposition modelling." *International Journal of Advanced Manufacturing Technology* 96 (9-12):4295-302. doi: 10.1007/s00170-018-1901-5.

Chen, L., X. Z. Zhang, Y. Wang, and T. A. Osswald. 2020. "Laser polishing of Cu/PLA composite parts fabricated by fused deposition modeling: Analysis of surface finish and mechanical properties." *Polymer Composites* 41 (4):1356-68. doi: 10.1002/pc.25459.

Chen, Lan, Xinzhou Zhang, and Shuyuan Gan. 2020. "Effects of laser polishing on surface quality and mechanical properties of PLA parts built by fused deposition modeling." *Journal of Applied Polymer Science* 137 (3):48288. doi: 10.1002/app.48288.

Chen, Y. F., Y. H. Wang, and J. C. Tsai. 2019. "Enhancement of surface reflectivity of fused deposition modeling parts by post-processing." *Optics Communications* 430:479-85. doi: 10.1016/j.optcom.2018.07.011.

Chohan, J. S., and R. Singh. 2017. "Pre and post processing techniques to improve surface characteristics of FDM parts: a state of art review and future applications." *Rapid Prototyping Journal* 23 (3):495-513. doi: 10.1108/Rpj-05-2015-0059.

Chohan, J. S., R. Singh, and K. S. Boparai. 2016. "Parametric optimization of fused deposition modeling and vapour smoothing processes for surface finishing of biomedical implant replicas." *Measurement* 94:602-13. doi: 10.1016/j.measurement.2016.09.001.

Chohan, J. S., R. Singh, K. S. Boparai, R. Penna, and F. Fraternali. 2017. "Dimensional accuracy analysis of coupled fused deposition modeling and vapour smoothing operations for biomedical applications." *Composites Part B-Engineering* 117:138-49. doi: 10.1016/j.compositesb.2017.02.045.

Chung, H., and S. Das. 2006. "Processing and properties of glass bead particulate-filled functionally graded Nylon-11 composites produced by selective laser sintering." *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing* 437 (2):226-34. doi: 10.1016/j.msea.2006.07.112.

Colpani, A., A. Fiorentino, and E. Ceretti. 2019. "Characterization of chemical surface finishing with cold acetone vapours on ABS parts fabricated by FDM." *Production Engineering-Research and Development* 13 (3-4):437-47. doi: 10.1007/s11740-019-00894-3.

Colpani, Alessandro, Antonio Fiorentino, and Elisabetta Ceretti. 2020. "Design and Fabrication of Customized Tracheal Stents by Additive Manufacturing." *Procedia Manufacturing* 47:1029-35. doi: https://doi.org/10.1016/j.promfg.2020.04.318.

Conner, Brett P., Guha P. Manogharan, Ashley N. Martof, Lauren M. Rodomsky, Caitlyn M. Rodomsky, Dakesha C. Jordan, and James W. Limperos. 2014. "Making sense of 3-D printing: Creating a map of additive manufacturing products and services." *Additive Manufacturing* 1-4:64-76. doi: https://doi.org/10.1016/j.addma.2014.08.005.

Coppola, Antonio, Filomena Impero, Cuono Ruggiero, Fabrizio Scala, and Antonino Squillace. 2019. "Set-Up of an Experimental Procedure for the Surface Smoothing of FDM Parts through Acetone Vapor." *Key Engineering Materials* 813:447-52. doi: 10.4028/www.scientific.net/KEM.813.447.

Cotabarren, I., C. A. Palla, C. T. McCue, and A. J. Hart. 2019. "An assessment of the dimensional accuracy and geometry-resolution limit of desktop stereolithography using response surface methodology." *Rapid Prototyping Journal* 25 (7):1169-86. doi: 10.1108/Rpj-03-2019-0060.

Crane, N. B., Q. Ni, A. Ellis, and N. Hopkinson. 2017. "Impact of chemical finishing on laser-sintered nylon 12 materials." *Additive Manufacturing* 13:149-55. doi: 10.1016/j.addma.2016.10.001.

de Campos, B. M., L. C. Bandeira, P. S. Calefi, K. J. Ciuffi, E. J. Nassar, J. V. L. Silva, M. Oliveira, and I. A. Maia. 2011. "Protective coating materials on nylon substrate by sol–gel." *Virtual and Physical Prototyping* 6 (1):33-9. doi: 10.1080/17452759.2010.491938.

Delfs, P., Z. Li, and H.J. Schmid. 2015. Mass finishing of laser sintered parts. Paper presented at the Proceedings of the 26th Annual International Solid Freeform Fabrication Symposium, Austin, TX, USA Aug 10–12.

Dewey, M. P., and D. Ulutan. 2017. "Development of Laser Polishing as an Auxiliary Post-Process to Improve Surface Quality in Fused Deposition Modeling Parts." *Proceedings of the Asme 12th International Manufacturing Science and Engineering Conference - 2017, Vol 2*.

Dixit, N. K., R. Srivastava, and R. Narain. 2019. "Improving surface roughness of the 3D printed part using electroless plating." *Proceedings of the Institution of Mechanical Engineers Part L-Journal of Materials-Design and Applications* 233 (5):942-54. doi: 10.1177/1464420717719920.

Dizon, J. R. C., A. H. Espera, Q. Y. Chen, and R. C. Advincula. 2018. "Mechanical characterization of 3D-printed polymers." *Additive Manufacturing* 20:44-67. doi: 10.1016/j.addma.2017.12.002.

Eiliat, H., and R. J. Urbanic. 2018. "Minimizing voids for a material extrusion-based process." *Rapid Prototyping Journal* 24 (2):485-500. doi: 10.1108/Rpj-05-2017-0092.

Ellis, A., R. Brown, and N. Hopkinson. 2015. "The effect of build orientation and surface modification on mechanical properties of high speed sintered parts." *Surface Topography-Metrology and Properties* 3 (3). doi: 10.1088/2051-672x/3/3/034005.

Equbal, A., and A. K. Sood. 2014a. "Metallization on FDM Parts Using the Chemical Deposition Technique." *Coatings* 4 (3):574-86. doi: 10.3390/coatings4030574.

Equbal, A., and A.K. Sood. 2014b. "Electroless plating of copper on different shaped ABS parts: A comparison." *International Journal of Advanced Materials Manufacturing and Characterization* 4:32-41. doi: 10.11127/ijammc.2014.03.05.

Feng, X. H., Z. Z. Yang, S. S. H. Rostom, M. Dadmun, S. Q. Wang, Q. W. Wang, and Y. J. Xie. 2018. "Reinforcing 3D printed acrylonitrile butadiene styrene by impregnation of methacrylate resin and cellulose nanocrystal mixture: Structural effects and homogeneous properties." *Materials & Design* 138:62-70. doi: 10.1016/j.matdes.2017.10.050.

Fernandez, S., M. Jimenez, J. Porras, L. Romero, M. M. Espinosa, and M. Dominguez. 2016. "Additive Manufacturing and Performance of Functional Hydraulic Pump Impellers in Fused Deposition Modeling Technology." *Journal of Mechanical Design* 138 (2). doi: 10.1115/1.4032089.

Fischer, M., and Volker Schöppner. 2013. "Some investigations regarding the surface treatment of Ultem*9085 parts manufactured with Fused Deposition Modeling." *24th International SFF Symposium - An Additive Manufacturing Conference, SFF 2013*:805-15.

Galantucci, L. M., F. Lavecchia, and G. Percoco. 2009. "Experimental study aiming to enhance the surface finish of fused deposition modeled parts." *Cirp Annals-Manufacturing Technology* 58 (1):189-92. doi: 10.1016/j.cirp.2009.03.071.

Galantucci, L. M., F. Lavecchia, and G. Percoco. 2010. "Quantitative analysis of a chemical treatment to reduce roughness of parts fabricated using fused deposition modeling." *Cirp Annals-Manufacturing Technology* 59 (1):247-50. doi: 10.1016/j.cirp.2010.03.074.

Gao, H., D. V. Kaweesa, J. Moore, and N. A. Meisel. 2017. "Investigating the Impact of Acetone Vapor Smoothing on the Strength and Elongation of Printed ABS Parts." *Jom* 69 (3):580-5. doi: 10.1007/s11837-016-2214-5.

Garg, A., A. Bhattacharya, and A. Batish. 2016. "On Surface Finish and Dimensional Accuracy of FDM Parts after Cold Vapor Treatment." *Materials and Manufacturing Processes* 31 (4):522-9. doi: 10.1080/10426914.2015.1070425.

Garg, A., A. Bhattacharya, and A. Batish. 2017. "Chemical vapor treatment of ABS parts built by FDM: Analysis of surface finish and mechanical strength." *International Journal of Advanced Manufacturing Technology* 89 (5-8):2175-91. doi: 10.1007/s00170-016-9257-1.

Graf, D., S. Neermann, L. Stuber, M. Scheetz, and J. Franke. 2018. "Pushing the Boundaries of 3D-MID: Pulse-Width Modulated Light Technology for Enhancing Surface Properties and Enabling Printed Electronics on FFF-Printed Structures." *2018 13th International Congress Molded Interconnect Devices (Mid)*:39-43.

Guo, J., J. M. Bai, K. Liu, and J. Wei. 2018. "Surface quality improvement of selective laser sintered polyamide 12 by precision grinding and magnetic field-assisted finishing." *Materials & Design* 138:39-45. doi: 10.1016/j.matdes.2017.10.048.

Gupta, B., and N. Anjum. 2003. "Plasma and Radiation-Induced Graft Modification of Polymers for Biomedical Applications." *Radiation Effects on Polymers for Biological Use* 162:35-61.

Hambali, R. H., K. M. Cheong, and N. Azizan. 2017. "Analysis of the influence of chemical treatment to the strength and surface roughness of FDM." *International Technical Postgraduate Conference, 2017* 210. doi: 10.1088/1757-899x/210/1/012063.

Hart, K. R., R. M. Dunn, J. M. Sietins, C. M. H. Mock, M. E. Mackay, and E. D. Wetzel. 2018. "Increased fracture toughness of additively manufactured amorphous thermoplastics via thermal annealing." *Polymer* 144:192-204. doi: 10.1016/j.polymer.2018.04.024.

Impens, D., and R. J. Urbanic. 2015. "Assessing the Impact of Post-Processing Variables on Tensile and Compression Characteristics for 3D Printed Components." *Ifac Papersonline* 48 (3):652-7. doi: 10.1016/j.ifacol.2015.06.156.

Impens, D., and R. J. Urbanic. 2016. "A comprehensive assessment on the impact of post-processing variables on tensile, compressive and bending characteristics for 3D printed components." *Rapid Prototyping Journal* 22 (3):591-608. doi: 10.1108/Rpj-02-2015-0018.

ISO. 2015. "Additive Manufacturing - General Principles - Terminology." In. Geneva, Switzerland: International Organization for Standardization.

Jayanth, N., P. Senthil, and C. Prakash. 2018. "Effect of chemical treatment on tensile strength and surface roughness of 3D-printed ABS using the FDM process." *Virtual and Physical Prototyping* 13 (3):155-63. doi: 10.1080/17452759.2018.1449565.

Jin, Y. F., Y. Wan, B. Zhang, and Z. Q. Liu. 2017. "Modeling of the chemical finishing process for polylactic acid parts in fused deposition modeling and investigation of its tensile properties." *Journal of Materials Processing Technology* 240:233-9. doi: 10.1016/j.jmatprotec.2016.10.003.

Jo, K. H., Y. S. Jeong, J. H. Lee, and S. H. Lee. 2016. "A Study of Post-Processing Methods for Improving the Tightness of a Part Fabricated by Fused Deposition Modeling." *International Journal of Precision Engineering and Manufacturing* 17 (11):1541-6. doi: 10.1007/s12541-016-0180-z.

Kannan, S., and D. Senthilkumaran. 2014a. "Assessment of mechanical properties of Ni-coated ABS plastics using FDM process." *International Journal of Mechanical and Mechatronics Engineering* 14:30-5.

Kannan, S., and D. Senthilkumaran. 2014b. "Investigating the influence of electroplating layer thickness on the tensile strength for fused deposition processed abs thermoplastics." *International Journal of Engineering and Technology* 6:1047-52.

Khan, M. S., S. B. Mishra, M. A. Kumar, and D. Banerjee. 2018. "Optimizing Surface Texture and Coating Thickness of Nickel Coated ABS-3D Parts." *Materials Today-Proceedings* 5 (9):19011-8. doi: DOI 10.1016/j.matpr.2018.06.252.

Khorasani, E. R., and H. Baseri. 2013. "Determination of optimum SLA process parameters of H-shaped parts." *Journal of Mechanical Science and Technology* 27 (3):857-63. doi: 10.1007/s12206-013-0111-1.

Kulkarni, P., and D. Dutta. 2000. "On the integration of layered manufacturing and material removal processes." *Journal of Manufacturing Science and Engineering-Transactions of the Asme* 122 (1):100-8. doi: Doi 10.1115/1.538891.

Kumar, A., Z. Alam, D. A. Khan, and S. Jha. 2019. "Nanofinishing of FDM-fabricated components using ball end magnetorheological finishing process." *Materials and Manufacturing Processes* 34 (2):232-42. doi: 10.1080/10426914.2018.1512136.

Kumar, Krishnan, and Gurunathan Saravana Kumar. 2015. "An experimental and theoretical investigation of surface roughness of poly-jet printed parts." *Virtual and Physical Prototyping* 10 (1):23-34. doi: 10.1080/17452759.2014.999218.

Kumbhar, N. N., and A. V. Mulay. 2018. "Post Processing Methods used to Improve Surface Finish of Products which are Manufactured by Additive Manufacturing Technologies: A Review." *Journal of The Institution of Engineers (India): Series C* 99 (4):481-7. doi: 10.1007/s40032-016-0340-z.

Kumbhar, N.N., and A.V. Mulay. 2016. Finishing of Fused Deposition Modelling (FDM) Printed Parts by CO2 Laser. Paper presented at the Proceedings of 6th International & 27th All India Manufacturing Technology, Design and Research Conference.

Kuo, C. C., C. M. Chen, and S. X. Chang. 2017. "Polishing mechanism for ABS parts fabricated by additive manufacturing." *International Journal of Advanced Manufacturing Technology* 91 (5-8):1473-9. doi: 10.1007/s00170-016-9845-0.

Lalehpour, A., C. Janeteas, and A. Barari. 2018. "Surface roughness of FDM parts after post-processing with acetone vapor bath smoothing process." *International Journal of Advanced Manufacturing Technology* 95 (1-4):1505-20. doi: 10.1007/s00170-017-1165-5.

Lavecchia, F., G. Percoco, E. J. Pei, and L. M. Galantucci. 2018. "Computer Numerical Controlled Grinding and Physical Vapor Deposition for Fused Deposition Modelled Workpieces." *Advances in Materials Science and Engineering* 2018. doi: 10.1155/2018/9037490.

Lee, J. Y., J. An, and C. K. Chua. 2017. "Fundamentals and applications of 3D printing for novel materials." *Applied Materials Today* 7:120-33. doi: 10.1016/j.apmt.2017.02.004.

Lee, J. Y., A. P. Nagalingam, and S. H. Yeo. 2020. "A review on the state-of-the-art of surface finishing processes and related ISO/ASTM standards for metal additive manufactured components." *Virtual and Physical Prototyping*. doi: 10.1080/17452759.2020.1830346.

Lee, J. Y., W. S. Tan, J. An, C. K. Chua, C. Y. Tang, A. G. Fane, and T. H. Chong. 2016. "The potential to enhance membrane module design with 3D printing technology." *Journal of Membrane Science* 499:480-90. doi: 10.1016/j.memsci.2015.11.008.

Lee, K. M., H. Park, J. Kim, and D. M. Chun. 2019. "Fabrication of a superhydrophobic surface using a fused deposition modeling (FDM) 3D printer with poly lactic acid (PLA) filament and dip coating with silica nanoparticles." *Applied Surface Science* 467:979-91. doi: 10.1016/j.apsusc.2018.10.205.

Leite, M., A. Varanda, A. R. Ribeiro, A. Silva, and M. F. Vaz. 2018. "Mechanical properties and water absorption of surface modified ABS 3D printed by fused deposition modelling." *Rapid Prototyping Journal* 24 (1):195-203. doi: 10.1108/Rpj-04-2016-0057.

Leonardi, Francesco, Serena Graziosi, Riccardo Casati, Francesco Tamburrino, and Monica Bordegoni. 2019. "Additive Manufacturing of Heterogeneous Lattice Structures: An Experimental Exploration." *Proceedings of the Design Society: International Conference on Engineering Design* 1 (1):669-78. doi: 10.1017/dsi.2019.71.

Leong, K. F., C. K. Chua, G. S. Chua, and C. H. Tan. 1998. "Abrasive jet deburring of jewellery models built by stereolithography apparatus (SLA)." *Journal of Materials Processing Technology* 83 (1-3):36-47. doi: Doi 10.1016/S0924-0136(98)00041-7.

Leuteritz, G., and R. Lachmayer. 2018. "Additive Manufacturing of Reflective Optics: Evaluating Finishing Methods." *Laser 3d Manufacturing V* 10523. doi: 10.1117/12.2289998.

Li, G. W., J. Zhao, J. L. Jiang, H. Jiang, W. Z. Wu, and M. X. Tang. 2018. "Ultrasonic strengthening improves tensile mechanical performance of fused deposition modeling 3D printing." *International Journal of Advanced Manufacturing Technology* 96 (5-8):2747-55. doi: 10.1007/s00170-018-1789-0.

Mali, H. S., and A. Manna. 2009. "Current status and application of abrasive flow finishing processes: a review." *Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture* 223 (7):809-20. doi: 10.1243/09544054JEM1311.

Mali, H. S., B. Prajwal, D. Gupta, and J. Kishan. 2018. "Abrasive flow finishing of FDM printed parts using a sustainable media." *Rapid Prototyping Journal* 24 (3):593-606. doi: 10.1108/Rpj-10-2017-0199.

McCullough, E. J., and V. K. Yadavalli. 2013. "Surface modification of fused deposition modeling ABS to enable rapid prototyping of biomedical microdevices." *Journal of Materials Processing Technology* 213 (6):947-54. doi: 10.1016/j.jmatprotec.2012.12.015.

Medellin, Anthony, Wenchao Du, Guanxiong Miao, Jun Zou, Zhijian Pei, and Chao Ma. 2019. "Vat Photopolymerization 3D Printing of Nanocomposites: A Literature Review." *Journal of Micro and Nano-Manufacturing* 7 (3). doi: 10.1115/1.4044288.

Metel, A. S., M. M. Stebulyanin, S. V. Fedorov, and A. A. Okunkova. 2018. "Power Density Distribution for Laser Additive Manufacturing (SLM): Potential, Fundamentals and Advanced Applications." *Technologies* 7 (1). doi: 10.3390/technologies7010005.

Miguel, M., M. Leite, R. Ribeiro, A. M. Deus, L. Reis, and M. F. Vaz. 2019. "Failure of polymer coated nylon parts produced by additive manufacturing." *Engineering Failure Analysis* 101:485-92. doi: 10.1016/j.engfailanal.2019.04.005.

Mireles, Jorge, A. Adame, David Espalin, Francisco Medina, R. Winker, T. Hoppe, B. Zinniel, and R. Wicker. 2011. "Analysis of Sealing Methods for FDM-fabricated Parts." *22nd Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2011*.

Neff, C., E. A. Rojas-Nastrucci, J. Nussbaum, D. Griffin, T. M. Weller, and N. B. Crane. 2019. "Thermal and Vapor Smoothing of Thermoplastic for Reduced Surface Roughness of Additive Manufactured RF Electronics." *Ieee Transactions on Components Packaging and Manufacturing Technology* 9 (6):1151-60. doi: 10.1109/Tcpmt.2019.2910791.

Neff, C., M. Trapuzzano, and N. B. Crane. 2018. "Impact of vapor polishing on surface quality and mechanical properties of extruded ABS." *Rapid Prototyping Journal* 24 (2):501-8. doi: 10.1108/Rpj-03-2017-0039.

Ngo, T. D., A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui. 2018. "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges." *Composites Part B-Engineering* 143:172-96. doi: 10.1016/j.compositesb.2018.02.012.

Nguyen, T. K., and B. K. Lee. 2018. "Post-processing of FDM parts to improve surface and thermal properties." *Rapid Prototyping Journal* 24 (7):1091-100. doi: 10.1108/Rpj-12-2016-0207.

Nsengimana, J., J. Van der Walt, E. J. Pei, and M. Miah. 2019. "Effect of post-processing on the dimensional accuracy of small plastic additive manufactured parts." *Rapid Prototyping Journal* 25 (1):1-12. doi: 10.1108/Rpj-09-2016-0153.

Olivera, S., H. B. Muralidhara, K. Venkatesh, K. Gopalakrishna, and C. S. Vivek. 2016. "Plating on acrylonitrile-butadiene-styrene (ABS) plastic: a review." *Journal of Materials Science* 51 (8):3657-74. doi: 10.1007/s10853-015-9668-7.

Oskui, S. M., G. Diamante, C. Y. Liao, W. Shi, J. Gan, D. Schlenk, and W. H. Grover. 2016. "Assessing and Reducing the Toxicity of 3D-Printed Parts." *Environmental Science & Technology Letters* 3 (1):1-6. doi: 10.1021/acs.estlett.5b00249.

Pan, C., Y. F. Han, and J. P. Lu. 2020. "Design and Optimization of Lattice Structures: A Review." *Applied Sciences-Basel* 10 (18). doi: 10.3390/App10186374.

Pandey, P. M., N. V. Reddy, and S. G. Dhande. 2003. "Improvement of surface finish by staircase machining in fused deposition modeling." *Journal of Materials Processing Technology* 132 (1-3):323-31. doi: 10.1016/S0924-0136(02)00953-6.

Pandey, Pulak M., N. Venkata Reddy, and Sanjay G. Dhande. 2006. "Virtual hybrid-FDM system to enhance surface finish." *Virtual and Physical Prototyping* 1 (2):101-16. doi: 10.1080/17452750600763905.

Percoco, Gianluca, Fulvio Lavecchia, and Luigi Galantucci. 2012a. "Compressive Properties of FDM Rapid Prototypes Treated with a Low Cost Chemical Finishing." *Research Journal of Applied Sciences, Engineering and Technology* 4 (19):3838-42.

Percoco, Gianluca, Fulvio Lavecchia, and Luigi Maria Galantucci. 2012b. "Compressive properties of FDM rapid prototypes treated with a low cost chemical finishing." *Research Journal of Applied Sciences, Engineering and Technology* 4 (19):3838-42.

Prajapati, H., D. Chalise, D. Ravoori, R. M. Taylor, and A. Jain. 2019. "Improvement in build-direction thermal conductivity in extrusion-based polymer additive manufacturing through thermal annealing." *Additive Manufacturing* 26:242-9. doi: 10.1016/j.addma.2019.01.004.

Rankouhi, B., S. Javadpour, F. Delfanian, R. McTaggart, and T. Letcher. 2018. "Experimental Investigation of Mechanical Performance and Printability of Gamma-Irradiated Additively Manufactured ABS." *Journal of Materials Engineering and Performance* 27 (7):3643-54. doi: 10.1007/s11665-018-3463-y.

Saleh, N., N. Hopkinson, R. J. M. Hague, and S. Wise. 2004. "Effects of electroplating on the mechanical properties of stereolithography and laser sintered parts." *Rapid Prototyping Journal* 10 (5):305-15. doi: 10.1108/13552540410562340.

Salmi, M., K. S. Paloheimo, J. Tuomi, J. Wolff, and A. Makitie. 2013. "Accuracy of medical models made by additive manufacturing (rapid manufacturing)." *Journal of Cranio-Maxillofacial Surgery* 41 (7):603-9. doi: 10.1016/j.jcms.2012.11.041.

Schmid, M., A. Amado, and K. Wegener. 2014. "Materials perspective of polymers for additive manufacturing with selective laser sintering." *Journal of Materials Research* 29 (17):1824-32. doi: 10.1557/jmr.2014.138.

Schmid, M., C. Simon, and G. N. Levy. 2009. Finishing of SLS-Parts for Rapid Manufacturing (RM) - A Comprehensive Approach. Paper presented at the 20th, Solid freeform fabrication symposium.

Shaffer, S., K. J. Yang, J. Vargas, M. A. Di Prima, and W. Voit. 2014. "On reducing anisotropy in 3D printed polymers via ionizing radiation." *Polymer* 55 (23):5969-79. doi: 10.1016/j.polymer.2014.07.054.

Shen, X. C., and H. E. Naguib. 2019. "A robust ink deposition system for binder jetting and material jetting." *Additive Manufacturing* 29. doi: 10.1016/J.Addma.2019.100820.

Singh, A. K., S. Jha, and P. M. Pandey. 2011. "Design and development of nanofinishing process for 3D surfaces using ball end MR finishing tool." *International Journal of Machine Tools & Manufacture* 51 (2):142-51. doi: 10.1016/j.ijmachtools.2010.10.002.

Singh, A. K., S. Jha, and P. M. Pandey. 2013. "Mechanism of material removal in ball end magnetorheological finishing process." *Wear* 302 (1-2):1180-91. doi: 10.1016/j.wear.2012.11.082.

Singh, J., R. Singh, and H. Singh. 2016. "Repeatability of linear and radial dimension of ABS replicas fabricated by fused deposition modelling and chemical vapor smoothing process: A case study." *Measurement* 94:5-11. doi: 10.1016/j.measurement.2016.07.064.

Singh, R., S. Singh, I. P. Singh, F. Fabbrocino, and F. Fraternali. 2017. "Investigation for surface finish improvement of FDM parts by vapor smoothing process." *Composites Part B-Engineering* 111:228-34. doi: DOI 10.1016/j.compositesb.2016.11.062.

Singh, R., and A. Trivedi. 2017. "Experimental Investigations for Surface Roughness and Dimensional Accuracy of FDM Components with Barrel Finishing." *Proceedings of the National Academy of Sciences India Section a-Physical Sciences* 87 (3):455-63. doi: 10.1007/s40010-017-0367-4.

Singh, S., S. Ramakrishna, and R. Singh. 2017. "Material issues in additive manufacturing: A review." *Journal of Manufacturing Processes* 25:185-200. doi: 10.1016/j.jmapro.2016.11.006.

Singh, S., M. Singh, C. Prakash, M. K. Gupta, M. Mia, and R. Singh. 2019. "Optimization and reliability analysis to improve surface quality and mechanical characteristics of heat-treated fused filament fabricated parts." *International Journal of Advanced Manufacturing Technology* 102 (5-8):1521-36. doi: 10.1007/s00170-018-03276-8.

Suwanprateeb, J. 2006. "Improvement in mechanical properties of three-dimensional printing parts made from natural polymers reinforced by acrylate resin for biomedical applications: a double infiltration approach." *Polymer International* 55 (1):57-62. doi: 10.1002/pi.1918.

Suwanprateeb, J., and W. Suwanpreuk. 2009. "Development of translucent and strong three dimensional printing models." *Rapid Prototyping Journal* 15 (1):52-8. doi: 10.1108/13552540910925063.

Syam, W. P., K. Rybalcenko, A. Gaio, J. Crabtree, and R. K. Leach. 2019. "Methodology for the development of in-line optical surface measuring instruments with a case study for additive surface finishing." *Optics and Lasers in Engineering* 121:271-88. doi: 10.1016/j.optlaseng.2019.04.015.

Syam, W. P., J. W. Wu, B. Zhao, I. Maskery, W. Elmadih, and R. Leach. 2018. "Design and analysis of strut-based lattice structures for vibration isolation." *Precision Engineering-Journal of the International Societies for Precision Engineering and Nanotechnology* 52:494-506. doi: 10.1016/j.precisioneng.2017.09.010.

Taufik, M., and P. K. Jain. 2016. "CNC-assisted selective melting for improved surface finish of FDM parts." *Virtual and Physical Prototyping* 11 (4):319-41. doi: 10.1080/17452759.2016.1245943.

Taufik, M., and P. K. Jain. 2017. "Laser assisted finishing process for improved surface finish of fused deposition modelled parts." *Journal of Manufacturing Processes* 30:161-77. doi: 10.1016/j.jmapro.2017.09.020.

Tofail, S. A. M., E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, and C. Charitidis. 2018. "Additive manufacturing: scientific and technological challenges, market uptake and opportunities." *Materials Today* 21 (1):22-37. doi: 10.1016/j.mattod.2017.07.001.

Torrado, A. R., C. M. Shemelya, J. D. English, Y. R. Lin, R. B. Wicker, and D. A. Roberson. 2015. "Characterizing the effect of additives to ABS on the mechanical property anisotropy of specimens fabricated by material extrusion 3D printing." *Additive Manufacturing* 6:16-29. doi: 10.1016/j.addma.2015.02.001.

Torres, J., J. Cotelo, J. Karl, and A. P. Gordon. 2015. "Mechanical Property Optimization of FDM PLA in Shear with Multiple Objectives." *Jom* 67 (5):1183-93. doi: 10.1007/s11837-015-1367-y.

Turner, B. N., and S. A. Gold. 2015. "A review of melt extrusion additive manufacturing processes: II. Materials, dimensional accuracy, and surface roughness." *Rapid Prototyping Journal* 21 (3):250-61. doi: 10.1108/Rpj-02-2013-0017.

Uzcategui, A. C., A. Muralidharan, V. L. Ferguson, S. J. Bryant, and R. R. McLeod. 2018. "Understanding and Improving Mechanical Properties in 3D printed Parts Using a Dual-Cure Acrylate-Based Resin for Stereolithography." *Advanced Engineering Materials* 20 (12). doi: 10.1002/Adem.201800876.

Vaezi, M., and C. K. Chua. 2011. "Effects of layer thickness and binder saturation level parameters on 3D printing process." *International Journal of Advanced Manufacturing Technology* 53 (1-4):275-84. doi: 10.1007/s00170-010-2821-1.

Valerga, A. P., M. Batista, S. R. Fernandez-Vidal, and A. J. Gamez. 2019. "Impact of Chemical Post-Processing in Fused Deposition Modelling (FDM) on Polylactic Acid (PLA) Surface Quality and Structure." *Polymers* 11 (3). doi: 10.3390/Polym11030566.

Vicente, C. M. S., J. Fernandes, L. Reis, A. M. de Deus, M. F. Vaz, and M. Leite. 2019. "Effect of protective coatings on the water absorption and mechanical properties of 3D printed PLA." *Frattura Ed Integrita Strutturale* (48):748-56. doi: 10.3221/Igf-Esis.48.68.

Vinitha, M., A.N. Rao, and M.K. Mallik. 2012. "Optimization of speed parameters in burnishing of samples fabricated by fused deposition modeling." *Journal of Mechanical and Industrial Engineering* 2 (2):10-2.

Wady, P., A. Wasilewski, L. Brock, R. Edge, A. Baidak, C. McBride, L. Leay, A. Griffiths, and C. Valles. 2020. "Effect of ionising radiation on the mechanical and structural properties of 3D printed plastics." *Additive Manufacturing* 31. doi: 10.1016/J.Addma.2019.100907.

Wagner, John R., Eldridge M. Mount, and Harold F. Giles. 2014. "19 - Polymer Structure." In *Extrusion (Second Edition)*, edited by John R. Wagner, Eldridge M. Mount and Harold F. Giles, 225-32. Oxford: William Andrew Publishing.

Wang, L., Y. Ju, H. P. Xie, G. W. Ma, L. T. Mao, and K. X. He. 2017. "The mechanical and photoelastic properties of 3D printable stress-visualized materials." *Scientific Reports* 7. doi: 10.1038/S41598-017-11433-4.

Wang, Y. Q., Z. G. Liu, H. W. Gu, C. Z. Cui, and J. B. Hao. 2019. "Improved mechanical properties of 3D-printed SiC/PLA composite parts by microwave heating." *Journal of Materials Research* 34 (20):3412-9. doi: 10.1557/jmr.2019.296.

West, C., R. McTaggart, T. Letcher, D. Raynie, and R. Roy. 2019. "Effects of Gamma Irradiation Upon the Mechanical and Chemical Properties of 3D-Printed Samples of Polylactic Acid." *Journal of Manufacturing Science and Engineering-Transactions of the Asme* 141 (4). doi: 10.1115/1.4042581.

Wickramasinghe, Sachini, Truong Do, and Phuong Tran. 2020. "FDM-Based 3D Printing of Polymer and Associated Composite: A Review on Mechanical Properties, Defects and Treatments." *Polymers* 12:1529. doi: 10.3390/polym12071529.

Williams, R. E., and V. L. Melton. 1998. "Abrasive flow finishing of stereolithography prototypes." *Rapid Prototyping Journal* 4 (2):56-67. doi: Doi 10.1108/13552549810207279.

Wjesundera, P., J. Schutte, and J. Potgieter. 2017. "The effects of Acetone vapour inter-layer processing on Fused Deposition Modelling 3D Printed Acrylonitrile Butadiene Styrene." *2017 24th International Conference on Mechatronics and Machine Vision in Practice (M2vip)*:474-8.

Wohlers. 2020. "Wohlers Report 2020 - 3D Printing and Additive Manufacturing Global State of the Industry." In.

Wu, W. Z., J. L. Jiang, H. Jiang, W. Liu, G. W. Li, B. F. Wang, M. X. Tang, and J. Zhao. 2018. "Improving bending and dynamic mechanics performance of 3D printing through ultrasonic strengthening." *Materials Letters* 220:317-20. doi: 10.1016/j.matlet.2018.03.048.

Xu, Kaiwen, Tao Xi, and Chunrong Liu. 2019. "Design of the desktop vapor polisher with acetone vapor absorption mechanism." *Journal of Physics: Conference Series* 1303:012061. doi: 10.1088/1742-6596/1303/1/012061.

Yang, Y. R., L. Li, and J. Zhao. 2019. "Mechanical property modeling of photosensitive liquid resin in stereolithography additive manufacturing: Bridging degree of cure with tensile strength and hardness." *Materials & Design* 162:418-28. doi: 10.1016/j.matdes.2018.12.009.

Zaldivar, Rafael J., Tait D. McLouth, Dhruv N. Patel, Joseph V. Severino, and Hyun I. Kim. 2017. "Strengthening of plasma treated 3D printed ABS through epoxy infiltration." *Progress in Additive Manufacturing* 2 (4):193-200. doi: 10.1007/s40964-017-0032-0.

Zareiyan, B., and B. Khoshnevis. 2017. "Interlayer adhesion and strength of structures in Contour Crafting - Effects of aggregate size, extrusion rate, and layer thickness." *Automation in Construction* 81:112-21. doi: 10.1016/j.autcon.2017.06.013.

Zarringhalam, H., and N. Hopkinson. 2003. "Post-processing of Duraform™ parts for rapid manufacture." *University of Texas (Austin): Proceedings of the 14th Solid Freeform Fabrication (SFF) Symposium*.
Zhang, S. U., J. Han, and H. W. Kang. 2017. "Temperature-dependent mechanical properties of ABS parts fabricated by fused deposition modeling and vapor smoothing." *International Journal of Precision Engineering and Manufacturing* 18 (5):763-9. doi: 10.1007/s12541-017-0091-7.
Zhu, J. Y., J. L. Chen, R. K. Lade, W. J. Suszynski, and L. F. Francis. 2015. "Water-based coatings for 3D printed parts." *Journal of Coatings Technology and Research* 12 (5):889-97. doi: 10.1007/s11998-015-9710-3.
Ziaee, M., and N. B. Crane. 2019. "Binder jetting: A review of process, materials, and methods." *Additive Manufacturing* 28:781-801. doi: 10.1016/j.addma.2019.05.031.