A review of finishing processes for 3D printed metallic parts

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KEYWORDS

Additive Manufacturing,
Surface Integrity,
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ABSTRACT

Nowadays, metallic 3D printed parts are widely used in almost every sector, such as aerospace, automobile, medical, etc. However, the printed parts cannot be directly utilized as the surface roughness is very high. Therefore, post-processing techniques are required to improve its surface integrity. In the present manuscript, techniques such as Abrasive flow finishing (AFF), Magnetorheological abrasive flow finishing (MRAFF), Aerolap polishing (AP), and Laser polishing (LP) have been discussed. The mechanism of each process, along with its pros and cons, and applications also be discussed. This will help the researchers and industries to analyse which process is more efficient for a specific application.

1. Introduction

Additive manufacturing (AM), or 3D printing, is a revolutionary technology in producing metallic components, allowing for the creation of complex geometries by adding material layer by layer. Unlike traditional subtractive methods, such as machining, which removes material from a solid block, AM offers significant advantages like design flexibility, reduced waste, and the ability to produce intricate parts (Singh et al., 2020). However, metallic components produced by AM often require additional finishing to meet specific functional, aesthetic, and quality standards. Finishing is crucial to improve surface quality, as the layer-by-layer process can result in rough textures (Kumar et al., 2021), visible layer lines, or partially fused particles that can affect performance, especially in applications where smooth surfaces are essential, such as in fluid dynamics or medical implants. Achieving dimensional accuracy is another challenge; factors like thermal distortion and residual stresses can lead to deviations from the desired dimensions, necessitating post-processing methods like CNC machining or grinding to bring parts within tight tolerances (Kumar et al., 2022a). Additionally, the mechanical properties of additively manufactured parts, such as strength and fatigue resistance, can be compromised by defects like porosity or micro-cracks, which require treatments like hot isostatic pressing or heat treatment to improve material homogeneity. Furthermore, AM processes often involve support structures that must be removed without damaging the part, making post-processing necessary. The need for finishing is also driven by aesthetic requirements, corrosion resistance, and compliance with industry standards, especially in sectors like aerospace, automotive, and medical, where high-quality surface finishes and precise mechanical properties are critical. Thus, while additive manufacturing offers numerous benefits, the role of finishing processes is essential to realize the full potential of AM, ensuring that metallic components are reliable, durable, and meet the rigorous demands of modern engineering applications (Kumar et al., 2021).

There are several techniques that improve the surface integrity of metal additive components, such as abrasive flow finishing (Petare and Jain, 2018), magnetorheological abrasive flow finishing (Kumar et al., 2021), laser polishing (Ma et al., 2017) and, aerolap polishing (Ramesh et al., 2012), as presented in Fig. 1. In the following section, a detailed description of each process will be presented along with its pros and cons.

2. Discussion on Different Polishing Techniques

- Abrasive Flow Finishing (AFF)

AFF is a non-traditional finishing process in which the media is forced to flow through the close vicinity of the component to be polished. The media typically comprises two main elements

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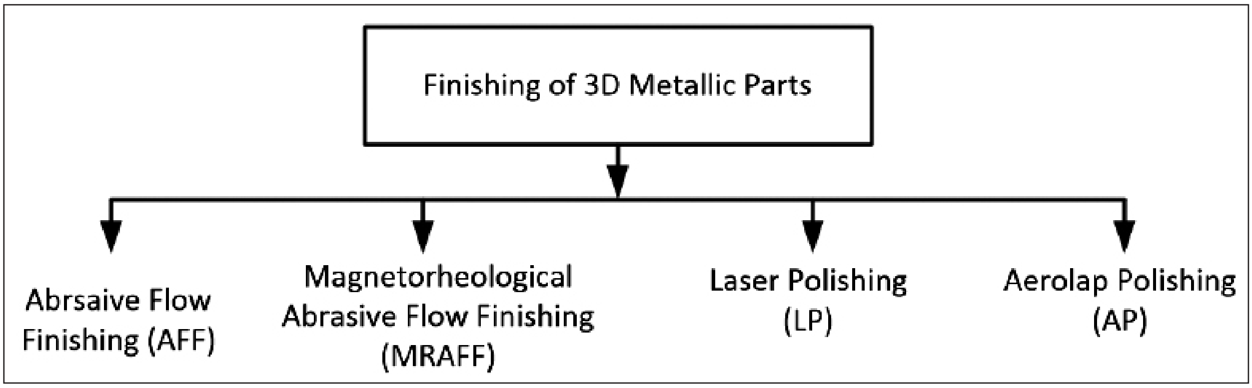

Fig. 1. Types of finishing processes for 3D metallic parts.

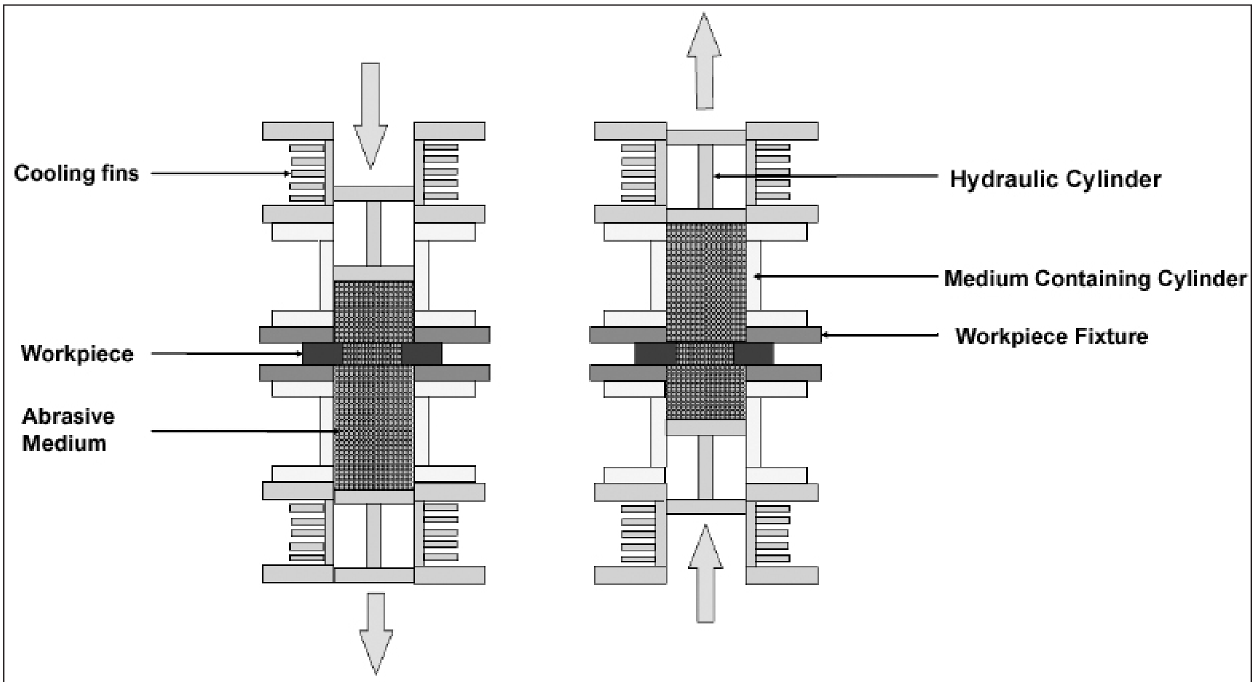

Fig. 2. Schematic representation of the AFF process.

– the carrier (a viscoelastic product, e.g., gels (hydrocarbon), oils (silicone oil or turpentine oil)) and the hard (abrasive) grains. Carrier media constituents and their concentrations significantly influence the rheological properties (viscosity, shear yield stress, or thixotropy) of AFM media which ultimately influences the efficiency of the AFM process. The most widely used abrasives are SiC, B_4C, CBN, Al_2O_3, and diamonds. The media can adopt any shape as per the component geometry; thus, it is a very versatile process that can finish any complex geometry.

The schematic experimental setup of the AFF process is shown in Fig. 2. The component is placed inside a fixture in two cylinders (top and bottom). The fixture has to be made as per the component dimensions. The media will move to and fro in the cylinders, sliding across the component and providing a good surface finish. Higher viscosity media are used where the passage is larger, and lower viscosity media are used where the passage is smaller or around radius edges (Kumar et al., 2021). The important process parameters of AFM are extrusion pressure, abrasive mesh size, processing time and media flow rate.

Petare and Jain (2018) critically reviewed the AFM process and its capabilities. They discussed the details of various workpiece materials, finishing medium, process parameters, and their responses. It also discussed various applications of AFM, such as avionics, automobiles, biomedical, gears, additive manufacturing, cutting tool inserts, die and mold manufacturing, and recast layer removal.

Kim and Kim (2004) utilized the AFM process to remove the burrs in spring collets. They observed

Table 1
Composition of media and their functions for MRAFF process (Kumar et al., 2022).

Sl. No.	Constituents	Functions
1	Carbonyl iron particles (CIPs)	Acts as magnetic particles
2	SiC abrasive	Abrasive which removes the material
3	Hydrogen peroxide (H_2O_2)	To dissolve the metal surfaces to aid abrasives
4	Nitric acid (HNO_3)	To stimulate the surfaces
5	Glycerol	Additive which acts as a stabilizer and also helps to control sedimentation.
6	Deionized water	To protect the media against corrosion

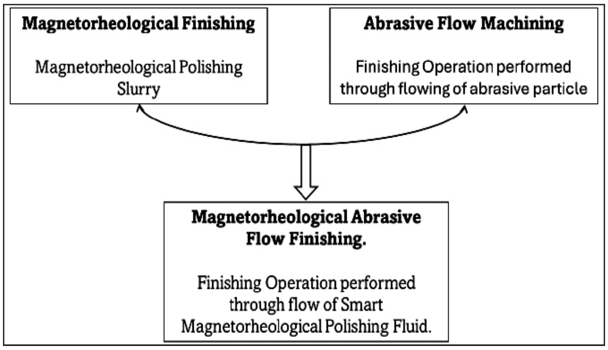

Fig. 3. Origin of the MRAFF process.

that the SiC media is superior to Al_2O_3 in terms of burrs removal. Better surface finish was observed in high viscosity media along with better circularity and concentricity. Venkatesh et al. (2014) utilized AFM for finishing of bevel gears. They developed a fixture such that the media should flow only to the gear tooth surface. The surface roughness was improved from 1.4 µm to 0.8 µm, with extrusion pressure have the highest percentage contribution for the improvement. Wu and Gao (2015) utilized AFM for the finishing of raceways of large bearing rings. The surface roughness achieved after grinding was 0.4 µm, however, after AFM, it was reduced to 0.1 µm. It was illustrated that the abrasives undergo sliding, rolling, and cutting such that the peaks from the surface get removed and the gap between peak and valley is minimized, reducing the surface roughness.

Along with these advantages, AFM also has certain disadvantages, such as its viscosity is not controllable, i.e., when the media moves through a narrow region, its viscosity increases and vice versa. The cutting depth of the abrasives on the surfaces relies on the implemented extrusion pressure and the media's rigidity (Cheema et al., 2012). Due to this, uniform material removal is not taking place; thereby, precise surface roughness, all across the surface, is difficult to obtain. Thus, media viscosity should be controlled externally (Wu & Gao, 2015; Kenda et al., 2014). To overcome this disadvantage of AFM, another technique is there, in which the media is magnetic in nature, and its viscosity gets controlled by the external magnetic field, as discussed in a subsequent section.

- **Magnetorheological abrasive flow finishing (MRAFF)**

The MRAFF process is a combination of abrasive flow machining (AFM) and magnetorheological finishing (MRF) as shown in Fig. 3. In the AFM process, the polymeric media is not controlled by external agents; however, in MRF, forces can be controlled by an external magnetic field. Combining these two processes, the MRAFF process, offers advantages of both the processes (Das et al., 2007). In this process, the media consists of ferromagnetic particles commonly known as carbonyl iron particles (CIP), abrasives, and the rheological fluid. The functions of each constituent of media are described in Table 1.

This media is also termed as smart media as its viscosity changes with respect to the magnetic field lines. Higher field lines lead to higher viscosity (Kumar et al., 2021).

Due to externally controlled viscosity, the media can be utilized to polish any complex surface, thereby creating a versatile finishing process.

The experimental setup of MRAFF process as shown in Fig. 4 is almost similar to the AFM i.e. top and bottom hydraulic cylinders in which the

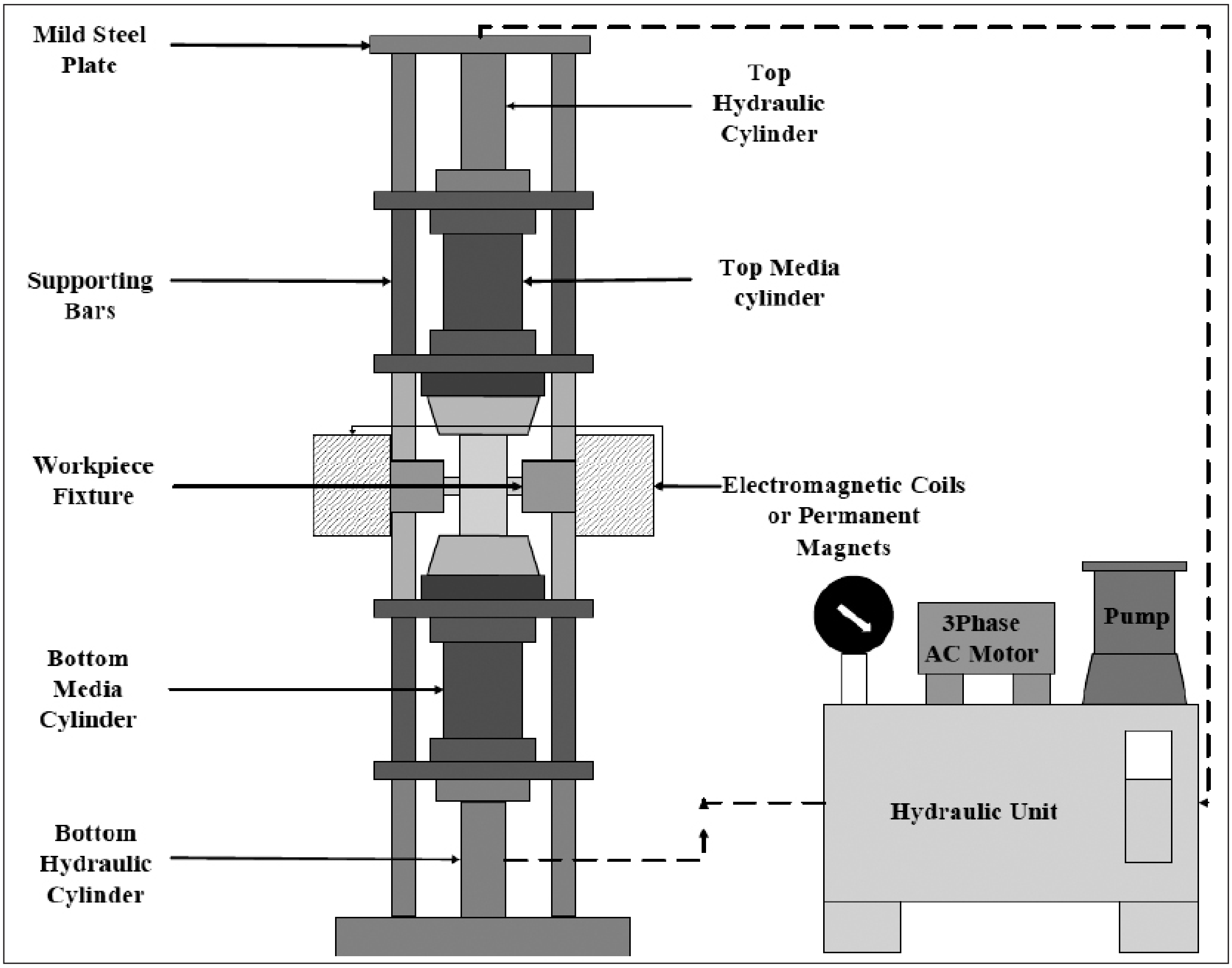

Fig. 4. Schematic representation of the MRAFF process.

media will flow to and fro, passing through the component to be finished. As the media viscosity is controlled by an external magnetic field, an electromagnetic coil or permanent magnets are placed in the near vicinity, such that the magnetic field can be aligned as per the requirement. A hydraulic unit is also attached to move the media from the top to the bottom cylinder and vice versa.

Das et al. (2007) utilized MRAFF for the nano-finishing of parts with complex geometry for industrial application. They assumed the media as Bingham plastic for stress evaluation and also attached a viscometer to study the variation of rheological properties in the effect of the magnetic field. They also developed a model for the prediction of material removal and surface roughness, which produces comparable results with the experimental values.

Das et al. (2011) utilized rotational-MRAFF (R-MRAFF) for the nano-finishing of steel and brass workpieces. In this process, the oscillatory motion of the workpiece also provides a rotational motion. It was concluded that R-MRAFF provides a better surface finish compared to MRAFF. The maximum %ΔRa (% change in surface roughness value) for steel and brass samples are 46.15% and 70.83%, respectively. It was also concluded that these processes are less efficient for magnetic materials compared to non-magnetic materials.

Nagdeve et al. (2017) utilized MRAFF to achieve a uniform nanoscale surface finish in the freeform surface of the femoral (Knee joint). A special tool is designed which is the negative replica of the knee joint and it is adjusted in such a manner that the medium flow velocity in the fluid flow is almost constant along the medium flow direction. In addition to this, a pulsating magnetic field is also attached to produce vibration, such that the interaction of the abrasive particles is uniform during the polishing.

The challenges faced by the AFF process are overcome by the MRAFF process. However, the

MRAFF process also has challenges, such as the same media cannot be used again, as particles from the components get trapped in between. The initial surface finish of the component should be in the range of 100-400 nm; otherwise, the finishing time will be very high, or frequent media changes will be needed. The process is mostly utilized for complex components; however, it requires a customized fixture. Overall, the cost of polishing will be very high.

- **Laser Polishing (LP)**

Laser polishing, another post-processing techniques to improve the surface roughness of additively manufactured parts. In LP, when a laser source is directed over the surface of the AM components in a controlled manner such that only the surface peaks are remelted. Due to the effect of gravity and surface tension, the liquid metal redistributes to fill the gap between the peak and valley after molten-pool formation. After scanning, the laser beam stops and temperature of heat-affected zone (HAZ) decreases, which results in the solidification of the molten pool,

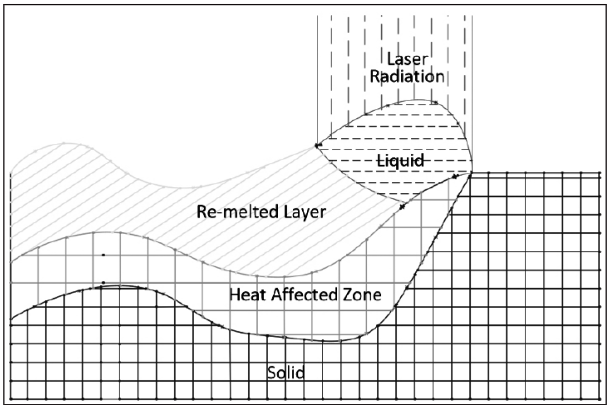

Fig. 5. Surface structuring during laser polishing.

thereby decreases the surface roughness (Ma et al., 2017). It does not change the bulk properties of the component, however, changes the surface morphology (Peng et al., 2021).

On the application of the laser to the surface of the component, the top layer turns into a liquid due to laser radiation, however the sub-surface also gets affected by the heat. As the laser source moves, there is a re-melted layer below the liquid layer, and below it, the heat-affected affected zone (HAZ) as shown in Fig.5. The HAZ produced will have a higher grain size compared to the base solid material, due to the entrapped heat. Due to this, the laser-polished components have some residual stress.

Lee et al. (2021) laser polished the additive manufactured titanium alloy to improve the fatigue performance. It was observed that the fabricated surface is very rough with non-uniform distribution of peaks and valley. During LP, there is no material waste, however, the measured cross-sectional area reduces significantly from 10.28 mm^2 to 9.75 mm^2. Zhou et al. (2021) studied laser polishing on Laser-Powder Bed Fusion AlSi10Mg alloy. It was observed that the surface roughness on the component in LP depends on the mass transfer caused by melting and re-solidification. Due to wetting and diffusion action of the melt pool, the mass is transferred from crests to troughs. The microstructure changed from a coarse columnar grain structure to fine equiaxed grain structure. The final R_a of the surface was reduced from 12.5 µm to 3.7 µm.

- **Aerolap Polishing (AP)**

Sand blasting, a popular technique to reduce the surface roughness of metal additive

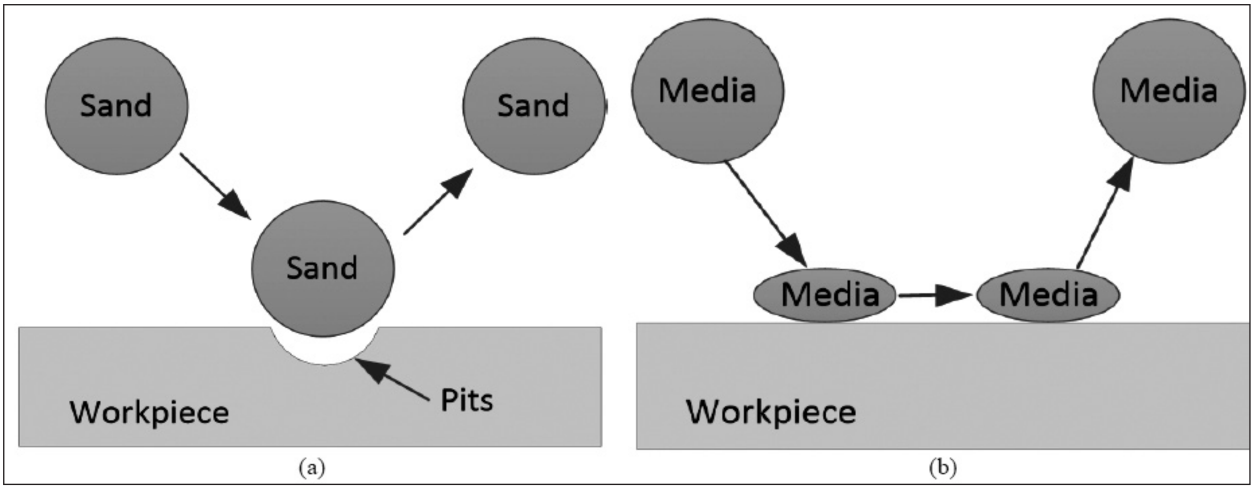

Fig. 6. Schematic representation of (a) sand blasting and (b) aerolap polishing.

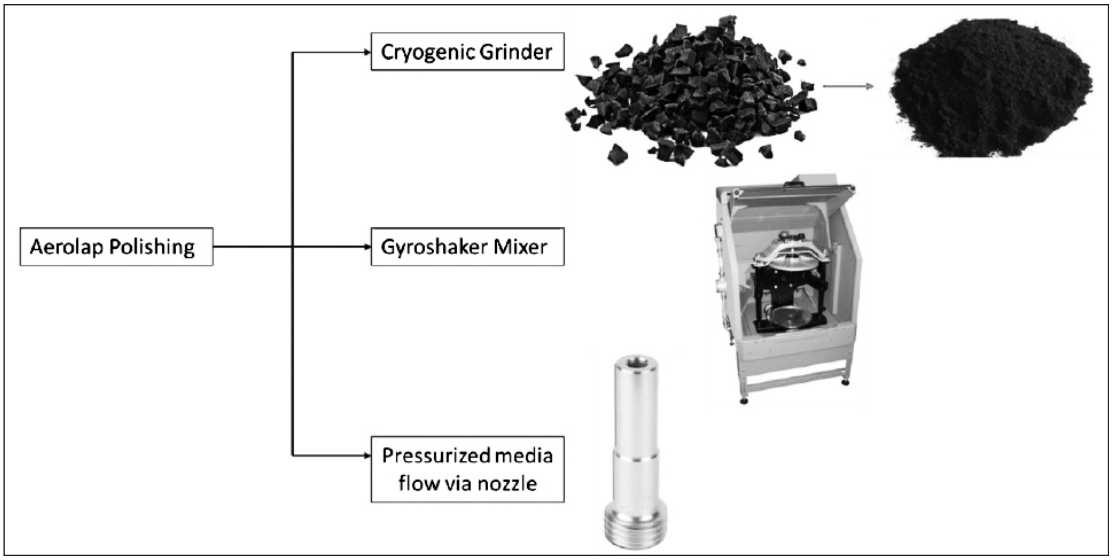

Fig. 7. Components involved in the experimental setup of aerolap polishing.

manufactured components, utilizes sand as the abrasive media to be flown over the surface. However, the sand directly impinging on the surface, creating surface defects such as edge chipping, micro-cracks, pits and gauge marks as shown in Fig. 6(a). To overcome these defects, another post-processing technique has been introduce namely Aerolap Polishing. In this process, the mechanism of chip removal from the material is similar to sand blasting, however the media plays an important role to avoid such surface defects (Ramesh et al., 2012).

The media constitute of rubber particles, being an elastic material, provides a cushioning effect to the abrasives, when it strikes the surface, as shown in Fig.6(b). Compared to sand, which digs the surface, aerolap polishing media stretches over the surface, without digging on the surface. The media mainly consists of multi-cone rubber granules, diamond powder (abrasive) and water (Ramesh et al., 2012). The rubber granules are prepared using cryogenic grinding, then the media is mixed uniformly in a gyroshaker mixer and, passes through a nozzle. The media is directed at an angle over the workpiece such that it will shear off the peaks from the surface, thereby reduces the surface roughness. The components involved in the experimental setup of aerolap polishing is shown in Fig.7.

Ramesh et al. (2012) utilized aerolap polishing to finish the polycrystalline diamond (PCD) inserts. Compared to Single crystal diamond, PCD are difficult to polished as the grains are randomly oriented. Previous research on polishing of PCD inserts suggests processes such as electro discharge grinding (EDG), dynamic friction polishing and grinding by a vitrified bonded diamond wheel. However, there is significant damage to the surface of the insert was observed.

Yamashita et al. (2022) performed short blast polishing (aerolap polishing) using viscoelastic media on mucosal surface of the denture base. The viscoelastic media deforms, glides and Lapps the surface to be polished when projected at an angle of 45°. It was observed that till 20 seconds of polishing, there is a significant reduction in the surface roughness while polishing with grit sizes of 400, 800 and 1500. After 20 seconds, there is no significant reduction in the surface roughness. In this system, complex additively manufactured components can be polished without damaging the surface.

3. Comparative Analysis of Different Polishing Technique

There are several techniques for polishing of 3D printed parts, however, only four of them are discussed here. Each process has its own advantages and disadvantages. Depending upon the user's requirement, the process is selected. In AFF, a dedicated fixture needs to be developed for the specific component. The major advantage of this process is that, as the media is in the form of slurry, it can easily pass through all the profiles and finishes. However, a major problem associated with this process is that the viscosity is not under control. Depending upon the intrinsic area, it passes, viscosity changes.

To overcome this, a new technology is developed as MRAFF. It is almost similar to the AFF, however the viscosity of the media can be controlled using a magnetic field. Its media consists of a magnetic particle, which allow to control the viscosity of the media as required. Thus, providing a localised and desired finish.

The above two processes are the mechanical-based finishing process in which the media physically slide over the surface to remove the peaks and valleys from the surface. However, both these processes require a dedicated fixture. This is time-consuming and not very suitable for customization. To minimise the time and cost, laser-based polishing is introduced. This method does not require any dedicated fixture to finish the surface; however, for a very complex surface, the laser source may not be able to reach at the desired location. Thus, it may not be suitable for a very complex surface.

To overcome these challenges, a new process, Aerolap Polishing, has been developed. Unlike AFM, there is no need to design a fixture for every new component. Thus, overall making it a more efficient process. In MRAFF also, dedicated fixture for a new component has to design, along with the optimization of magnetic field in the close vicinity of the component for the media movement. In case of laser polishing, as it is thermal- based process, induces residual stress over the component. However, in aerolap polishing, the media glides over the surface and without any thermal damage, improves the surface finish.

Apart from these polishing techniques, other polishing techniques are also there such as sand blasting (Minhas et al., 2021) and electrochemical polishing (EP) (Tyagi et al., 2019; Kumar et al., 2022b). However, sandblasting degrades the surface integrity of the additively manufactured component by impinging it on the surface. In EP, the surface integrity will improve; however, only conductive material can be electropolished.

4. Conclusions

In this paper, a detailed review of four processes mainly utilized for polishing additive-manufactured components was discussed. The four processes discussed are abrasive flow finishing, magnetorheological abrasive flow finishing, laser polishing, and aerolap polishing. All processes have their pros & cons; therefore, the process must be selected accordingly.

- In AFF, peaks are removed efficiently to produce good surface finish. However, a new fixture needs to be designed for every new component. The viscosity of media changes with respect to the cross-section area; however, it should be controlled for better precision.
- In MRAFF, the viscosity of the media is controlled by the magnetic field, which provides a superior finish. However, frequent leakage happens from cylinders during finishing due to high pressure. In this case, a unique fixture should also be developed for each component.
- In laser polishing, no need of any specific fixture is required. The laser moves in a predefined path and melts the top surface, which subsequently resolidifies to produce a good surface finish. However, as it is a thermal-based polishing, residual stresses are generated over the surface, and the cost of polishing is also high.
- In aerolap polishing, a viscoelastic media flows with high pressure over the component, which does not require any specific fixture to hold it. It does not produce any residual stress over the surface, and also, the cost of polishing is low. There are no indentation marks on the finished surface.

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