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Abrasive finishing of additively manufactured components

Jan C. Aurich (1)^{a,*}, Peter Krajnik (1)^b, Hitomi Yamaguchi (1)^c, Eraldo da Silva (2)^d, Jacques Platz^a

^a Institute for Manufacturing Technology and Production Systems, University of Kaiserslautern-Landau, 67663 Kaiserslautern, Germany

^b Department of Mechanical Engineering, Chalmers University of Technology, SE-41296 Gothenburg, Sweden

^c Department of Mechanical and Aerospace Engineering, University of Florida, 226 MAE-B, Gainesville, FL, USA

^d Department of Production Engineering, University of São Paulo, São Carlos School of Engineering, 13566-590 São Carlos, Brazil

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ABSTRACT

Additive manufacturing (AM) enables the production of complex, near-net-shape components, but as-built components exhibit high roughness and defects that compromise performance. Abrasive finishing processes are essential to achieve the required surface integrity, dimensional accuracy, and functional properties of components. This review examines state-of-the-art abrasive post-processing for AM, including grinding, abrasive fine-finishing, and mass finishing approaches. Interactions within AM process chains, effects on surface topography and mechanical properties, and industrial case studies are discussed. Current challenges and future research needs are identified to guide the integration of abrasive finishing into efficient AM process chains.

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1. Introduction

1.1. Motivation

Additive Manufacturing (AM) has emerged as an important technology in modern manufacturing. Its ability to fabricate highly complex geometries in near net shape, reduce material waste, and enable customization has created widespread adoption across industries such as aerospace, automotive, and medical [42]. By building components layer by layer, AM allows for design freedom, enabling the production of intricate structures, such as lattice geometries and internal channels, which are impossible to achieve with conventional manufacturing methods [40]. However, the same layer-by-layer nature that makes AM so versatile also introduces significant challenges, particularly regarding surface quality, dimensional accuracy, internal stresses, and inhomogeneous material properties, that need to be addressed to fully exploit its potential [111].

In the layer-by-layer process, the material is selectively deposited, melted, or solidified in thin, discrete layers, gradually forming a three-dimensional object [15]. Although this methodology offers considerable precision and adaptability, it also results in the formation of intrinsic surface irregularities due to the discrete nature of the layers and the thermal and material dynamics involved. One of the most prominent issues is the staircase effect, where the layered structure produces a rough, stepped surface, especially on sloped or curved geometries [26]. Additionally, powder-based AM processes such as powder bed fusion (PBF) and directed energy deposition (DED) often leave unmelted or partially melted powder particles adhered to the

surface. These adhered particles further increase the surface roughness and may compromise the functional performance [46]. In general, parts manufactured using PBF or DED tend to have higher levels of surface texture than parts manufactured using traditional methods, such as casting, forging, or machining.

Thermal fluctuations during the AM process further deteriorate surface integrity issues. Uneven heat transfer and rapid cooling cycles lead to the formation of residual stresses, and even microcracks near the surface [103]. Near-surface porosity, caused by incomplete melting or gas entrapment, can worsen mechanical performance, especially under cyclic loading conditions [115]. In addition, these defects create sites where corrosive agents or moisture can accumulate, compromising long-term durability in harsh operating environments.

Such surface imperfections pose limitations for AM components used in critical applications. For instance, aerospace and automotive industries require components with superior fatigue resistance [16], while medical implants require suitable surfaces for biocompatibility [101]. Without effective post-processing, these requirements cannot be reliably met, which hinders the broader adoption of AM technology.

According to ISO/ASTM 52900:2021 [75], post-processing is defined as a process step, or a series of steps, taken after completion of the AM build cycle to achieve the desired properties in the final product. Abrasive finishing is essential for addressing these challenges [28], as it enables controlled modification of surface texture and form parameters, which is crucial for achieving specific surface functionalities. The abrasive finishing process selection is primarily determined by geometric complexity—which affects surface accessibility—as well as the required surface properties and dimensional tolerances. Fixed- and loose-abrasive processes can both improve surface finish for additively manufactured components where conventional machining cannot be applied because of geometric inaccessibility, or limited material

* Corresponding author.

E-mail address: jan.aurich@mv.uni-kl.de (J.C. Aurich).

machinability [173]. This is particularly the case for components with internal geometries. While loose-abrasive processes offer better conformity to freeform shapes, fixed-abrasive processes are required when high precision and tight tolerance control are critical.

In this context, integrating abrasive finishing into the AM process chain is essential to realize the potential of AM. Abrasive finishing is established for conventionally manufactured components, and the fundamental process principles remain applicable to AM components. However, the application of abrasive finishing to AM components is not always straightforward, as AM modifies the boundary conditions under which the processes operate. Typical as-built surface characteristics, such as the staircase effect, or near-surface porosity, affect the abrasive-workpiece interaction, process capability, and surface integrity. Consequently, this review consolidates which established abrasive finishing approaches are transferable to AM components, where process adaptations are required, and how abrasive finishing can be integrated into AM process chains for the qualification of functional end-use components.

The paper is structured as follows: First, it provides a brief overview of relevant AM technologies, precision components, and the role of functional surfaces. Building on this, the interactions along the process chain are examined. This includes additive-subtractive process chains with geometrically defined cutting edges, as well as the influence of heat treatments and non-conventional manufacturing technologies. Next, the core of the paper presents a discussion of abrasive finishing technologies used for the post-processing of AM components. These technologies are categorized into four main groups: grinding (chapter 3); abrasive fine-finishing (chapter 4); mass finishing (chapter 5); and cavitation abrasive finishing (chapter 6). There is a discussion of the respective sub-technologies under each category, focusing on all aspects of surface integrity. The paper also presents selected industrial use cases that demonstrate the practical application of abrasive post-processing methods in AM. It is followed by a discussion of open research questions and potential future research directions in the field.

1.2. AM processes and materials considered

ISO 52900 [75] classifies AM processes into seven categories, each representing a specific approach to material deposition and solidification. The processes are shown in Fig. 1.

PBF uses a thermal energy source such as a laser beam (PBF-LB) or electron beam (PBF-EB) to selectively melt powdered material layer-by-layer. PBF-LB can be used with metals, ceramics and polymers, whereas PBF-EB is only suitable for conductive metallic materials and is generally not applicable to ferromagnetic alloys, as magnetized powder particles can deflect the electron beam and compromise positional accuracy. This variety of materials has led to widespread industrial adoption [144].

DED operates by feeding material, in the form of powder or wire, into a melt pool created by an energy source, commonly a laser (DED-LB), electron beam (DED-EB), or electric/plasma arc [1]. Typically, the materials used are metals/alloys, but ceramics, and composites are also employed [151]. DED has the capability to manufacture on top of existing components (e.g., for repair) and to produce large, intricate parts, including functionally graded or multi-material structures through controlled deposition strategies [126].

Material extrusion (MEX) involves the extrusion of material, typically in filament form, through a heated nozzle. It is predominantly used with polymers and known for its accessibility for non-industrial applications and cost efficiency. In industrial sectors, it is often utilized for prototyping [43].

Vat photopolymerization (VPP) uses light to cure liquid photopolymer resin. This technique is precise and suitable for applications requiring intricate geometries, such as dental or medical devices, subject to the availability of suitable photopolymer materials [124].

Binder jetting (BJT) deposits a liquid binding agent onto a powder bed to bond the particles together. Layers of powder are successively spread and bonded, creating the component. After printing, the component typically undergoes debinding and sintering or infiltration to enhance its strength. However, these steps are associated with significant shrinkage and subsequent distortion. The process supports a large range of materials, including metals, ceramics, and polymers [176].

Material jetting (MJT) involves the deposition of build material in droplet form, followed by curing or solidification layer by layer. The materials used are photopolymers, which are UV-curable resins, and wax-like materials [38].

Sheet lamination (SHL) involves the layer-by-layer bonding of sheets of material to form a part. The process is suitable for producing composite structures when different sheet materials are combined, but it can also employ single-material sheets such as metals or polymers depending on the intended application [44]. The materials used in AM are as diverse as the processes themselves. They range from metals to polymers to ceramics and composite materials. Metals, such as titanium alloys, stainless steels, and nickel-based superalloys, are widely used in high-performance applications due to their mechanical properties and corrosion resistance. Polymers, including engineering plastics such as polyamide and ABS (acrylonitrile-butadiene styrene), and advanced resins, enable lightweight designs, prototyping, and intricate structures. Ceramics and hard materials, including additively manufactured SiC and WC-Co cemented carbides [21] are increasingly used for applications requiring high hardness and thermal stability, where near-net-shape AM is particularly attractive and abrasive finishing is often indispensable to achieve functional surfaces. In this keynote paper, the scope is primarily on abrasive finishing of metal AM components, while selected ceramic- and multi-material examples are

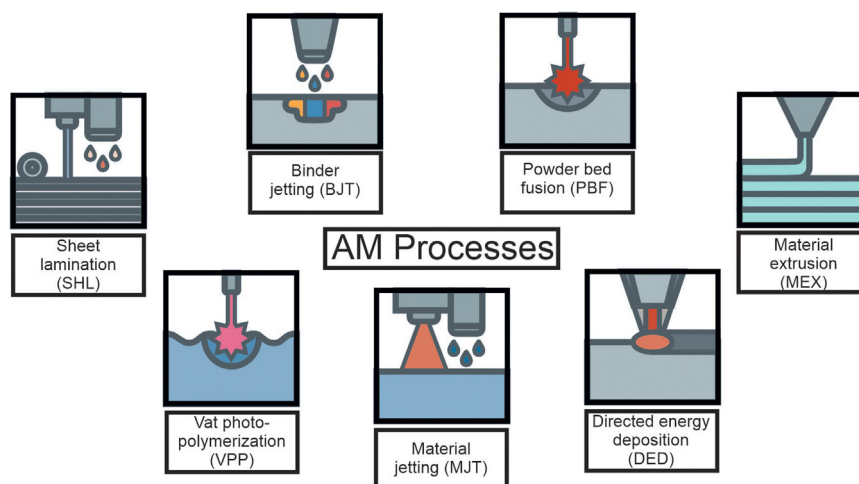


Fig. 1. AM Processes according to ISO/ASTM 52900.

included to illustrate broader material classes where finishing requirements are especially stringent.

In most AM processes, the as-built surface finish often does not meet application-specific surface quality requirements, particularly for precision components, and therefore necessitates post-processing. Due to the variety of materials, a wide range of post-processing methods are used. For materials that are difficult to machine, abrasive finishing may be the only economically viable alternative.

1.3. Precision components

Precision components are used in applications that require high dimensional and form accuracy as well as controlled surface quality within specified tolerances [55]. These components are critical for the functionality and reliability of systems in industries where operational conditions demand exceptional performance such as aerospace, medical, automotive, and energy. They are characterized by their tight dimensional tolerances, requiring dimensional variations to be controlled within the micrometer range [114]. Surface quality is another defining feature: smooth surfaces reduce friction and wear [150], enhance fatigue resistance [149], and ensure compatibility with other components or biological systems [35]. Furthermore, precision components demand material integrity, with uniform properties free of defects, such as porosity or inclusions, which can compromise mechanical performance [18]. In the context of this paper, the term *precision component* is used in a broad sense that also encompasses intricate components with complex geometries and demanding surface or dimensional requirements. Such parts are typically characterized by complex features, such as internal channels, thin walls, or lattice structures, for which compliance with specified tolerances and surface requirements necessitates advanced finishing technologies to obtain the intended functional characteristics.

The importance of precision components can be observed across a range of industries. In aerospace, components such as turbine blades must endure extreme mechanical and thermal stresses while maintaining aerodynamic efficiency. Even minor imperfections on their surfaces can increase drag, reduce efficiency, or cause premature failure [70]. In the medical field, implants, such as orthopedic and dental devices, require surfaces that are not only suitable in terms of roughness but also biocompatible to integrate seamlessly with the body. Inappropriate surface roughness or porosity on these implants can increase the likelihood of failure [164]. Similarly, in the automotive sector, components such as pistons, gears, and fuel systems must meet tight tolerance requirements to operate efficiently and withstand high-stress conditions [24]. In energy applications, wind turbines include precision components such as gears and bearings that must combine structural integrity with specific surface characteristics to optimize energy conversion [79]. Electronics manufacturing also relies on precision components, such as semiconductor molds and optical elements. The functionality of optical elements, such as lenses and mirrors, depends on exact control over their shape, surface smoothness, and optical properties [159]. A lens must exhibit the specified curvature to accurately focus or manipulate light, while its surface quality must minimize scattering and distortion of the transmitted light.

Traditionally, producing such precision components involves multi-step process chains that combine material-conversion, subtractive, and finishing techniques. For example, the manufacturing of a turbine blade or a lens typically includes casting or molding to create initial shapes, machining to refine the geometry, and finishing processes such as polishing to add functionalities. While effective, these traditional production chains can become time-consuming and cost-intensive when applied to components with high geometrical complexity, requiring multiple machining and finishing steps. In such cases, substantial material waste may be generated, particularly when intricate features must be manufactured by subtractive processes.

AM facilitates this by consolidating multiple steps into significantly shorter, more streamlined process chains. However, AM alone cannot meet the stringent surface quality and dimensional

accuracy required for precision components [35]. This is where abrasive finishing becomes a critical complement to AM, enabling the production of components with smooth surfaces and precise dimensions while preserving their complex geometries. For example, AM can produce turbine blades in near-net shape with integrated complex features, reducing the need for multiple manufacturing steps, while abrasive finishing is still required to achieve the specified surface quality. This approach significantly reduces the number of steps, minimizes material usage, and lowers overall production costs. The combined use of AM and abrasive finishing is particularly advantageous for low-volume, high-complexity components. Traditional methods often struggle to balance cost-effectiveness with precision when producing small quantities, but AM excels in such scenarios by eliminating the need for expensive molds or tooling. Abrasive finishing ensures that these components meet functional requirements, making the shortened process chain viable for a wide range of industries.

1.4. Functional surfaces

Functional surfaces are critical to the performance and reliability of precision components, as their characteristics directly influence interactions with the environment or other components (e.g., friction and wear, fluid transport and sealing, fatigue crack initiation, and corrosion) [96]. They refer to the specific regions of a component where surface quality and structure impact operational efficiency, durability, or performance [27]. These surfaces are defined and evaluated based on standardized parameters, such as those outlined in ISO 21920-2:2021 [73] and related standards, which provide a framework for assessing surface topography. In the context of this work, functional-surface requirements are discussed primarily to support the selection and application of abrasive finishing operations for AM components, as these are increasingly targeted for applications involving fluid flow, tribology, fatigue loading, and corrosion resistance.

As-built AM surfaces are typically irregular and feature topographical characteristics at multiple scales. Metal AM surfaces in particular may exhibit local high-aspect-ratio features (e.g., partially fused particles, spatter, and staircase artefacts) and near-surface heterogeneity in the material state, reflecting the local thermal history and defect populations [99]. Surface topography comprises all surface features across spatial wavelengths, including form and texture. Surface texture refers to the geometrical irregularities superimposed on the form and is typically quantified using parameters such as arithmetic mean height (R_a), or maximum height (R_z). While these parameters are widely reported and provide a practical first basis for comparison, their descriptive power for AM surfaces is limited, since feature-rich topographies may yield similar values. No universal threshold exists for these values, as the definition of a precision component or functional surface varies by industry and application. Optical components for example often require surface roughness in the range of a few nanometers [159], while aerospace components may target R_a values below $0.5\ \mu\text{m}$ [92]. For many AM surfaces, these application-driven targets imply that the as-built texture must be substantially reduced by post-processing, with abrasive finishing representing a key route to achieve the required functional surface state. Functional performance, however, is not governed by topography alone: post-processing may also modify the near-surface material state, including residual stresses and, in some cases, hardness or microstructure, which are directly relevant to fatigue, wear, and corrosion resistance.

The functionality of a surface is also influenced by its texture and topographical distribution. Parameters such as skewness (R_{sk}) and kurtosis (R_{ku}) provide insight into the statistical profile of surface peaks and dales. These parameters are particularly important for applications where fluid retention or load-bearing capabilities are critical. For instance, a negative skewness ($R_{sk} < 0$) may be desirable for reducing friction in different contact conditions, while a high kurtosis ($R_{ku} > 3$) indicates sharp peak structures that could accelerate wear under sliding conditions [141]. Surface

directionality (anisotropy versus isotropy) can also strongly influence functional performance, particularly in tribological contacts [78]. This is directly relevant for AM components; for example, in AM-based repair/remanufacturing the finishing strategy must produce appropriate bearing and lubrication characteristics, such as a stratified texture with load-supporting plateau features and deeper dales that act as lubricant reservoirs (see Section 7.1).

The functionality of surfaces also depends on their compatibility with operational demands. Medical implants, for instance, require rougher surface regions for better osseointegration [152] and regions with minimal surface roughness to reduce risk of infection from bacteria. In contrast, sealing surfaces in hydraulic systems demand tight tolerances and low waviness to prevent leakage [143]. Standards such as ISO 25178-2:2021 [74] extend surface characterization to areal (3D) parameters, providing a more comprehensive framework for assessing functional surfaces. This is particularly relevant for AM surfaces, which are often anisotropic and directional; representative areal measurements can therefore capture surface structure and feature relationships more effectively than profile measurements. In addition to parameters such as the arithmetic mean height (S_a), and root mean square height (S_q) parameters derived from the areal material ratio (Abbott-Firestone) curve describe surface topography in three regions spanning its vertical range: a peak region that is preferentially reduced during abrasive finishing, a core region representing the bulk of the surface, and a region occupied by the deepest valleys. The vertical extents of these regions are quantified by the reduced peak height (S_{pk}), core height (S_{sk}), and reduced valley depth (S_{vk}), respectively.

2. Interactions in the process chain

2.1. Typical manufacturing process chains

In order to produce ready-to-use components, the other downstream processes in the process chain after AM need to be considered. Typical manufacturing process chains are shown in Fig. 2. The scope is limited to downstream post-processing; AM pre-processing (e.g., build preparation, slicing, and scan-path generation) are not covered, except insofar as they determine the as-built surface state that must be addressed by post-processing.

Depending on the AM process, a raw or used component can be used as a substrate. For example, DED can build on top of an existing component to repair sections of it or to add features to a raw component. In other AM processes, the component to be manufactured is built completely layer by layer based on the 3D data of the virtual component.

As previously mentioned, the as-built AM component properties like surface roughness or residual stresses are often insufficient for most applications. Therefore, several post-processing steps can be combined, depending on the operating conditions of the final component, to meet the requirements. It must be considered that post-processing

steps may alter not only the targeted properties (such as surface characteristics) but also other properties, such as residual stresses, or near-surface microstructure, which may not always be intended.

A heat treatment can fulfil several purposes in this context. For example, hot isostatic pressing (HIP) is widely adopted for metal components to improve density and microstructure homogeneity, while stress relief may be necessary for internal strain energy relaxation [98]. Machining and other surface treatments such as electro- or laser polishing (LP) can be used either in addition to heat treatment or directly after the AM process to smooth the surface texture and achieve a favorable surface integrity while meeting dimensional tolerances [111]. Integrating abrasive finishing into the process chain offers several advantages. Grinding, polishing, and mass finishing are particularly effective in addressing the unique challenges of AM surfaces, especially those made of difficult-to-machine materials [28]. Furthermore, processes such as abrasive flow machining (AFM) and magnetic field-assisted finishing (MAF) are capable of improving the quality of internal channels or intricate cavities that cannot be machined. In addition to technological benefits, abrasive finishing processes can also offer economic advantages. For example, mass finishing processes do not require clamping devices and allow multiple components to be processed simultaneously.

The objective is to identify and apply the most efficient combination of post-processing methods to enable the economical production of precision components.

2.2. Heat treatment

In AM process chains, thermal post-processing is frequently required to modify the as-built condition prior to subsequent operations. Due to rapid solidification and repeated layer-wise thermal cycling, AM components often exhibit elevated residual stresses, microstructural anisotropy, and local inhomogeneities, which can influence the response in post-processing and finishing operations (e.g., through changes in hardness). Heat treatments such as stress-relief annealing, HIP, or alloy-specific solution and ageing treatments modify the residual stress state and microstructure (and thus mechanical properties), which can affect abrasive finishing behavior [109]. Importantly, residual stresses inherent to metal AM can drive form deviations (e.g., warpage) that may increase when constraints change, such as during support removal or build-plate separation [166]. While stress-relief heat treatment is applied to mitigate these stresses, stress relaxation at elevated temperature can also lead to additional shape change [153]. Consequently, finishing is required not only to improve surface quality but also to achieve specified dimensional and geometric tolerances.

One commonly applied heat treatment is stress-relief annealing, used to mitigate internal residual stresses caused by rapid thermal cycling during the AM process [41]. This process involves heating the component to a suitable temperature below the phase-

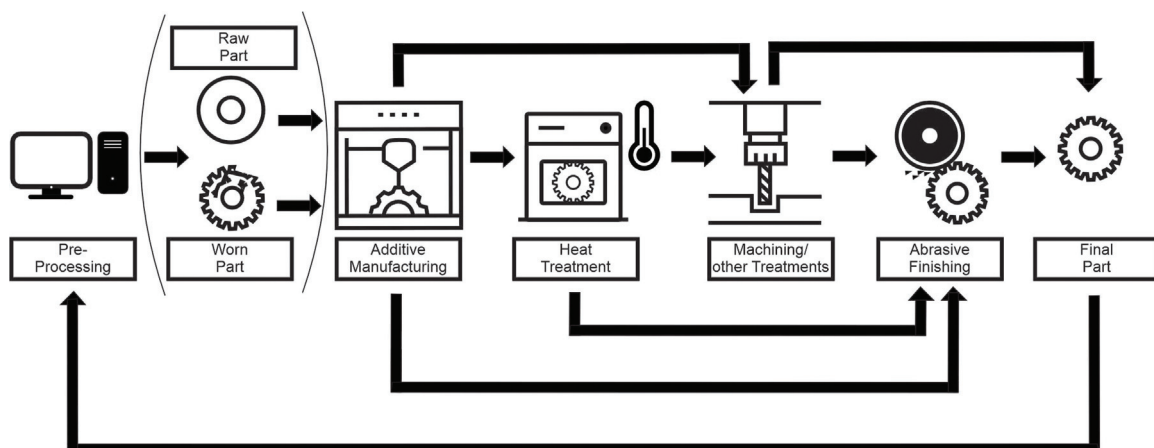


Fig. 2. Typical manufacturing process chains.

transformation range, holding it at that temperature for a defined period of time, and then cooling it uniformly. This reduces the energy stored in the material's lattice structure, thereby improving dimensional stability and minimizing the risk of distortion or cracking in subsequent operations [32].

HIP is another critical technique, particularly for metallic AM components produced via PBF or DED. HIP treatment improves the quality of the additively manufactured components by promoting densification [64], reducing residual stress, and homogenizing the microstructure [132]. Additionally, HIP has been shown to enhance properties such as corrosion resistance [161] and fatigue strength [133]. The process involves heating the material to a temperature below the melting point of the base alloy while applying continuous isostatic pressure for a specified duration.

For precipitation-hardenable alloys, such as specific aluminum or nickel-based alloys, solution treatment and aging is a widely adopted heat treatment [98]. This process involves dissolving alloying elements in the material at elevated temperatures (solution treatment), followed by quenching and reheating the material at lower temperatures (aging) to form fine particles that strengthen it [69]. The resulting microstructure enhances yield and tensile strength and improves the retention of mechanical strength at elevated temperatures, which is crucial for demanding environments [17].

Heat treatments enable tailoring material properties to meet specific design and functional requirements. However, altering properties such as hardness and strength directly impacts subsequent processes in the process chain, which must be considered [34]. While these effects are established for conventionally manufactured components, they must be reconsidered for AM process-chains due to the distinct as-built microstructures. Abrasive finishing processes, such as grinding or polishing, must consider the altered mechanical properties of heat-treated parts. Hardening material reduces the material removal rate and increases processing time [130], and tailoring finishing parameters to maintain efficiency and effectiveness may be necessary. Therefore, an effective manufacturing strategy must balance the benefits of heat treatment in improving material properties with the challenges posed by downstream operations. Only by optimizing the interplay between heat treatment and subsequent processes precision components can be produced cost effectively.

2.3. Machining

While AM enables the production of near-net-shape components, machining is often required to achieve the necessary dimensional accuracy and surface quality. Milling is the most common post-processing process, providing a suitable surface finish for most applications. Abrasive finishing is typically applied when higher precision is required or the work material is difficult to machine.

Compared to conventional materials, AM-produced components present unique challenges during machining. Materials, produced through casting, forging, or extrusion, generally exhibit uniform and predictable microstructures. In contrast, AM materials often feature significant microstructural variations, including differences in grain size and shape, as well as strong crystallographic texture along the build direction. These features contribute to anisotropic mechanical behavior and can lead to direction-dependent machining responses as well as locally varying material behavior associated with spatial heterogeneity in microstructure and defect populations. AM materials may contain porosity defects, attributable to melt pool dynamics during the printing process. Such pores can reduce work material tensile strength and ductility—when present in or near the surface being machined, they may contribute to discontinuous material removal and variability in tool loading, thereby influencing chip formation and tool wear. The interplay between AM process characteristics, microstructural properties, and machinability was comprehensively examined by Malakizadi et al. [109], with emphasis on how the as-built microstructures govern not only tensile strength, hardness, and

ductility, but also the precipitation state and associated workpiece abrasiveness (i.e., the type, size, and volume fraction of hard particles/inclusions) which together directly control machinability. While machining with defined cutting edges has been extensively studied, the abrasive finishing of AM components remains less explored, despite its importance for achieving the final surface integrity required in precision applications.

2.4. Other non-abrasive post-processing treatments

2.4.1. Electropolishing

Electropolishing (EP) is a non-contact electrochemical machining process that removes a controlled amount of material from metallic surfaces, resulting in a smoother and damage-free finish [56]. The process involves immersing a workpiece in an electrolyte where anodic electrochemical dissolution removes surface material. The method relies on the electrochemical reaction between anodic and cathodic electrodes, wherein material is removed when a DC/AC current is applied. A characteristic of EP is its ability to effectively finish complex geometries and internal surfaces while preserving the crystallographic integrity of the work material. A notable property of EP is its inherent passivation of the workpiece, leading to the formation of thin oxide films, which enhance corrosion resistance [171] or reduce hydrogen uptake [19]. Given the complexity of the EP process involving electrochemical reactions, its efficiency and outcome are influenced by multiple parameters, including current density, electrolyte composition, and temperature.

A notable advancement in the field of EP is the Hirtisation® technology, a patented three-step electrochemical post-processing method that integrates electrochemical jet machining, EP smoothing, and EP brightening [58]. The technology comprises the application of ramped and pulsed direct current, with voltage profiles that are tailored to the material type and the initial roughness. For example, Hirtisation® has been demonstrated to reduce surface roughness for PBF-LB/316L from $Sa = 20 \mu\text{m}$ to $Sa = 7 \mu\text{m}$ primarily through complete removal of sintered/semi-sintered powder from the as-built surface [50]. In this study by Gunnerek et al., preferential material removal was also observed along melt pool and melt-track boundaries. For the investigated as-built condition, this was associated with locally formed notches (up to $10 \mu\text{m}$), attributed to boundary-related microstructural/chemical differences; accordingly, it should not be interpreted as an intended or generally expected outcome independent of microstructural state or prior heat treatment. This work further highlighted that the material-removal response depends strongly on the AM-induced starting surface state (including scan strategy, melt-pool characteristics, and initial roughness), underscoring that process–microstructure interactions must be treated explicitly when applying chemical/electrochemical post-processing to AM surfaces.

2.4.2. Laser polishing

As a non-contact surface-finishing method, LP utilizes high-intensity laser beams to smooth AM surfaces through localized melting and re-solidification. The process is generally categorized into two distinct categories: continuous wave and pulsed wave polishing. Each of these categories exerts a distinct influence on the melt pool dynamics, the amount of heat input, and the resulting surface finish. LP is most effective when the initial surface condition falls within a certain roughness threshold. This is because surfaces with high amplitudes or spatial wavelengths that exceed a critical value cannot be fully removed [36]. The interaction between LP and microstructure remains complex, with grain refinement and secondary phase precipitation observed in re-melted regions, leading to localized hardness variations [106].

LP has been successfully applied across various AM materials, with surface roughness reductions exceeding 90% in some cases [22]. Studies show that optimizing laser parameters—such as beam power, scanning speed, focal position, and overlap strategies—is crucial to

achieving consistent surface quality. Nonetheless, challenges persist due to the surface irregularities of as-built materials. For instance, challenges include determining a strategy that accommodates local topography variations and managing thermal energy to prevent oxidation, texture changes, or residual stresses [113]. Femtosecond-laser polishing with high pulse frequency has emerged as a promising alternative, enabling precise control over energy input, reducing roughness through remelting, and refining the microstructure without inducing significant thermal damage [131].

2.5. Combined processes

Combining additive and subtractive manufacturing in a single production equipment aims to overcome AM technologies limitations while maximizing the advantages of the use of AM in terms of producing complex geometries in near net shape, cost-effective manufacturing of complex parts and repair of damaged components [170]. Machining refines dimensional and geometrical accuracy and provides the required surface quality, but cutting conditions must be carefully selected to avoid introducing new surface defects due to the release of internal stress and induced residual stress [107]. However, in many implementations, AM and subtractive processes are not performed simultaneously, and several hours of cooling may be required before machining can begin—which is a limiting factor for serial production. A more viable alternative is the automated AM-to-CNC workflow, in which additive and subtractive operations are conducted on separate, dedicated systems connected via a robotic cell. These systems integrate automated loading/unloading of components, in-line inspection, AM deposition, and CNC machining, ensuring a seamless transition between additive and subtractive steps. The following subsection explores combined manufacturing processes, focusing on fully-integrated machines that combine additive and subtractive manufacturing within a single production equipment.

Reasons for implementing combined additive and subtractive processes include repairing damaged parts, matching surface finishing, printing complex parts and multi materials in a single clamping step, allowing that every surface to be printed and machined using a same coordinate system. It ensures that tight dimensional and geometrical tolerances were achieved while saving material stock [142]. The combination of a laser-based AM and the versatility of CNC machining centers is suitable for implementing the combined strategy [142].

Combined additive and subtractive processes can be performed in newly designed or retrofitted machining centers with an integrated nozzle cladding system [142]. There are unique economic and quality-related benefits to using combined equipment that outweigh the automated AM-to-CNC workflow; being twice as efficient, as pointed out by Schuh et al. [140]. However, while milling is commonly available on these platforms, finishing and fine-finishing operations are less frequently implemented and may require adaptation of the process-machine interface. In most cases, spindle characteristics and clamping systems are designed for efficient milling, which do not necessarily cover the speed range, stiffness, or clamping systems typically used for grinding and polishing. Milling is typically performed after the AM step to reduce the roughness and correct geometrical and dimensional errors. The combined equipment can include a LP step before milling to improve microstructure and smooth surface finishing [147]. No additional tooling is required to perform LP, as the cladding system can be used as a laser source.

In contrast, implementing abrasive finishing as a combined process requires integration of a suitable tooling system, including dressing, and operating conditions within the available spindle-speed range. This integration challenge is not unique to AM, as incorporating abrasive processes into machining centers has historically not always been the most viable approach in production. Nevertheless, the scenario can be most favorable for high-value, complex components and repair operations, where reduced setups and improved flexibility can outweigh added integration. Additionally, when implementing a MAF

process, the preliminary design—encompassing tool geometry, selection of magnetic field type, and the size and arrangement of the magnets—can be carried out on traditional machining centers to reduce development time. This approach was proposed by Souza et al. [148], who conducted a series of experiments using a dedicated CNC machine center to develop a high-efficiency grinding process with small-diameter wheels over a range of design and configuration options, followed by MAF post-processing of additively manufactured 316L stainless steel parts.

Another option to incorporate grinding and polishing is the approach proposed by Pratap et al. [129], designed for implementation in machining centers. The authors proposed a hybrid tool composed of a stiff grinding tool and a shape-adaptive grinding (SAG) tool, as presented in Fig. 3. This concept can be extended to post-processing of AM components, with proper adjustment of pad constituents (rubber and abrasive grits) and grinding-wheel specification. More broadly, the CIRP keynote by Yan et al. [167] addresses shape-adaptive abrasive finishing processes in a general (non-AM-specific) context and outlines their typical applications, namely surfaces with non-uniform curvature and/or local geometric discontinuities that limit the use of non-conforming tools.

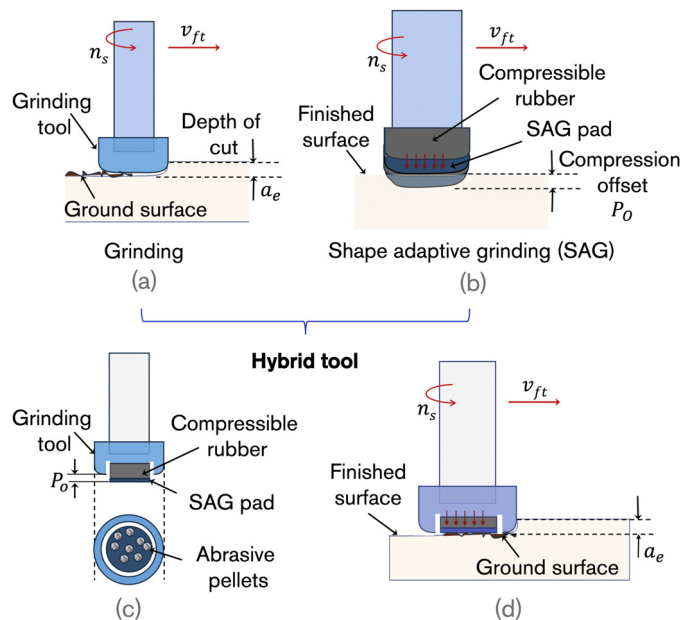


Fig. 3. Proposed design of a hybrid grinding tool and its material removal principle (adapted from [129]).

Sefene et al. [142] listed the challenges to adopting combined equipment in industrial settings, including economic aspects, the need for accurate process planning, and the requirement for more sophisticated control and software capabilities to integrate additive and subtractive manufacturing steps. The reduced number of powder suppliers worldwide, the impact of powder production on sustainability [33] and logistics issues can be considered obstacles to implementing effective business models for adopting combined equipment in industry.

To summarize, if the objective is the production of new parts, dedicated machines are generally more effective in terms of utilization and throughput. Conversely, if the objective is the repair of high-value molds, dies, or aerospace components—where the part already exists and only requires material addition—the combined machine is unparalleled, as it eradicates the complications associated with re-fixturing and re-aligning damaged parts.

3. Grinding

Grinding is traditionally regarded as a finishing process for precision components when stringent requirements on form accuracy,

dimensional tolerances, and surface integrity must be met. In the context of grinding AM materials, however, a fundamental understanding of grindability remains limited. Grindability refers to the ease with which a work material can be ground and encompasses a range of process parameters and work-material conditions that affect the grinding process and the resulting surface integrity. Grindability assessment involves analyzing factors such as grinding forces/specific energy, wheel wear and wheel loading, surface roughness, residual stresses, etc. These parameters are interdependent and are heavily influenced by the material's properties, including hardness, microstructure, and inclusions. Therefore, grindability cannot be characterized by single metric. Rather, it requires evaluating grinding outputs based on criteria such as the following [65]:

- Mechanical: e.g., specific grinding energy (relating to material flow stress, strain, strain rate, hardness, etc.);
- Tribological: friction and wheel wear (caused by grit/bond fracture, microchipping, attrition processes/abrasive dulling, chemical reaction between the workpiece and the abrasive, etc.); and
- Thermal: grinding temperature and tendency for thermal damage (workpiece burn by, for example, tempering, formation of tensile residual stresses, and/or material phase transformations such as rehardening).

Most grindability studies on AM materials have focused on steels, particularly 316L stainless steel and on alloys such as Ti6Al4V and Ni-based Alloy 718. This section will examine the specific challenges associated with grinding these materials, with a focus on the latest research findings and their implications for improving the surface integrity of AM components.

3.1. Grinding of steels

In one of the first publications on grindability of additively manufactured steel, Kirsch et al. [91] investigated the surface grinding of PBF-LB/316L stainless steel using conventional aluminium oxide wheels (#80 mesh). The study aimed to compare the grindability of conventional steel (cast, rolled, solution-annealed, and water-quenched) with two AM materials exhibiting different defect sizes and densities resulting from different volumetric energy densities applied during the AM build (33.3 J/mm^3 vs. 119 J/mm^3). Grindability was assessed by measuring grinding forces and surface finish. In shallow-cut grinding with a $5 \mu\text{m}$ depth of cut ($Q_w = 1.3 \text{ mm}^2/\text{s}$), the dense AM microstructure generated approximately 40% higher specific tangential force compared to conventional steel, attributed to the latter's roughly 30% lower hardness. In contrast, creep-feed grinding with a 0.25 mm depth of cut ($Q_w = 0.4 \text{ mm}^2/\text{s}$) resulted in similar forces for both materials, suggesting that hardness alone does not account for the observed differences in grindability. Grinding reduced the as-built surface roughness by about 90%, from $R_z = 42\text{--}44 \mu\text{m}$ to $R_z = 3\text{--}6 \mu\text{m}$, depending on the grinding mode. It was observed that cracks in the surface of the ground AM material produced with lower volumetric energy density were indicative of underlying pores. No significant near-surface microstructural alterations or changes in microhardness were observed due to the grinding processes, suggesting that residual porosity, rather than the grinding process itself, primarily determines the achievable surface finish.

The research by Zhang et al. [172] provides a comprehensive analysis of the surface integrity and mechanical properties of ground PBF-LB/304L stainless steel by electron backscatter diffraction and transmission electron microscopy to characterize grinding-induced microstructural changes in the near-surface region. The main finding was that grinding improved surface integrity and more than doubled the fatigue life, primarily by removing near-surface lack of fusion (LOF) defects that act as dominant crack-initiation sites in the as-built condition. Under the applied rough grinding conditions ($Q_w = 12.8 \text{ mm}^2/\text{s}$) R_a decreased from 5.7 to $0.6 \mu\text{m}$ and R_z from 57.2 to $10.7 \mu\text{m}$. Representative surface morphologies are shown in Fig. 4 (a–c) for the as-built state, where adhered/incompletely melted

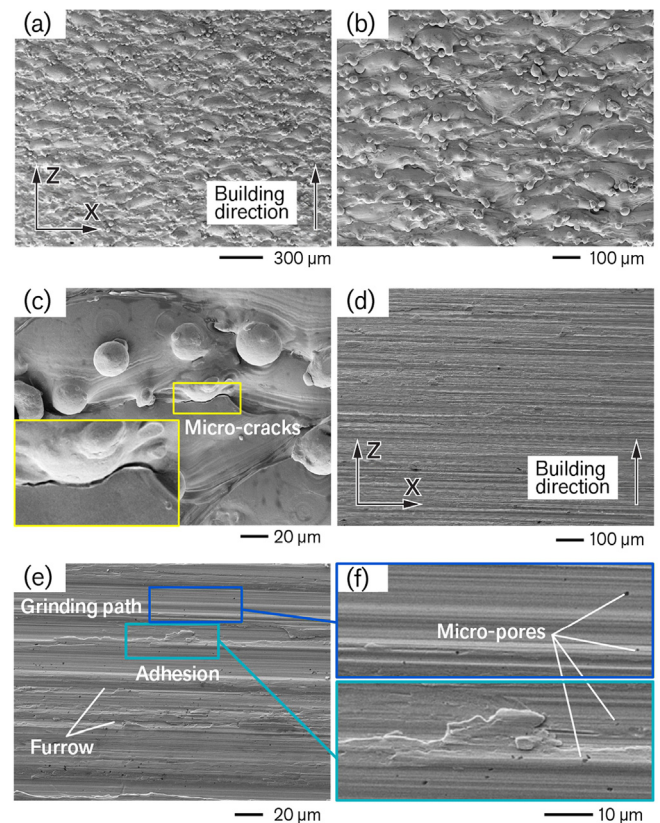


Fig. 4. SEM surface morphologies of PBF-LB/304L stainless steel in the (a–c) as-built and (d–f) ground conditions (adapted from [172]).

particles and surface-connected defects are evident, and in Fig. 4 (d–f) after grinding, where the surface is dominated by grinding marks and isolated local damage or debris features.

To further illustrate (sub)surface integrity, Fig. 5 compares the as-built and ground states in the XY and XZ planes. The XY view shows that grinding (0.25 mm stock removal) removed partially molten particles and near-surface LOF-related defects while internal pores remained, whereas the XZ view reveals a dense population of subsurface cracks beneath the ground surface that was reported to grow preferentially along the build direction.

Yazdanpanah et al. [168] investigated the stress corrosion cracking (SCC) susceptibility of PBF-LB/316L steel, focusing on the effects of grinding-induced residual stresses. Pore-density measurements showed a low pore density of approximately 8 pores/mm^2 , indicating that the specimens were close to full density. The as-built surface roughness was high ($R_a = 14.75 \mu\text{m}$, $R_{ku} = 2.55$, $R_{sk} = 1.54$), necessitating grinding. The dominant microstructure was fully austenitic with minor oxide inclusions. SEM-EDX mapping showed no significant microscale variations in chemical composition, confirming the homogeneity of the as-built material. As-built compressive residual stresses ($-130 \pm 9 \text{ MPa}$) were reduced by 50% to $-65 \pm 12 \text{ MPa}$ after solution annealing. However, grinding resulted in tensile residual stresses at the surface for all conditions, which increased with the specific material removal rate (from $Q_w = 0.9$ to $2.8 \text{ mm}^2/\text{s}$).

The research showed that higher tensile residual stresses intensified SCC, with cracks initiating at surface defects and propagating along melt-pool boundaries, highlighting the need for optimized grinding to mitigate SCC, which is especially important in post-processing of additively manufactured nuclear reactor components.

The above studies have largely focused on AM materials with anisotropic microstructures and printing defects, often highlighting the challenges and differences in grindability compared to conventional steel. In contrast, Hoier et al. [66] investigated the grindability of AM and conventional materials with similar microstructures. Here, a special PBF-LB process was developed for 3D printing 42CrMo4 (AISI 4140) low-alloy steel with in situ heat treatment of

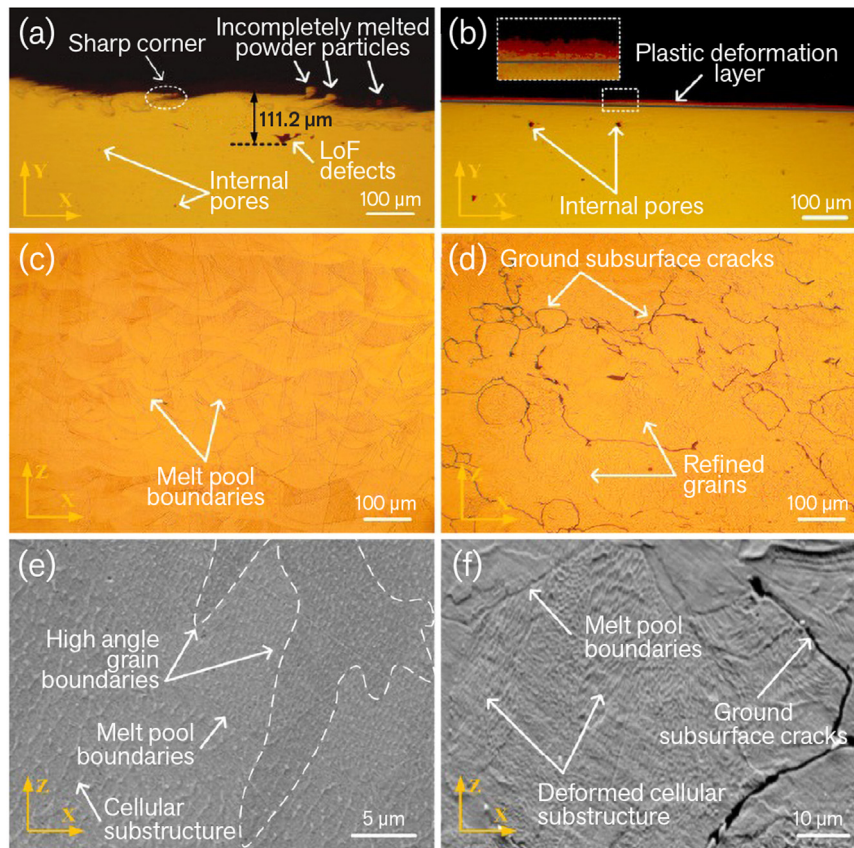


Fig. 5. XY planes (a, b) and XZ planes (c, d) of as-built and ground samples. SEM microstructure images (e, f). Build direction along the Z axis (adapted from [172]).

the material to produce tempered martensite directly in the as-printed state—achieving microstructural and mechanical properties (defect-free with a fine martensitic microstructure of high density, >99.8%) superior to those of the conventionally-produced material [63]. For most grindability criteria, the two materials showed comparable behavior. The specific grinding energies were similar; with the AM material showing only slightly lower values (below 7%). Moreover, the grinding direction relative to the build direction had no measurable influence on specific grinding energy, unlike the orientation-dependent responses often reported in machining of AM materials. This is consistent with the limited anisotropy of the investigated material and suggests that anisotropy may have a weaker effect in grinding, where multi-grit, microscale abrasive engagement tends to average out local directional effects. Thermal effects should also be considered, since grinding temperature is closely linked to surface integrity; however, the similar specific grinding energies suggest that major differences in thermal loading were unlikely to dominate the response in the present case. This is consistent with the residual-stress profiles, which showed comparable compressive surface stresses under finishing conditions for both materials, and tensile surface stresses under rough grinding due to stronger thermal effects. A notable difference was found in wheel wear. The AM material exhibited

about 30% higher wheel wear (reflected by a lower *G-ratio*). This was associated with differences in non-metallic inclusions: the conventional material contained elongated MnS inclusions together with oxides (Fig. 6a), whereas the AM material, owing to its low sulfur content, contained no MnS inclusions and instead exhibited only spherical oxide inclusions (Fig. 6b).

The AM material also showed higher oxygen content, consistent with oxide formation related to powder surface oxides and oxygen control during PBF-LB. The higher wheel wear of the AM material was likely related to its less favorable inclusion population, since sulfide inclusions are generally beneficial for grindability owing to their lubricating effect, whereas hard oxide inclusions tend to promote wheel wear. Oxide chemistry is also relevant, since modification such as Ca-treatment can reduce oxide hardness and abrasiveness. Thus, even when AM steel exhibits favorable bulk microstructure and comparable grinding energy and surface integrity, inclusion engineering and oxygen control remain important for achieving favorable grindability.

Most studies on the grindability of AM steel have focused on materials produced by PBF-LB, with relatively less attention given to those produced by DED-LB. Grinding of DED-LB/316L stainless steel was investigated in [148] as part of a post-processing chain. Here, grinding was performed using a conventional aluminum-oxide wheel (38A;

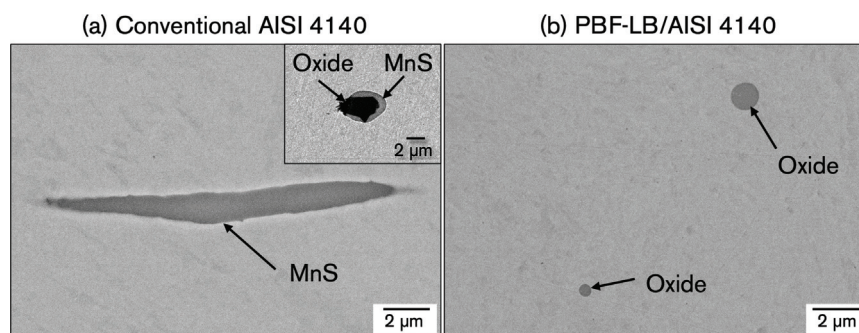


Fig. 6. MnS and oxide inclusions in the conventional AISI 4140 material (a) and oxide inclusions in the PBF-LB/AISI 4140 steel (b) [66].

grade K) with an 80-grit abrasive size. The ground surfaces exhibited negative skewness ($R_{sk} < 0$) indicating a more plateau-like (bearing) surface texture than the as-built and milled samples, which showed positive R_{sk} values due to the adhered unmelted/partially melted powder particles and milling feed marks. MAF was subsequently applied as an abrasive fine-finishing step to reach sub-micrometer roughness; the preceding milling/grinding steps primarily defined part geometry and the initial surface topography for efficient polishing. Notably, only pre-ground surfaces retained negative skewness after MAF, underscoring the role of grinding in producing a favorable texture state for downstream tribological performance. This was consistent with tribological testing of ground and polished PBF-LB/AISI H13 hot-work tool steel [49] where grinding and polishing reduced the coefficient of friction by approx. one order of magnitude (0.1–0.01) relative to the as-printed condition. These values should be interpreted as tribo-system responses, as the tests were performed in a pin-on-disk configuration against hardened AISI 52100 bearing-steel disks (≈ 800 HV) with a ground counter-surface ($R_a \approx 0.1 \mu\text{m}$); hydrodynamic lubrication was reported only for the ground-and-polished surface state among the conditions investigated.

3.2. Grinding of titanium- and nickel-based alloys

The grindability of additively manufactured alloys, such as Ti6Al4V titanium alloy and Alloy 718 is largely dependent on the state of the material, which varies significantly depending on the AM method employed (DED-LB, PBF-LB, or PBF-EB) and the specific fabrication and post-treatment parameters.

Kadivar et al. [80] investigated the specific energy in micro-grinding of conventional/extruded (340 ± 5 HV) Ti6Al4V (Grade 5) alloy and PBF-EB/Ti6Al4V alloy (345 ± 10 HV). With regard to the finished surface properties, comparable surface topographies were observed using identical grinding parameters, irrespective of the fabrication method employed for the materials in question. The surface roughness parameters (S_a , R_a , and R_z) exhibited comparable values. In all cases, it was observed that some material debris remained on the ground surface. The material microstructure resulting from different material-fabrication processes (conventional vs. PBF-EB) was found to have a considerable influence on the specific energy, although the material hardness was similar. For instance, grinding in a direction parallel to the material-build direction resulted in a specific energy that was 20–30% higher than that observed when grinding perpendicularly to the build direction. The specific energy when grinding perpendicularly was found to be comparable to micro-grinding conventional materials. The observed differences in specific energy were attributed to build-direction-dependent chip-formation efficiency (chipping ratio/pile-up formation) and to strain hardening of the piled-up material. Given the acicular AM microstructure, the latter was discussed as potentially influenced by crystallographic orientation and as a factor that can increase resistance when successive abrasive engagements remove the hardened pile-up. Nevertheless, at higher grinding aggressiveness (grit-penetration depth), the specific-energy values were found to be almost identical for all materials.

In a conventional application, Guo et al. [51] investigated profile grinding of PBF-EB/Ti6Al4V with a CBN wheel. The authors compared profile accuracy, surface roughness, and residual stresses before and after grinding. Grinding notably improved the surface finish, reducing R_a from $30 \mu\text{m}$ to $2 \mu\text{m}$. Additionally, the formation of a deformed layer with an approximate thickness of $2 \mu\text{m}$ was observed. The deformed layer exhibited an elevated dislocation density and microhardness in the vicinity of the surface. Subsequent electropolishing effectively removed the deformed layer and reduced the compressive residual stresses. The residual stresses present in the as-built state were also compressive, likely due to the preheating of the build plate during the printing of the material.

The SAG of PBF-EB/Ti6Al4V and PBF-LB/Ti6Al4V effectively removed the semi-sintered particles from the as-built surface

texture, achieving a surface roughness of approximately $10 \text{ nm } R_a$ from initial roughness values of $4\text{--}5 \mu\text{m } R_a$; thereby improving the surface finish by approximately three orders of magnitude [6]. Using a compliant tool with nickel-bonded diamond pellets, SAG demonstrated superior capability in finishing free-form surfaces, making it particularly suitable for post-processing of AM materials. Accordingly, SAG is a viable alternative to conventional grinding when the non-conforming geometry of a grinding wheel constrains tool access on complex freeform surfaces. Moreover, the process demonstrated consistent dimensional accuracy, with a variation of less than $\pm 5 \mu\text{m}$, even on complex free-form shapes, and improved the overall surface reflectivity. The SAG process can now be precisely controlled, thanks to the models that describe its mechanics at multiple scales (macro- and micro-level) [174]. Finally, the process can be implemented on a dedicated 7-axis polishing machine or a 5-axis machining center [20]. The finishing capabilities of these machine types was demonstrated on SAG of PBF-LB/17-4PH stainless steel.

In contrast to titanium alloys, the grindability of nickel-based superalloys such as AM-fabricated Alloy 718 has been more extensively researched. Karthick Raaj et al. [85] evaluated a sequential post-processing route for PBF-EB/Alloy 718, comparing the as-built condition with grinding, burnishing, and their combination. The as-built components exhibited R_a surface roughness of around $21 \mu\text{m}$, which was significantly reduced to about $0.18 \mu\text{m}$ after grinding, a two-order-of-magnitude improvement. The as-built residual stresses were tensile ($+189 \text{ MPa}$), and contrary to expectations, grinding further increased these stresses to approximately $+300 \text{ MPa}$, likely due to too-high grinding temperatures. Burnishing was then applied to impose controlled near-surface plastic deformation, thereby increasing microhardness and achieving compressive residual stresses.

The work by Lee et al. [100] provides important insights into the fatigue behavior of post-processed PBF-LB/Alloy 718. The grinding process itself is not well described, which unfortunately makes the experiments difficult to reproduce. However, grinding substantially improved surface roughness but could still leave surface grooves (grinding marks) that acted as stress concentrators, such that crack initiation remained surface-dominated in the ground condition. The study further showed that the combination of grinding and drag finishing was the only post-processing route that yielded negative skewness values ($R_{sk} = -0.14$), consistent with a more plateaued, isotropic-like surface texture. Superimposing drag-finishing on the ground surface reduced the influence of grinding marks and shifted crack initiation away from the surface, with cracks initiating predominantly from microstructural features (persistent slip bands/crystallographic facets) and, in some cases, from subsurface lack-of-fusion defects. Overall, the results indicated that fatigue performance in this investigation was governed primarily by surface topography/roughness, while residual-stress effects were discussed only qualitatively and treated as secondary.

Vaisakh Babu and Setti [3] studied the grindability of as-built PBF-LB/Alloy 718 (no post-heat treatment/HIP) and compared it with wrought material. Unlike the wrought condition, the AM material showed no substantial increase in specific grinding energy with successive passes, which the authors attributed to more frequent brittle micro-fracture of alumina grits promoted by AM porosity, since pore/keyhole features locally reduce surface support and facilitate deeper grit penetration and higher transient contact loads, thereby exposing fresh cutting edges. Moreover, the specific normal force showed a considerably higher increase compared to the specific tangential force, a finding that is consistent with observations made for AM steel [66].

3.3. Other grinding applications

Ultraprecision grinding of silicon carbide optics remains one of the most time-consuming and costly finishing operations, particularly when fabricating freeform or lightweight mirrors from CVD-coated blanks. To address these limitations, Horvath et al. [67,68]

investigated AM routes to produce near-net-shape SiC mirror pre-forms suitable for direct grinding and polishing, motivated by the need to shorten the production chain for large freeform optical components. BJT combined with chemical vapor infiltration (CVI) enabled densification of as-built SiC components to approximately 90–92 % relative density and the formation of a dense outer layer that was directly grindable. Comparative grinding trials on CVD/SiC and BJT–CVI/SiC were performed. Rough grinding employed a 325/400 grit bronze-bond wheel, and finishing used a 2/4 μm copper resin-bond wheel. Process parameters were systematically varied, with typical cutting depths of 0.15 mm, feed per revolution of 0.20 mm, and wheel speeds between 20 and 58 m/s. The results showed comparable processability but lower specific grinding energy and forces for the BJT–CVI material, attributed to micro-structural differences and the relatively weak bonding between powder particles and the CVI matrix in the AM composite [68]. Finish grinding achieved surface roughness values below 10 nm RMS, suitable for infrared optical applications, although residual porosity currently limits polishing to visible-grade specifications. These findings demonstrate the potential of combining BJT, CVI densification, and precision grinding to deliver optical-grade SiC components in a significantly shorter process chain while preserving the design freedom enabled by topology-optimized mirror structures.

Post-processing is also required for unconventional materials such as high-entropy alloys (HEAs), which can be additively manufactured. Guo et al. [52] investigated various post-processing operations on PBF-LB/CoCrFeMnNi. This is considered a prototype HEA with a stable, single, face-centered cubic phase and rather low hardness (about 350 HV after grinding). In this work, an electroplated grinding wheel was used to finish ground samples with a very low specific material removal rate of $Q_w = 0.3 \text{ mm}^2/\text{s}$. This resulted in a 90% reduction in R_a from 30 μm as-printed surface to 3.5 μm . In addition, a tenfold increase in compressive residual stress was observed (approximately –40 MPa for as-printed and –400 MPa for ground samples). The analysis of surface integrity also revealed surface plastic deformation with orientation toward the grinding direction.

4. Abrasive fine-finishing

Abrasive fine-finishing includes various finishing processes, which can be classified by the tools used [59]. This chapter deals with processes using abrasive flow media (such as AFM and MAF), as well as polishing.

4.1. Abrasive flow machining

Fig. 7 shows a schematic of two-way AFM finishing of an internal passage. In AFM, abrasive-laden media composed of abrasive and a viscoelastic polymer (often a non-Newtonian fluid) is extruded through the workpiece passages. The unique characteristic of the polymer—its shear-thinning or shear-thickening behavior—allows

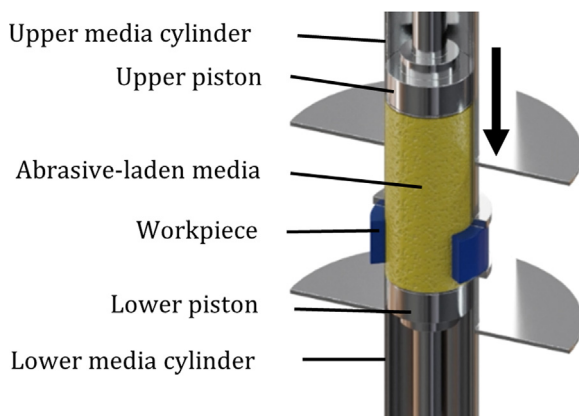


Fig. 7. AFM principle [courtesy of Extrude Hone].

it to effectively guide the abrasive grains in the media against the target surface where the media slides and removes material from the target surface. Forcing the media back and forth inside the target passage facilitates surface machining [59].

Many parameters influence material removal and the resulting surface roughness of the workpiece surface. They include the workpiece materials, abrasive type, size, and concentration; media properties, temperature, pressure, and flow rate; media displacement; etc. The media temperature generally changes during processing; this influences the viscosity and media pressure—and thus the media flow rate. Therefore, control of the media temperature is essential for obtaining consistent performance.

In the internal finishing of a component, the media can easily be made to flow through passages to finish the component surface. Complex parts (such as airfoils) do not naturally have appropriate media passages, so a passage needs to be created around the component with a determined clearance for the abrasive-laden media. The media is forced through this clearance to finish the component surface. Design and control of this clearance is, therefore, another key parameter.

AFM has been applied to a wide range of component geometries (including complex internal passages, freeform surfaces, and orifices) made of various materials, including complex parts made using AM. For example, PBF-LB enables fabrication of metallic parts with complex internal passages (e.g., heat exchangers) but creates rough surfaces. Surface finishing of the complex internal passages in metallic AM parts is a significant application of AFM. Experiments using a rectangular right-angle channel in additively manufactured Ti6Al4V showed that the media viscosity significantly influences the material removal and the resultant surface topography. Increasing the media viscosity leads to enhanced material removal (due to the engagement of more micro-cutting abrasive particles) but a decrease in wall-slip velocity and abrasive-particle normal stress. Moreover, the use of high-viscosity media diminishes the effects of the AM-build-orientation angle on material removal, although the defect layer thickness is increased with the AM-build-orientation angle [125].

Modelling of AFM has played a key role in predicting the material removal and resulting surface roughness [53,77]. Computational fluid dynamics (CFD) is a powerful tool to simulate the media flow inside a target passage, correlate the flow characteristics and the material removal, and predict the resulting surface roughness. This approach has been successfully implemented in the internal finishing of Ti6Al4V [125] and 316L stainless steel channels [138] made using PBF-LB.

Fig. 8 shows a case using tooling to create media passages for steel-blade finishing [95].

AFM is not only used to reduce the surface roughness of AM parts but also to alter their mechanical properties. Some examples include the enhancement of fatigue strength of components with internal channels made of maraging steel 300 [57] and the increase of compressive residual stress of AlSi10Mg alloy tubes [125] and Ti6Al4V lattice structures [76]. The efficacy of AFM finishing of turbine blades and the effects of the processed surface (e.g., roughness) on heat transfer and aerodynamic losses were also demonstrated on PBF-LB/NiCoCr-based alloy (GRX-810) turbine blades [105]. In addition to metallic parts, AFM has been applied to AM polymeric parts, such as PLA (polylactic acid) and ABS parts made by fused deposition modelling (FDM). An interesting trend found in the literature is the development of new media that are more affordable and sustainable than commercially available media for finishing AM polymeric parts.

For example, waste vegetable oil mixed with glycerin [160] and corn starch [61] have been used to create new media with viscosity between 0.2 Pa·s and 3 Pa·s (traditional media have viscosities several orders of magnitude higher). For example, mixing groundnut-oil-based media with fuller's earth (clay) and SiC grains gave a viscosity of 60 Pa·s. When finishing PLA airfoils using this media, the

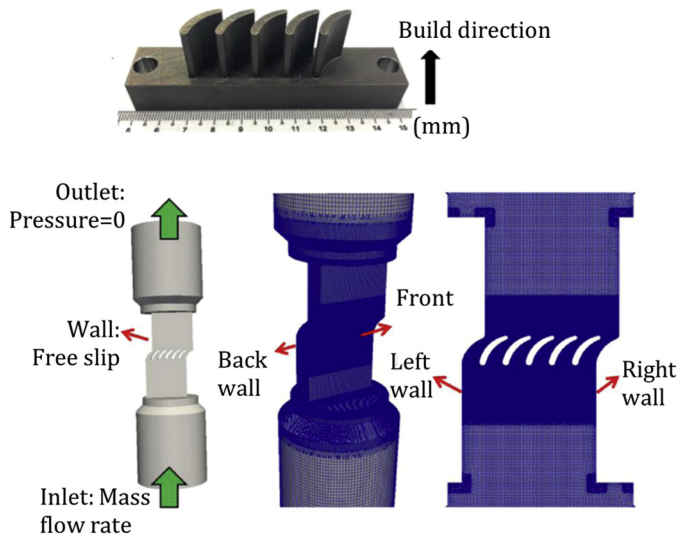


Fig. 8. As-printed airfoils and computational domain with boundary conditions and mesh distribution [95].

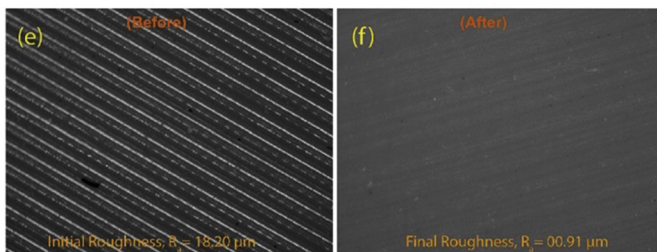


Fig. 9. Optical images (x500) of before and after finishing of aerofoil workpiece made with FDM of PLA [62].

initial surface roughness R_a of $18.2 \mu\text{m}$ was reduced to $0.9 \mu\text{m}$, and the staircase effect was eliminated in 90 min (Fig. 9) [62].

Hydrogel-based media is another cost-effective/sustainable media developed as an alternative to commercially available media. The media viscosity can be increased to more than $600 \text{ Pa}\cdot\text{s}$ by altering the additives in the media [30]. Its efficacy for AM polymeric parts was also demonstrated by the finishing of a polyamide 12 femoral head made using PBF in addition to FDM parts made using PLA and ABS [31,117].

A new affordable/sustainable media (such as biodegradable galactomannan-polymer-based media) was also developed for finishing AM metallic parts. The feasibility of this media was demonstrated with copper and 316L stainless steel parts made using atomic diffusion additive manufacturing [5].

4.2. Magnetic field-assisted finishing

Fig. 10 shows MAF principles. Like AFM, MAF uses a tool (e.g., a magnetic-particle brush) that naturally conforms to the workpiece

geometry in a magnetic field, and the tool stiffness can be adjusted by the magnetic field at the finishing area, as shown in Figs. 10 (a) and (b). When the magnetic field is moved, the tool follows it, dragging the abrasives across the workpiece surface, finishing the surface. As shown in Fig. 10 (c), the tool enables finishing of internal surfaces of nonferromagnetic parts where a conventional polishing tool is not easily introduced.

Since the magnetic force acting on the magnetic tool is a major component of the finishing force, parameters affecting the magnetic force (i.e., volume and susceptibility of the magnetic tool and the magnetic field intensity and gradient) must be precisely controlled to obtain the tool motion required to achieve the desired material removal and surface roughness [59]. Magnetic-field analysis is a powerful tool for the design of the magnetic-field generator and the estimation of the magnetic-particle brush formation and strength [25]. In addition, the following parameters also affect the material removal in MAF: workpiece material, geometry, and initial surface conditions; abrasive type and size; lubricant type and condition; relative speed between the magnetic tool (or mixture of magnetic tool and abrasive) and the target surface.

Recent advancement of AM technology enables easy manufacturing of complex geometries. MAF is listed with AFM as a commonly applied process that mechanically finishes complex geometries, especially internal passages in AM parts. Unlike AFM, however, MAF is significantly influenced by the magnetic properties and component geometry, which determine the magnetic field and material removal at the finishing area. For example, the case with five arrayed steel-blades shown in Fig. 8 is appropriate for AFM but may be inappropriate for MAF because the magnetic tools cannot be easily introduced into the space between the blades. Other examples that MAF is not appropriate for finishing include an internal finishing of channels in ferromagnetic parts and channels with thick walls inside nonferromagnetic parts.

Fundamental studies of MAF material-removal characteristics for AM parts found in the literature have been often conducted using nonferromagnetic 316L stainless steel and Al-Si alloys made with PBF. These materials are widely used in industries such as automotive, aerospace, and the medical industry. If a workpiece is axisymmetric and rotatable at high speeds, the principal motion of the mixture of magnetic particles and abrasive against the surface can be achieved by workpiece rotation. An example is shown in Fig. 11.

To accelerate the material removal and/or to finish large areas, an additional reciprocation is typically added to the rotation. In contrast, non-axisymmetric workpieces that do not have circular cross sections or are not rotatable (e.g., AlSi10Mg waveguides made by PBF [162] and NASA HR-1 channels made using DED [71]) require vibration/oscillation along the workpiece axis to achieve appropriate principal magnetic-tool motion against the target surface.

Rough surface, low geometrical accuracy, and non-homogeneous mechanical properties are inherent issues of AM parts. For example, AM-surface roughness and mechanical properties can be different even if the parts are printed in the same batch. AM-

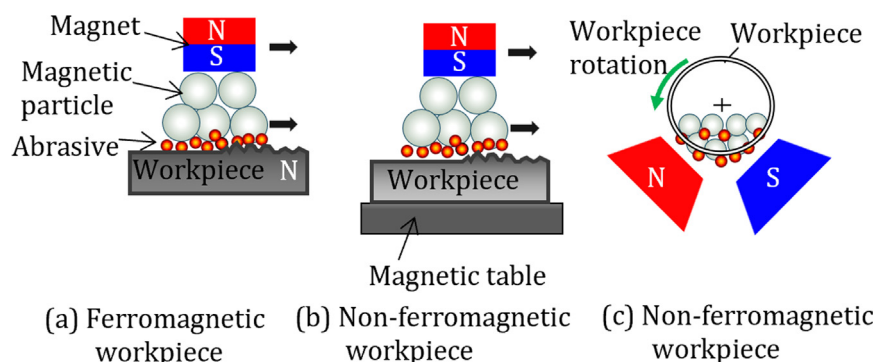


Fig. 10. Processing principle of MAF.

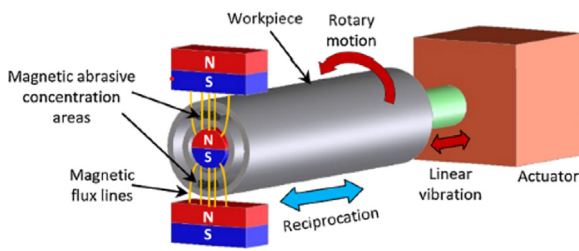


Fig. 11. Principle of internal finishing of double layered workpiece [54].

component surface roughness depends on the printing strategy. However, MAF enables finishing either 316L or AlSi10Mg to similar levels regardless of the printing strategies applied. Note that the time needed to bring the surface roughness to the same level depends on the initial surface conditions [165,175].

Some reports have included the effects of MAF on the microstructures and the mechanical properties of AM parts. Tensile residual stress has been detected on unprocessed PBF-LB/316L stainless steel component surfaces. The effect of MAF polishing on the residual stress on the stainless steel component surface was insignificant [165].

A study of PBF-LB/AlSi10Mg parts showed that MAF enables removal of the work-hardened layer introduced during the preceding grinding process, reducing the surface hardness [157]. Souza et al. [148] demonstrated the effect of MAF combined with milling and grinding processes on DED-LB/316L stainless steel. Milling and grinding induced tensile- and compressive residual stress in machined/ground surfaces. In contrast, the effect of MAF on residual stress on the finished surface was less significant than the effect of milling and grinding processes. In addition to 316L and Al-Si alloys, the effect of MAF on Ni-based superalloys used for engine components has been studied. Li et al. [104] demonstrated the effects of MAF combined with heat treatments (homogenization and aging) on the microstructures and mechanical properties of PBF-LB/Alloy 718 parts during polishing. Similar to 316L components, as-printed Alloy 718 parts exhibit tensile residual stress across their surfaces. As is commonly known, the magnitude and nonuniformity of tensile residual stress can be decreased by heat treatment. Applying MAF to heat-treated surfaces alters the tensile residual stress to compressive residual stress, enhancing ductility by 23%, which exceeds that of wrought Alloy 718 [104].

Another study was conducted with parts made of PBF-EB/Haynes 282. AM parts are often removed from the base material using wire electro-discharge machining (WEDM). The average values of the measured roughness R_a of the WEDM-machined and as-printed surfaces were 3.10 μm , and 38.2 μm , respectively. This study examined how the surface condition, whether as-built or produced by WEDM, influences material removal and the resulting surface roughness when using nickel-coated or uncoated diamond abrasives [136]. Since the Ni-coated diamond abrasive is magnetic, it is noted that the magnetic-field design affects the presence of diamond abrasive during polishing, which changes the material-removal characteristics. For Ni-coated diamond abrasive, the reduced sharpness of abrasive cutting edges due to the coatings hinders the material removal rate. However, once the Ni coating is worn off while sliding over the hard and rough as-printed AM surface, the diamond abrasive cutting edges participate in finishing

and facilitates material removal. As a result, the material removal rate for the Ni-coated diamond abrasive was greater for the as-printed AM surface than for the WEDM-machined surface. While the Ni-coated diamond-abrasive size was approximately unchanged after finishing the WEDM-machined surface, the Ni-coated diamond-abrasive size was reduced after finishing the as-printed AM surface due to the loss of the Ni coating. For uncoated diamond abrasive, the material removal for the WEDM-machined surface was greater than the as-printed AM surface. This is because the smoother surface (i.e., WEDM-machined surface) facilitated relative motion with the uncoated diamond abrasive compared with the as-printed AM surface. The uncoated diamond-abrasive appearance remained mostly unchanged after finishing the WEDM-machined and the as-printed AM surfaces.

4.3. Conventional polishing

Conventional and manual polishing can be used to smooth AM parts. However, polishing generally requires extensive time to smooth the component surface, especially rough surfaces made by AM. To minimize the time required for smoothing the surface, polishing has been applied after some material removal processes (e.g., milling, grinding, sanding, barrelling, etc.).

The study by Iquebal et al. [72] demonstrated a multi-step combined process for PBF-EB/Ti6Al4V parts. In addition, the authors observed changes in the Ti6Al4V surface generated by PBF-EB with polishing time, and these changes revealed the surface-smoothing mechanism. In polishing, material removal occurs at the initial stage, and the primary action of smoothing involves material redistribution and bridging between neighboring asperities [72]. As shown in Fig. 12, the dales between asperities (indicated by a yellow arrow) were diminished by plastic flow of the neighboring material and not by abrasion; this results in smoothing [72].

5. Mass finishing

Most mass-finishing processes involve placing multiple workpieces together with abrasive media (that contains abrasive grains in a bonded matrix with a characteristic structure/porosity) in a rotating or vibrating container, typically with a liquid compound. The movement of the container causes the abrasive media to slide over the surfaces and edges of the workpieces, removing material and wearing themselves away [128]. This results in irregular machining marks on the workpiece surface due to the disordered movements of the abrasive media. The compound solution collects the abraded material.

Mass finishing processes are classified into barrel finishing (tumbling), vibratory finishing, centrifugal disc and barrel finishing, and spindle (drag) finishing, according to how the relative movement between the abrasive bodies and the workpiece is generated [60]. These processes often provide economical post-processing, especially for finishing the complex geometries of AM components [10] primarily because workpieces can be processed in bulk, which results in significant cost savings. Additionally, these processes offer a high level of automation and produce uniform results [128]. The fundamental principles and mechanisms of mass finishing processes are well established and do not differ between AM and

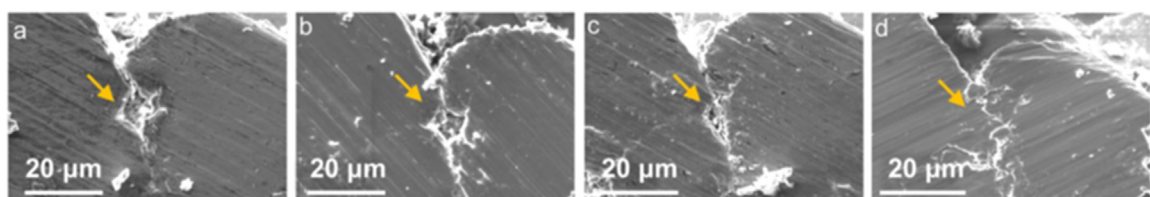


Fig. 12. SEM-photographs of changes in dales between asperities ~10 μm in size (indicated by arrows) with time (every 90 s) during polishing [72].

conventionally manufactured components; a comprehensive treatment was provided in [59]. The following subsections therefore focus on the specific aspects that arise when these processes are applied to AM components, in particular the influence of the as-built surface state, near-surface defect populations, and AM-induced material properties on finishing outcomes.

5.1. Barrel finishing (tumbling)

Barrel finishing is a mass finishing technique used to refine surfaces, deburr, and remove material through the interaction of abrasive media and workpieces in a rotating barrel. During operation, the charge—comprising workpieces, abrasive media, water, and chemical compounds—moves upward along the barrel wall until a critical angle is reached. It then cascades downward to create an active layer. This movement generates mechanical abrasion, enhancing surface quality [11]. The process efficiency depends on several parameters, including media type and size, barrel rotation speed, processing time, and fill percentage.

Barrel finishing has proven effective in improving the surface characteristics and mechanical properties of AM components. Studies have demonstrated its adaptability for various materials, such as aluminum alloys [134], titanium alloys [29], stainless steel [118], nickel alloys [102], and polymers [10].

For instance, Rümmler et al. [134] investigated the finishing of PBF-LB/AlSi10Mg components in a three-step process using ceramic abrasives of different geometry (polyhedral: 50 rpm, 60 min; pyramidal: 300 rpm, 90 min; cylindrical: 300 rpm, 30 min). While the media geometry was specified, the media size was not reported. The process reduced the surface roughness from $Ra \sim 14 \mu\text{m}$ to $\sim 3 \mu\text{m}$, primarily through the removal of AM-typical surface features such as adhered and partially melted particles and pronounced peak-dale structures. The improved surface condition was accompanied by higher static tensile properties (yield strength increased from 247 MPa to 268 MPa, ultimate tensile strength increased from 390 MPa to 430 MPa).

Similarly, research by Denti et al. [29] on PBF-LB/Ti6Al4V components revealed that tumbling reduced the average surface roughness and altered surface skewness from positive to negative values. Visual observations of the changing surface morphology were made based on the SEM images shown in Fig. 13.

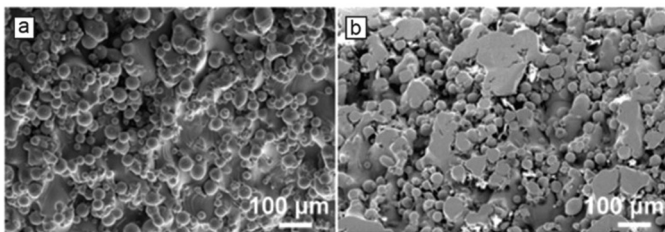


Fig. 13. SEM-images of the Ti6Al4V as-built surface (a) and tumbled surface (b) (adapted from [29]).

The surface of the as-built material shows adhering spherical powder particles. After tumbling, small flat regions with limited extensions were observed while the original structure remained visible. With this consideration, the shift in the skewness can be explained. This change in surface morphology reduces stress concentration sites, which is beneficial for mechanical performance. Despite the pronounced roughness reduction, fatigue testing using a run-out criterion of $N = 6 \times 10^6$ cycles ($R = 0$) showed that tumbling did not achieve run-out at $\sigma_{\max} = 200$ MPa and failed after $\sim 4.5 \times 10^5$ cycles, whereas the as-built condition reached run-out at the same stress level. This inferior fatigue performance was attributed to the purely erosive nature of the chosen tumbling process, which removes surface material without inducing beneficial compressive residual stresses and

can expose AM-typical surface connected defects (e.g., near-surface porosity/LOF) thereby promoting crack initiation. Consequently, the fatigue response of AM components to tumbling is strongly governed by the resulting defect state rather than roughness alone.

In a study by Boschetto et al. [12], an observation of the surface structure was performed. It was shown that barrel finishing mainly removed the peaks, whereas the dales of the surface profile were only slightly modified. This can be attributed to the dale sizes, which are smaller than the media size, meaning that no material can be removed there. A longer processing time is able to improve this issue; however, this can cause further damage due to microfatigue and microcracking phenomena. In addition, the as-built part surface morphologies differ depending on the plane orientation relative to the build direction. The upward-facing surface (0°) is mainly governed by melt-track/scan-line topography and typically exhibits lower roughness than the side surfaces. In contrast, vertical sidewalls (90°) are dominated by layerwise stair-stepping and adhered/partially fused particles [123]. Accordingly, different surface directions (e.g., 0° , 45° , or 90°) require different processing times to achieve the same surface quality [13]. This is shown in Fig. 14. For this reason, a single component can therefore exhibit different surface qualities at different locations.

Further research focused on optimizing barrel finishing parameters for the post-processing of AM parts, which is essential for achieving consistent, effective results. The Bagnold number (Ba) predicts the flow behavior of granular materials. At low Ba values (<40), macro-viscous flows, such as slurry or sludge-like flows, dominate. For Ba values above 450, however, fluid viscosity becomes negligible compared to interparticle collisions, resulting in grain-inertial flows. Between these ranges lies a transitional regime. There are six distinct motion types in barrel finishing: sliding, slumping, rolling, cascading, cataracting, and centrifuging. The type of motion depends on the fill level and rotational speed of the barrel. Bed behavior diagrams were experimentally developed to map these motions as functions of fill level and barrel speed. Notably, only rolling and cascading motions lead to efficient material removal. They are characterized by a continuous flow resembling an avalanche, which creates relative motion between the media and the workpieces, enabling smooth and effective mechanical material removal [14].

Additional studies on Alloy 718 demonstrated that barrel finishing not only improved surface roughness but also improved corrosion resistance and induced compressive residual stresses, which can explain the enhanced fatigue resistance [102]. The as-built component showed tensile residual stresses of $\sigma_R \cong +120$ MPa in the top near-surface layer, whereas barrel finishing led to a shift to compressive stresses of $\sigma_R \cong -201$ MPa. This shift was attributed to the plastic deformation induced by the mechanical treatment. Furthermore, due to the applied mechanical forces, a decrease in grain size and an increase in hardness in the near-surface layers could be detected. The hardening depth is approximately $80 \mu\text{m}$ after barrel finishing.

However, barrel finishing has limitations. Complex geometries, such as internal channels and deep cavities, often pose challenges for abrasive media accessibility, leading to uneven surface treatment. Additionally, barrel finishing can result in excessive radiusing of edges, which may be undesirable for components requiring precise edge definition [13]. Another drawback is the long processing times often required to achieve the desired surface quality, which can limit the applicability of tumbling as a post-processing step for AM components, e.g., for on-demand spare part manufacturing where short lead times are a key advantage.

5.2. Centrifugal disc finishing

In centrifugal disc finishing, workpieces and abrasive media are placed in a container with a rotating disc at the bottom. The disc

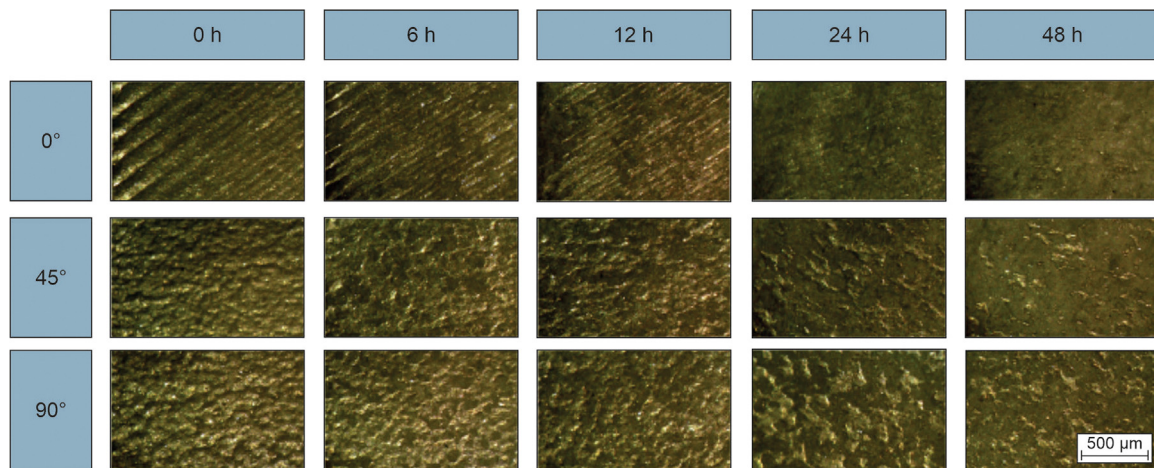


Fig. 14. Specimen surfaces at different processing times (adapted from [13]).

rotation generates centrifugal forces that move the parts and media in a toroidal motion, creating mechanical interactions. These interactions enable relatively high material removal rates and improved surface quality, which is particularly relevant for AM components with pronounced as-built roughness where efficient processing is required to reach functional-surface states. The applicability of centrifugal disc finishing for the post-processing of additively manufactured parts has been proven in studies on a wide range of materials. Examples include stainless steels [108,145], titanium alloys [93,158], and copper alloys [45].

Kopp et al. [93] applied the Discrete Element Method (DEM) to analyze centrifugal disc finishing of additively manufactured Ti6Al4V components. This modelling approach is particularly relevant for AM parts, as their complex geometries and orientation-dependent as-built surface states lead to varying media accessibility and non-uniform local finishing results that are difficult to design by empirical trial and error. The DEM simulations quantified contact forces and contact frequencies between the abrasive media and the workpiece as a function of media shape and disc speed, and correlated a derived contact-intensity parameter with experimentally observed roughness reduction. For prismatic media, a pronounced roughness reduction was achieved (R_a from 17.9 μm in the as-built state to 2.1 μm after 120 min), whereas spherical media resulted in lower material removal and roughness reduction due to the reduced effective contact intensity. The results demonstrate that, for AM components, DEM-based modelling can support the design of centrifugal disc finishing by predicting local finishing efficiency and highlighting limitations in regions with restricted media access.

In a study by Fuchs et al. [37], the authors evaluated the influence of process parameters such as duration, media size, and tank filling quantity, on the post-processing of 316L stainless steel. The results showed that surface roughness (R_a) decreased by up to 95% after 3 h of processing, reaching final R_a values as low as 0.37 μm . The use of smaller abrasive media resulted in smoother surfaces, while larger media achieved higher material removal rates. The tank-filling quantity exhibited an inverse relationship with material removal, as lower fillings generated higher collision forces, enhancing surface interactions. These findings emphasize the adaptability of centrifugal disc finishing for achieving application-specific surface qualities, particularly for sealing surfaces, where R_a values less than 0.8 μm are essential [97]. In comparison, tests were carried out with vibratory finishing. Within the same processing time, vibratory finishing only improved the as-built surface R_a by 52%.

For copper cold-sprayed samples, Gleason et al. [45] investigated the surface evolution under centrifugal disc finishing using polyester-bound zircon abrasive media. The results showed that surface roughness significantly decreased within the first 10 min of processing due to the removal of loosely bonded powder particles. The

study revealed that material removal rates decreased as material hardness increased: harder samples exhibited slower rates of material removal. The initial reduction in surface roughness was attributed to the abrasion of fine-scale features and areas with incomplete particle bonding. However, prolonged finishing times demonstrated that further improvement in surface uniformity requires the removal of the mesoscale peak-to-valley topography, since large surface peaks restrict media access to valley regions. Therefore, sufficient material must be removed to eliminate the larger-scale peaks.

In research by Soja et al. [145], the impact of centrifugal disc finishing on various surface orientations of PBF-LB/17-4 PH stainless steel, including horizontal, vertical, and inclined surfaces was studied. Centrifugal disc finishing was performed in an Erba Turbe-60 machine using Rösler RXF 10/12 DZS ceramic media at a constant speed of 179 rpm, with runtimes between 0.5 and 8 h. After 4 h, the inclined surface roughness decreased from $R_a = 13.6 \mu\text{m}$ to 2.9 μm , and the vertical surface showed a comparable reduction from 13.5 μm to 2.9 μm . Consistent with the peak-removal behavior discussed for mass finishing processes, Centrifugal disc finishing preferentially removed surface peaks and produced plateau-like topographies while valleys remained largely unaffected. Edges were also affected: the external corner radius increased to 0.47 mm after 4 h and to 0.69 mm after 8 h (the initial radius was not reported). As with mass finishing in general, this selective action is governed by controllable parameters such as machine speed, runtime and media choice. The study emphasized that the dominant limitation over extended runtimes is media wear, which progressively reduces the process efficiency. Accordingly, a near-linear material removal behavior is reported between 1 and 4 h, whereas longer runtimes provide smaller incremental roughness improvements while increasingly compromising part integrity, i.e., dimensional fidelity through excessive edge rounding.

5.3. Centrifugal barrel finishing

In centrifugal barrel finishing, components and abrasive media are placed in barrels mounted on a rotating turret. As the turret spins, the barrels rotate on their axes, creating centrifugal forces that drive the sliding and impact of the media against the components. This interaction is effective for deburring, polishing, and smoothing AM components. Its effectiveness has been demonstrated with different materials, including titanium alloys [81,83] and stainless steel [90].

Kahlin et al. [81] studied Ti6Al4V fatigue specimens produced by PBF-EB and PBF-LB subjected to centrifugal barrel finishing. The finishing process had three stages with different media and processing times. The average reduction of the specimen diameter per side was 220 μm for PBF-EB and 180 μm for PBF-LB. The greater material

removal for PBF-EB is consistent with its larger initial as-built surface roughness, which requires more material to be removed to fully eliminate the effect of the surface topography. Residual stress measurements showed that centrifugal barrel finishing generated compressive residual stresses on the surface (~ -550 MPa) for both materials, consistent with a work-hardening effect, whereas the PBF-LB specimen showed only minor hardness changes. At 5×10^6 cycles, centrifugal barrel finishing in combination with a HIP treatment increased the fatigue strength relative to the respective as-built reference level by 100% (150 MPa) for PBF-EB specimens and 125% (335 MPa) for PBF-LB specimen. Despite similarly compressive residual stresses, the post-processed fatigue level of the PBF-EB specimen remained markedly lower. The authors attribute this to the persistence of deep surface dales after CF in PBF-EB specimen, which remained dominant crack initiation sites. Kahlin et al. conclude that centrifugal barrel finishing can raise the fatigue limit of non-HIP PBF-LB specimen to levels comparable to conventional wrought material, whereas for PBF-EB specimen comparable fatigue levels generally require machining combined with HIP.

Khorasani et al. [90] used centrifugal barrel finishing to post-process PBF-LB/316L stainless steel. They used two types of pyramidal ceramic media elements (with 3×3 mm and 6×6 mm base area), varied the rotational speed (100–160 rpm) and the processing time (200–240 min). The specimens were built horizontally, and the surface roughness was evaluated in three in-plane directions relative to the laser scan movement (parallel, perpendicular and 45°) to capture the directional roughness dependency typical of AM components. The reference (as-built) R_a values were 5.34 μm (parallel), 7.70 μm (perpendicular), and 6.33 μm (45°). After centrifugal barrel finishing, 2.01 μm , 3.37 μm , and 2.78 μm were achieved, corresponding to reductions of approx. 62%, 56%, and 56%. The best overall surface quality in all three directions was obtained at 140 rpm with 6 mm media and 200 min processing time. Within these 200 min, the surface peaks are removed efficiently, whereas longer processing times can worsen the surface roughness via increased impact effects. They further reported that higher rotational speeds raise the process temperature (thermal softening), highlighting that parameter optimization for AM components must balance peak/particle removal and roughness homogenization against over-processing and media wear.

In a study by Kahlin et al. [82], different surface finishing techniques were compared for Ti6Al4V components manufactured by PBF-EB and PBF-LB. Two abrasive processes (centrifugal finishing and abrasive brushing) and two processes primarily aimed at introducing compressive residual stresses (shot peening and laser shock peening) were analyzed. Fig. 15 shows the S_z values achieved after the different post-processing techniques and highlights that on rough AM as-built surfaces, residual stress treatments alone can leave relatively high S_z values,

whereas abrasive material removal can reduce S_z more and is therefore essential when the AM topography itself dominates stress concentration.

For abrasive brushing, the authors used robot-controlled abrasive brushes with force feedback (three stages from bulk removal to polishing), brush feed rates of 125 mm/min (gauge) down to 50 mm/min (grip transition). Centrifugal finishing was applied as a three-step process totaling 270 min with three different media types (specified only by manufacturer name). The roughness values of the PBF-EB specimens are consistently higher than the PBF-LB values. This corresponds to the higher initial surface roughness after the PBF-EB process. Only abrasive brushing and centrifugal finishing were able to remove a considerable amount of material from the surface. However, some dales in the surface topography still remained after centrifugal barrel finishing. Abrasive brushing was able to remove those dales completely. In terms of fatigue performance, centrifugal finishing outperformed abrasive brushing and produced the best results for the PBF-LB specimen. The fatigue life increased by a factor of 7.1 compared to the as-built conditions, surpassing all other material and post-processing conditions. Once the rough surface is smoothed, fatigue can become governed by AM defect populations, including near-surface LOF opened during post-processing and pores resulting from the AM process, which explains why the fatigue life improvements differ strongly between abrasive processes and between PBF-LB and PBF-EB. With a total processing time of 270 mins, centrifugal finishing is the most time-consuming process. However, several components can be finished in one batch.

5.4. Spindle (Drag) finishing

Drag finishing (also known as spindle finishing) is a mass-finishing process that enhances surface quality and mechanical properties of components. During this process, workpieces are fixed on a rotating holder and dragged through a container filled with abrasive media. The movement and friction between the workpieces and the media deburr, polish, and smooth the surfaces. For finishing of AM components, drag finishing is used for post-processing of various materials. These include titanium alloys [39,127], steels [88,137], and nickel alloys [84,100,112].

In a study by Lee et al. [100], a substantial reduction in surface roughness was achieved when using drag finishing. As-built surfaces, characterized by stair-step effects and adhered powder particles, initially had a R_a value of 4.35 μm . Drag finishing reduced this to 2.71 μm . However, inspection of the height maps/line profiles shows that the longer-wavelength, layer-wise (stair-step) surface undulations remained largely unchanged. Thus, drag finishing primarily attenuated high-frequency asperities/adhered particles rather than removing the low-spatial frequency component of the as-built topography. In addition to surface quality, drag finishing had a moderate impact on fatigue performance, particularly in the high-cycle fatigue regime. The compressive residual stresses induced by the process mitigated stress concentrations associated with sharp surface features, thereby improving fatigue life compared to the as-built condition. Despite these benefits, the study revealed that drag finishing alone could not fully eliminate fatigue-critical surface defects. A notable advancement was observed with hybrid approaches combining grinding and drag finishing. This combined process resulted in the lowest surface roughness ($R_a = 0.31$ μm) among all surface conditions studied in this investigation and correspondingly showed the best fatigue performance (highest fatigue resistance). Compared to drag finishing alone, the combined process eliminated machining marks, further reduced surface waviness, and fully removed AM-related surface-connected pores. The study attributed the enhanced fatigue life primarily to the comprehensive removal of surface irregularities and the reduction of stress concentration sites.

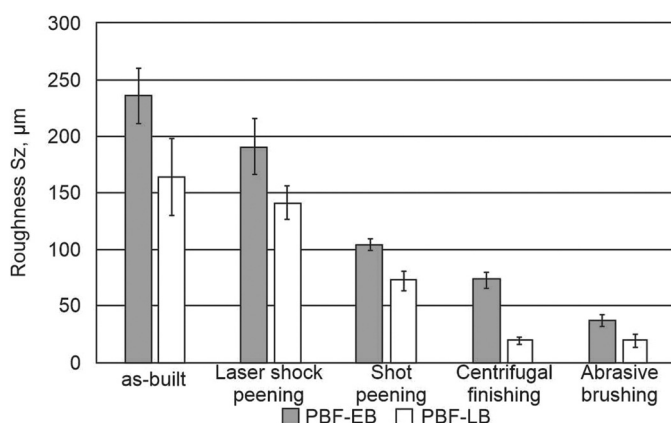


Fig. 15. Surface roughness comparison for Ti6Al4V specimens manufactured by PBF-EB and PBF-LB in the as-built condition and after different processes (adapted from [82]).

Although drag finishing mostly focuses on surface refinement, it also induces minor subsurface modifications. Kaynak et al. [86] detected a slight increase in surface hardness in 316L stainless steel specimens, with hardness values rising from approximately 270 HV in the as-built state to 285 HV near the surface after drag finishing. This effect is attributed to localized plastic deformation and is more pronounced in harder materials. For example, an 11% increase in surface hardness was observed in Alloy 718, which can be attributed to strain hardening [87]. The hardened layer, however, was relatively shallow, extending only about 15 μm beneath the surface. It has been shown that the increase in hardness due to drag finishing can increase wear resistance. The authors performed dry reciprocating ball-on-flat tests (ASTM G133) without lubricant/cooling for 40 min at 15 N and 6 mm stroke length, using a 6 mm WC-Co ball as a counterbody. Under these conditions, the coefficient of friction decreased from 0.66 (as-built) to 0.59 after drag finishing. The study further reports a specific wear rate (normalized by load and sliding distance, not time). Using this definition, the specific wear rate decreased from 6.09 $\text{mm}^3/\text{N}\cdot\text{mm}$ (as-built: $R_a = 19\text{--}24\text{ }\mu\text{m}$) to 5.68 $\text{mm}^3/\text{N}\cdot\text{mm}$ after drag finishing ($R_a = 2.56\text{ }\mu\text{m}$) [87].

Numerical simulations have provided valuable insights into optimizing drag finishing conditions and improving the understanding of abrasive mechanisms. In a study by Malkorra et al. [112], the authors developed a 2D finite-element model to analyze mechanical loadings at the interface between abrasive media and the workpiece surface. Four media types that differed in shape (spherical and pyramidal) and size, were studied and correlated with experimental data to evaluate surface roughness evolution. Experimental tests on PBF-LB/Alloy 718 samples (initial $S_a \cong 6\text{ }\mu\text{m}$) revealed that surface roughness improvements depended on the media type and the surface orientation angles relative to the media flow (0° , 30° , 60° , and 90°). The largest roughness reductions occurred in the frontal ($\sim 0^\circ$) and intermediate zones ($\sim 30^\circ$, $\sim 60^\circ$), where both normal and shear stresses are significantly higher than in the lateral zone ($\sim 90^\circ$). A slightly better surface finish at intermediate orientation angles ($\sim 30^\circ$) can be correlated to the maximum shear stress in this area. In contrast, sliding velocity, which peaks at approximately 60° and is lowest in the frontal zone, does not correlate with the observed roughness reduction pattern, indicating that surface roughness improvement is governed by mechanical stresses rather than sliding velocity. Roughness reduction is governed predominantly by preferential removal of surface peaks, while severe plastic deformation is not significant, since dales remained largely unaffected. However, media geometry and size controlled the magnitude of the interface (contact) stresses: The pyramidal media generated higher normal contact stresses (up to 45 kPa) than spherical media (20 kPa), explaining their higher polishing efficiency.

5.5. Vibratory finishing

Studies have demonstrated the applicability of vibratory finishing to the post-processing of numerous AM materials, for example

stainless steels [48,86], aluminum alloys [7,9], titanium alloys [4,8], nickel alloys [87,135], and polymers [89].

Bernhardt et al. [8] investigated the post-processing of PBF-LB/Ti6Al4V, using a defined process chain and a wrought Ti6Al4V reference for comparison for achieving implant-relevant surface states. As a preliminary step, all specimens were sandblasted (SB), which already removes a large fraction of the adhered powder particles typical of PBF surfaces (see Fig. 16). Subsequent vibratory finishing was carried out under wet conditions in two stages: a coarser material-removal stage using pyramidal ceramic media (referred to as vibratory grinding (VG) by the authors) and a finer polishing stage using cylindrical ceramic media (vibratory polishing (VP)). The authors state process durations of up to 1200 min (VG) and 120 min (VP). The surface topography results after the different steps can be seen in Fig. 16. The as-built condition ($R_a = 22.7\text{ }\mu\text{m}$) was reduced after SB ($R_a = 16.9\text{ }\mu\text{m}$) and then improved by the combined SB-VG-VP route to $R_a = 0.22\text{ }\mu\text{m}$, reaching a roughness state that is on the same order as the wrought reference ($R_a = 0.29\text{ }\mu\text{m}$) provided by a medical device manufacturer. It should be noted that the specific forming process and surface finishing history of the wrought reference were not reported by Bernhardt et al.; the comparison therefore refers to the final surface states rather than to identical processing routes. This demonstrates how vibratory finishing can be used to bring AM-typical, particle- and layer-induced topographies into a range commonly achieved with conventionally produced implant materials.

Besides the improvement in the surface topography of AM samples, vibratory finishing can improve fatigue behavior. The as-built surface structure consists of sharp peaks and dales. The dales can act as sharp micronotches that promote crack initiation [34]. Vibratory finishing removes this peak-dale surface structures. Simultaneously, a shift from tensile residual stresses (+106 MPa) in the as-built state towards compressive residual stresses (−383 MPa) together with a reduced surface roughness (R_a from approx. 8 μm to 0.3 μm) was detected, which also explains the improvement in fatigue behavior [34].

Furthermore, the influence of process parameters on the resulting surface integrity of AM Alloy 939 components was studied [135]. The study employed different abrasive shapes, including ceramic pellets and cubes with different sizes, to evaluate their effectiveness in reducing surface irregularities and improving surface texture. Initial roughness values ($R_a = 6.62\text{ }\mu\text{m}$) were reduced by up to 82%, achieving R_a values as low as 1.1 μm after 4 h of processing. The type of abrasive media and the addition of fluids played critical roles in determining the extent of material removal and the uniformity of the processed surfaces. However, fluids had a limited impact on improving surface texture, and dry processing yielded comparable results. The process also caused plastic deformation, leading to a 50 HV increase in microhardness in the zone near the surface, which was about 20 μm thick and attributed to plastic deformation/work hardening.

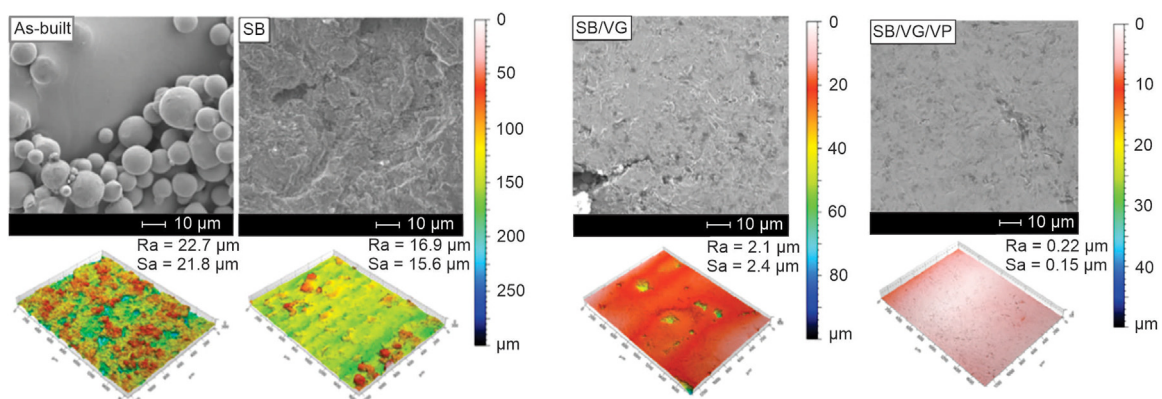


Fig. 16. Surface topography in the as-built state, after sandblasting (SB), after SB and vibratory grinding (VG), after SB, VG and vibratory polishing (VP) (adapted from [8]).

The effectiveness of vibratory finishing relies heavily on processing time, amplitude, and frequency [146]. Higher vibration intensities can lead to faster material removal, but they may also increase the risk of uneven surfaces or over-polishing. Using additional elements, such as fluids or chemical compounds, can further refine surfaces, but they must be carefully controlled to prevent adverse effects.

6. Cavitation abrasive finishing

Cavitation abrasive finishing comprises ultrasonic cavitation abrasive finishing (UCAF) and hydrodynamic cavitation abrasive finishing (HCAF).

6.1. Ultrasonic cavitation abrasive finishing

UCAF is a nonconventional method for post-processing of AM components patented by Rolls-Royce [156]. The technology employs the cavitation process, as demonstrated in a case study by Tan and Yeo [154]. The method entails immersing the metallic component in a slurry comprising abrasive grits and introducing ultrasonic waves via an ultrasonic horn, as illustrated in Fig. 17.

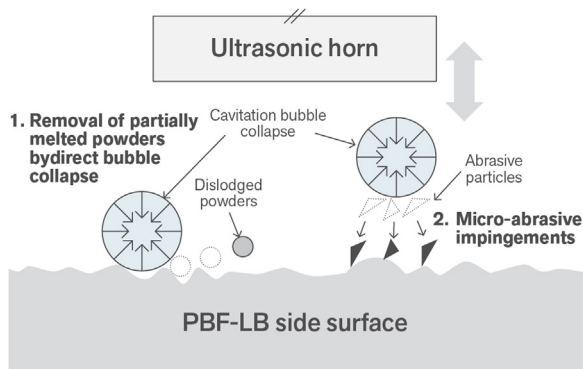


Fig. 17. Schematic illustration of an ultrasonic cavitation abrasive finishing (UCAF) process (adapted from [154]).

These waves, operating within a frequency range of 20–40 kHz, induce acoustic cavitation in the slurry. The collapse of cavitation bubbles in the vicinity of the workpiece surface gives rise to the generation of high-energy shockwaves, which in turn result in the formation of high-velocity micro-jets. These effectively remove the rough PBF layer, typically composed of partially-melted powder particles.

This process is particularly advantageous for the finishing of complex internal geometries and channels, where conventional methods are less effective. Introducing abrasives (such as 400–1200 mesh SiC) into the slurry facilitates enhanced material removal through the action of abrasive mechanisms. The cavitation-induced shockwaves accelerate the grits, which then engage in abrasive ploughing and cutting of the work material, thereby improving surface roughness. UCAF therefore utilizes both the cavitation effect and abrasive mechanisms simultaneously to improve the surface roughness.

To ensure a uniform surface finish, this method maintains fluid homogeneity through the continuous circulation of the slurry, while the controlled vibration of the component, achieved by directly mounting it onto the ultrasonic horn, further enhances the precision of the surface modification. The efficacy of the system is primarily governed by the output power density of the ultrasonic horn, which must exceed 10^5 W/m^2 to ensure sufficient cavitation effects. Experiments have demonstrated the effectiveness of UCAF, with a reduction in R_a values of up to a 45% on PBF-LB/Alloy 625 components (see Fig. 18).

Furthermore, the capability of UCAF was demonstrated for the finishing of simple internal channels (3 mm in diameter, 20 mm in length) of the same material [155]. The authors observed that the

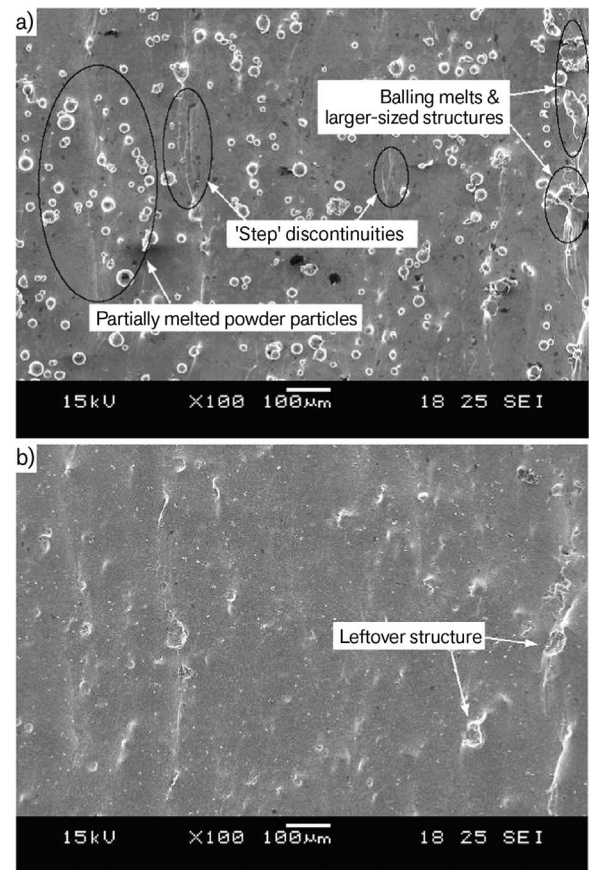


Fig. 18. SEM images of the PBF-LB surface before and after UCAF. (a) as-built surface with partially melted powder particles, balling melts, and discontinuities; (b) surface after 30 mins of UCAF with substantial removal of partially-melted powders but some larger leftover structures and surface discontinuities remaining (adapted from [154]).

R_a values of these internal surfaces exhibited an improvement of approximately 15–25%, depending on the section of the channel. However, the efficiency of cavitation-based material removal was diminished due to attenuation effects, particularly at the exit section of the channel. The efficiency was improved by adding abrasives into the process, which helped to mitigate the attenuation effects and facilitated the formation of cavitation bubbles, particularly when larger grit sizes were used. The study revealed that abrasive sizes of approximately $50 \mu\text{m}$ yielded the most uniform improvement in surface roughness across the length of the channel.

6.2. Hydrodynamic cavitation abrasive finishing

HCAF, also patented by Rolls-Royce [169], builds upon the UCAF process by introducing a closed-loop hydrodynamic system that optimizes both upstream and downstream cavitation conditions. This method facilitates enhanced surface finishing, particularly for internal channels, through the generation of cavitation bubbles via ultrasonic excitation (as illustrated in Fig. 19). This allows for

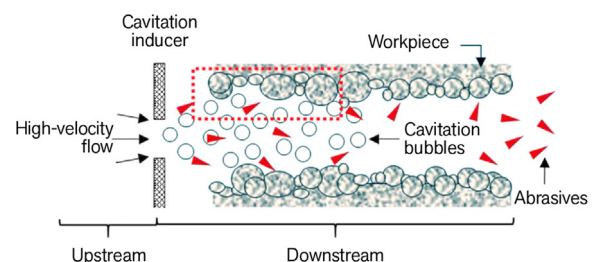


Fig. 19. Schematic illustration of a hydrodynamic cavitation abrasive finishing (HCAF) chamber (adapted from [121]).

precise control over the intensity of the cavitation through the adjustment of liquid and slurry parameters.

The material removal mechanism in HCAF can be controlled by adjusting the process parameters to separate or combine three distinct mechanisms: (i) pure-cavitation finishing, (ii) pure-abrasive finishing, and (iii) cavitation-assisted abrasion.

In pure-cavitation finishing, the erosion process is dominated by cavitation-induced effects, whereby the collapse of cavitation bubbles near the surface effectively removes smaller asperities and loosely attached particles. In pure-abrasive finishing, material removal is achieved only through the mechanical action of abrasive grits, which are particularly effective for eroding larger surface irregularities. The most effective and versatile mode is the combined HCAF, in which the implosion of cavitation bubbles accelerates abrasive grits, resulting in enhanced material removal and a finer surface finish (see Fig. 20).

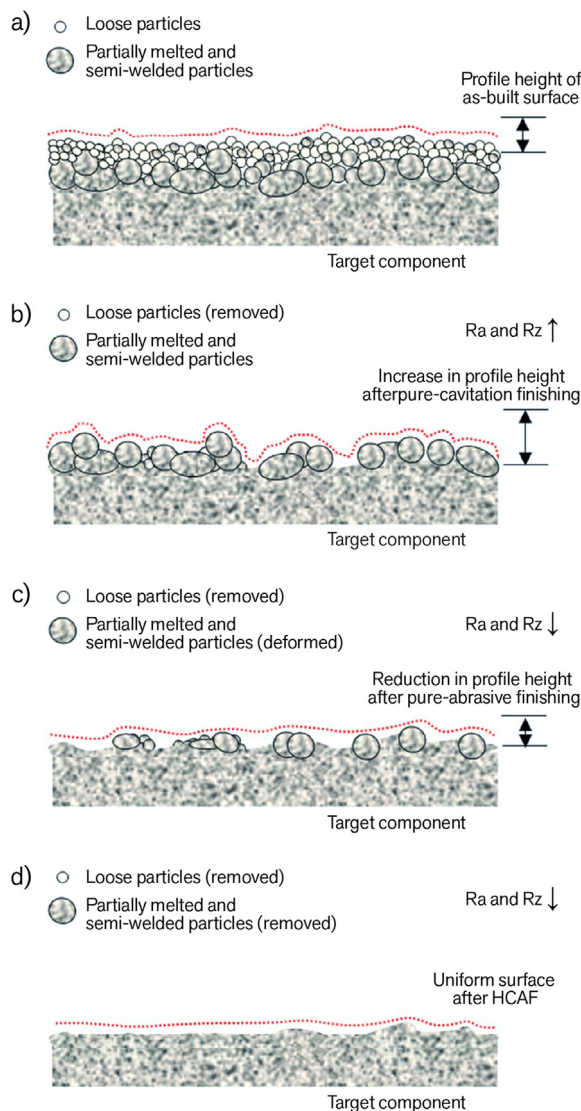


Fig. 20. Surface enhancement during the HCAF process: (a) As-built surface; (b) After pure-cavitation finishing with loose particles removed; (c) After pure-abrasive finishing with deformed and partially removed larger particles; (d) Uniform surface achieved after combined hydrodynamic cavitation abrasive finishing (HCAF) (adapted from [121]).

In the application of HCAF to post-process the internal channels of PBF-LB/AlSi10Mg components [120], the cavitation-induced material removal was found to be the dominant mechanism, with abrasive action playing a secondary role. The study reported a substantial enhancement in surface finish, with the as-built surface roughness ($S_a = 34 \mu\text{m}$) being reduced to $S_a = 10 \mu\text{m}$, representing a 70% improvement. This improvement was largely attributed to the

synergistic effects between cavitation erosion and abrasion. The research further highlighted the importance of optimizing the abrasive concentration and cavitation intensity to maximize these synergistic effects.

The capabilities of HCAF were further enhanced by integrating a multi-jet nozzle design [121]. This MJ-HCAF technology features high-pressure cavitation (up to 35 MPa) in proximity to a low-pressure slurry (e.g., 1.5 MPa). The combined effect of cavitation bubbles and abrasive particles accelerates the abrasives into intricate zones within complex internal channels, effectively finishing the surface.

The process for the finishing of PBF-LB/AlSi10Mg aluminium alloy exhibited improvements in surface roughness, with reductions in the range of 60–90% (final $S_a \leq 1 \mu\text{m}$ and $S_z \leq 20 \mu\text{m}$) achieved in 15 mins using $30 \mu\text{m}$ SiC grits. It is noteworthy that the use of a low abrasive concentration ($\leq 1 \text{ wt. } \%$) allowed for efficient surface finishing while maintaining excellent dimensional accuracy, even in channels for rocket injectors as small as 1 mm in diameter and 100 mm in length. Furthermore, the MJ-HCAF process has been utilized to post-process intricate channels in fuel injection/spray nozzles with multiple branches [122]. The authors reported a substantial peak smoothing, with a 75% improvement in the entrance zones, while observing a uniform finish across all branches of the nozzle, achieving a surface roughness of $R_a < 2 \mu\text{m}$ and $R_z < 20 \mu\text{m}$ ($\sim 80\%$ reduction). Additionally, the study highlighted an overall reduction in surface roughness ranging from 50% to 90%, depending on the specific location within the nozzle. X-ray computed tomography revealed that the surface-quality improvement was achieved while maintaining overall geometric conformity and keeping the critical nozzle dimensions within tolerance, although localized material removal/enlargement was observed in some regions.

Recent advancements by Rolls-Royce have expanded post-processing capabilities through the implementation of cavitation-based abrasive-free methods for the internal surface finishing of AM components. The objective was to enhance acoustic cavitation streaming without the use of abrasives by introducing a patented optical cavitation process using nanosecond laser pulses [116]. This method utilizes laser-induced shockwaves in a liquid medium to generate cavitation bubbles, whose implosion produces secondary shockwaves and microjets that refine internal surfaces with high precision. By facilitating non-contact material removal, this approach presents a promising alternative for the finishing of complex internal geometries, particularly in aerospace applications. However, its broader implementation is currently constrained by proprietary limitations.

7. Industrial use cases

7.1. Remanufacturing of bearings using DED-LB and abrasive fine finishing

Heavy-duty industries, such as steelmaking, paper mills, mining, and energy rely on large, high-load bearings that operate under extreme conditions—including elevated temperatures, heavy loads, contamination, and corrosive environments. In these sectors, bearing failures can lead to costly downtime and operational disruptions. As a result, repair and remanufacturing are essential operations for prolonging service life, reducing costs, and enhancing sustainability.

In conventional bearing repair, worn raceways are machined away, typically removing up to 0.025 mm in the radial direction. To maintain the original bearing clearance, the rolling elements are replaced with oversized ones that match the amount of material removed during grinding. AM offers a promising remanufacturing route by restoring the raceway surface with a cladding layer that repairs the original load-carrying surface. This process eliminates the need to alter the size of the bearing rings and rolling elements, ensuring dimensional integrity. While AM-based remanufacturing is not yet fully established in the industry, it presents a viable

solution for increasing the circularity of bearings while maintaining original design specifications.

To remanufacture bearings (e.g., spherical roller bearings), a patent application for applying stainless steel cladding to AISI 52100 bearing rings using DED-LB [2] has recently been published. For DED-LB/laser cladding, achieving low porosity is primarily a matter of material design/selection and process control, whereas PBF-LB often employs HIP to achieve full density [119], while plasma transferred arc welding relies on subsequent metal-forming techniques such as ring rolling to obtain a fully dense structure [23]. In the case of laser cladding, heat treatment (such as induction hardening) is only employed to achieve the desired hardness level (e.g., 58 HRC), rather than to address porosity concerns.

The DED-LB may utilize a tailored stainless-steel powder (e.g., particles within the 50–150 μm size range) comprising 0.15–0.30 wt% carbon and 0.6–0.9 wt% boron, thereby ensuring enhanced surface hardness and mitigating the likelihood of cracking. The initial/first deposited layer is typically thinner (~ 0.3 mm, obtained by high-speed deposition to minimize heat input), followed by thicker layers (~ 0.6 – 0.9 mm, obtained by slower scan speeds) to improve adhesion and material mixing.

While the patented method does not specifically address post-processing, the following guidelines have a general validity in the finishing of precision (e.g., tolerance class 5) bearings. The remanufactured raceways may undergo hard turning/grinding and superfinishing. Finish grinding is typically done using a shoe-centerless grinding with aluminum oxide (80–180 grit) wheels, to achieve R_a of 0.3–0.8 μm , R_z of 3–5 μm , skewness of R_{sk} -1 – 0 , and a root mean square gradient R_{dq} of 12–18°. Grinding induces compressive residual stresses, typically ranging from -400 MPa to -200 MPa. Subsequent improvement of the ground surfaces through superfinishing is often undertaken to enhance rolling contact fatigue resistance and tribological properties. Superfinishing can yield the following characteristic surface finishes: $R_a = 0.025$ – 0.1 μm , $R_z = 1$ – 2 μm , R_{sk} of -1.5 to -0.5 , and $R_{dq} = 5$ – 12° . Residual stresses can be further compressed to a level between -800 MPa and -400 MPa. Abrasive finishing must also ensure that a remanufactured bearing meets the required tolerances for circular radial runout and axial runout, per ISO 492:2023 specifications; note that the AM repair itself imposes no specific requirements on the abrasive finishing processes.

7.2. Grinding of automotive brake discs

The incorporation of brake discs in European passenger cars can be traced back to the 1950s, when they became a standard feature. Each wheel is equipped with a hub-mounted disc, with a brake unit

that is rigidly attached to the suspension system. The caliper employs two brake-pad assemblies, one on each side of the disc. Upon the application of the brake, hydraulic pressure forces the brake pads against the disc, causing wear and generating particulate matter (PM). These consist of metallic and carbonaceous particles, as well as oxides and other compounds that are released into the atmosphere, contributing to air pollution, particularly in urban areas with high traffic density. The new Euro 7 emission standard sets limits on the amount of PM emissions that can be discharged from braking systems, (e.g., PM₁₀ and PM_{2.5}, airborne PM with diameters ≤ 10 μm and ≤ 2.5 μm , respectively). This regulation obliges manufacturers to develop brake systems that comply with the new limits, which can be achieved through the development of new brake pads and discs.

EMAG, for example, has industrialized DED-LB solution—building on the extremely high-speed laser material deposition (EHSL) concept originally developed at Fraunhofer ILT in Aachen [139]—for manufacturing hard-coated brake discs. In this process, the material powder is fed into the focus of a laser beam, where it melts and metallurgically bonds to the underlying layers. The resulting multi-layer material (shown in Fig. 21) consists of a cast iron substrate, a stainless steel bonding layer (hardness of 382 HV0.1), and a top friction layer (573 HV0.1). The friction layer features a stainless-steel matrix reinforced with 30 vol% TiCN and variable amounts of Mo₂C (e.g., 5 vol%), ensuring an optimal balance between hardness and toughness, preventing excessive brittleness while providing superior wear and thermal resistance.

The AM parameters (e.g., laser power, spot diameter, powder feed rate, overlap, and gas flow rates) used to obtain such a cladding are proprietary and therefore not provided; however, typical processing parameters can be found in [163].

The as-deposited coating exhibits a high surface roughness (R_z up to 100 μm), necessitating grinding to achieve the desired roughness of max. $R_z = 5$ μm , the axial runout is less than 20 μm , flatness less than 10 μm , and disc thickness variation within 0.002 mm circumferentially and 0.012 mm radially. The grinding process is conducted using a specialized vertical, double-sided surface grinder (VLC 450 DG), shown in Fig. 22, generating a cross-hatched surface finish.

Typically, a cup grinding wheel consisting of a steel hub with metal-bonded cBN (or diamond) segments is used (e.g., Tyrolit GRAVIS). The grit size ranges from 126 to 252 μm . Grinding fluid is a synthetic solution. The multi-material composition of the brake-disc cladding, characterized by the presence of hard particles within a soft matrix, necessitates the optimization of both the wheel specification and the grinding parameters. Moreover, grinding in a low-speed and high-torque mode

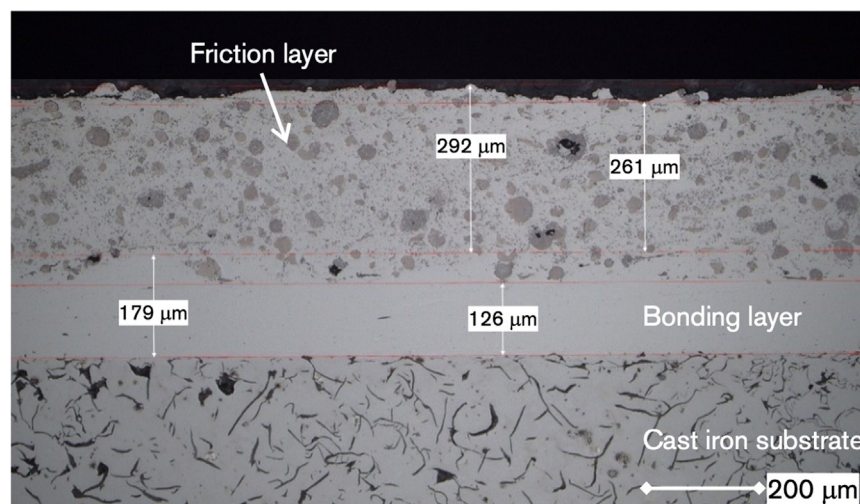


Fig. 21. SEM of a multi-layer cladding on a cast iron substrate, featuring an X8CrMn20-10 stainless steel bonding layer (126 μm) and a 261 μm friction layer reinforced with TiCN-Mo₂C [EMAG Group].



Fig. 22. Double-sided surface grinding of brake disc [EMAG Group].

requires entirely new machine capabilities and self-sharpening of the wheels. The employment of optimized grinding technology facilitates the post-processing of brake discs with surface areas ranging from 80,000–100,000 mm² and stock-removal allowances of 120–200 µm within a cycle time of 1.5–2 mins. This ensures high throughput, rendering the technology suitable for large-scale production.

7.3. Applications of AFM

AFM can be performed using either one-way flow or two-way flow. Two-way AFM is more commonly used than the one-way AFM. The principle of two-way AFM was described in Section 4.1. In contrast, the media in one-way AFM is pushed in one direction through the workpiece/tooling. This is particularly useful for components requiring a specific flow direction that is parallel to the AFM media-flow direction.

Fig. 23 shows examples of representative AM parts finished using AFM. In many cases, the entire surfaces were smoothly finished, regardless of complex geometries (e.g., stators, square tubes, impellers, blisks, etc.).



Fig. 23. Some representative AM components processed with AFM [courtesy of Extrude Hone].



(a) Tooling for impeller



(b) Finished impeller

Fig. 24. AFM for finishing of Ti6Al4V alloy AM impeller. Media displacement (Step 1: Media-1, 16,500 in³, Step 2: Media-2, 7500 in³); AFM process time (Step 1: 282 min, Step 2: 20 min). [courtesy of Extrude Hone].



Fig. 25. 316L stainless steel AM gas manifold.

Media displacement: Step 1: Media-1, 1075 in³, Step 2: Media-2, 150 in³; AFM process time: Step 1: 180 min, Step 2: 20 min. [courtesy of Extrude Hone].

As discussed in Section 4.1, both processing conditions and tooling design that optimizes the media passage are key for removing material effectively. Fig. 24 shows a case study of AFM finishing of a Ti6Al4V impeller. The initial surface roughness 10–12 µm *Ra* was reduced to 0.6 µm *Ra*.

Fig. 25 shows a case study of the internal finishing of a 316L stainless steel gas manifold. The internal passages were smoothed from 10–12 µm *Ra* to 0.4–0.6 µm *Ra*.

Fig. 26 shows a comparison of AM channel surfaces finished by AFM and by chemical polishing (CP). In AFM, the material is gradually removed from the peaks of the surface undulations when the pressurized media slides over the target surface. However, the media undergoes a pressure drop along the channel surfaces (if the target passage consists of slender and complex geometries). This raises difficulties in sliding media over the channel surface, reducing the material removal rate. Fig. 26 (c) shows such an example, and the as-printed surface remained. CP removes material along the channel surface, but leaves the relatively long wavelength-undulations unprocessed (Fig. 26 (d)). The combined processes (AFM+CP) successfully create smooth surfaces (Fig. 26 (b)); confirming the efficacy of creating smooth surfaces for finishing AM components, each with their respective advantages.

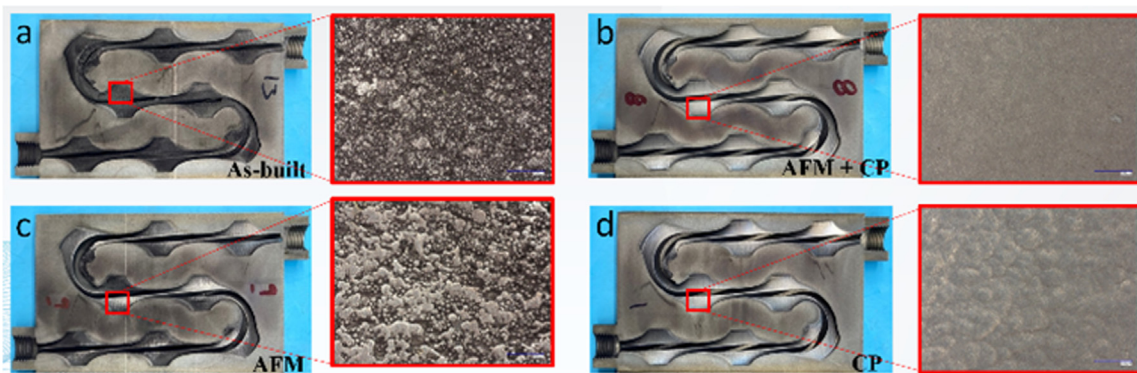


Fig. 26. AM internal passages: (a) As-built sample, (b) AFM+CP, (c) AFM, (d) CP. [courtesy of R.E.M].

Gradl et al. [47] reported the experimental evaluation of surface-enhancement methods for DED-LB-fabricated microchannels (2.54×2.54 mm) made of NASA HR-1 Fe-Ni-Cr alloy, which is used in liquid rocket engines. The methods used included AFM, chemical-mechanical polishing (CMP), chemical milling (CM), pulsed electrochemical machining (PECM), and a thermal energy method.

As shown in Fig. 27, AFM and CM generated smoother surfaces (that impact the discharge coefficient of microchannels) compared with CMP, PECM, and the thermal energy method. The discharge coefficient is the ratio between actual mass flow rate and what is predicted by theory [47]. The surface roughness values achieved by AFM and CM were comparable. The material removal by AFM was the least among the processes used. While AFM smooths the microchannel surfaces by removing material from the peaks, CM smooths the surfaces along the microchannel surface. As a result, AFM required less material removal than CM to finish the microchannel surface to a similar level without substantially increasing the cross-sectional area as with CM. These tests also demonstrate that AFM enhances the discharge coefficient of microchannels with the least material removal. Moreover, AFM will be useful for applications requiring a smooth surface with minimal material removal.

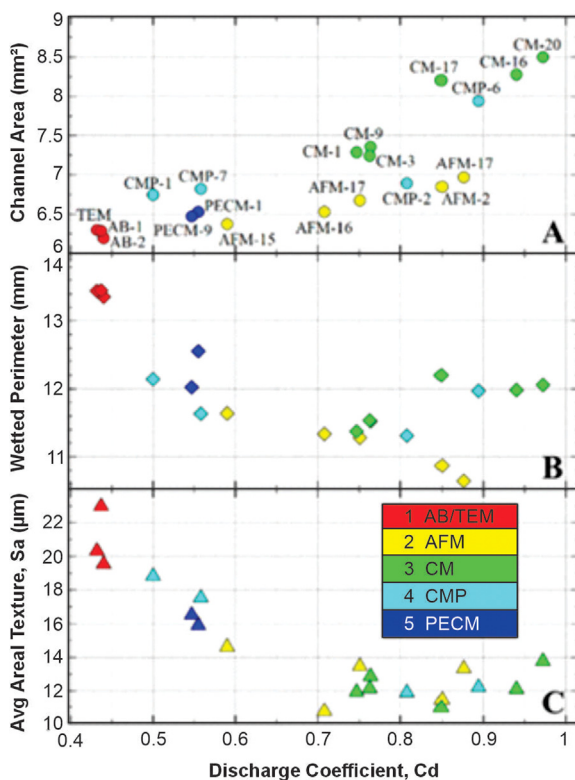


Fig. 27. Summary of Cd and comparison to: (A) measured channel cross-sectional area, (B) measured perimeter, and (C) measured average areal texture, S_a . The data is colored based on the surface enhancement process. [courtesy of Gradl at NASA Marshall Space Flight Center [47]].

7.4. Industrial mass finishing of AM parts

The mass finishing machine manufacturer OTEC uses their machines for a broad range of applications. Examples of additively manufactured components processed using OTEC machines include ear molds for hearing aids, clasp prostheses for dental applications, and turbine blades for the energy and aerospace sectors (see Fig. 28). Each of these components presents unique challenges and requirements. Their mass finishing operations focus on different goals, such as improving optics/haptics, aerodynamics, or solely smoothing surfaces.

This can be seen, for example, with additively manufactured turbine blades, which were post-processed using an OTEC drag

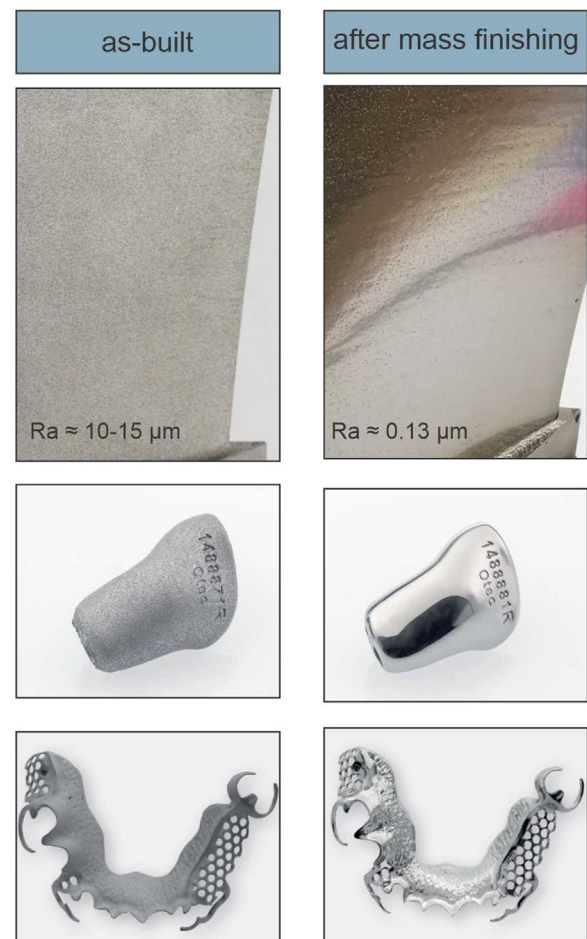


Fig. 28. Exemplary results in the as-built state and after mass finishing; turbine blades (top), ear molds (middle), and clasp prostheses (bottom). [courtesy of OTEC GmbH].

finishing machine. The chosen three-step process consisted of rough grinding for 5 h, fine grinding for 1 h, and polishing for 1 h. These terms (grinding and polishing) refer to the abrasive media used in the drag finishing process, which gradually become finer with each step. The result is shown in Fig. 28.

The original roughness of the as-built component ($R_a = 10-15 \mu\text{m}$) was reduced by a factor of 100 to achieve an R_a value of $0.13 \mu\text{m}$. The superior surface quality also contributes to increased efficiency in operation. Although the process has a very high throughput time, it is possible to machine several components at once. In addition, exemplary results in the as-built condition and after mass finishing are shown for ear molds and clasp prostheses, indicating a visible improvement in surface roughness.

Furthermore, OTEC used their disc-finishing CF-Series unit to improve the surface of metallic AM samples in a three-step process for research purposes. The differences in the downskin and upskin surfaces were studied. These surfaces are oriented differently with respect to the build direction. Upskin denotes upward facing (top) surfaces, whereas downskin denotes downward-facing (overhang or support-facing) surfaces. In the first step, ceramic media were used for 1 h of processing. In the second step, polymer grinding chips were used for 1 h, followed by a third step with porcelain media for 1 h. The R_a values of the downskin and upskin surfaces were analyzed (see Fig. 29).

Both surface types show improvement over the as-built condition across the processing steps. Due to inherent AM process characteristics (see Section 5), the downskin surface initially exhibits higher roughness than the upskin surface. Overall, the upskin surface maintains consistently better surface quality; however, the chosen processing time is insufficient to fully remove its initial unevenness. Surface quality remains inhomogeneous across the

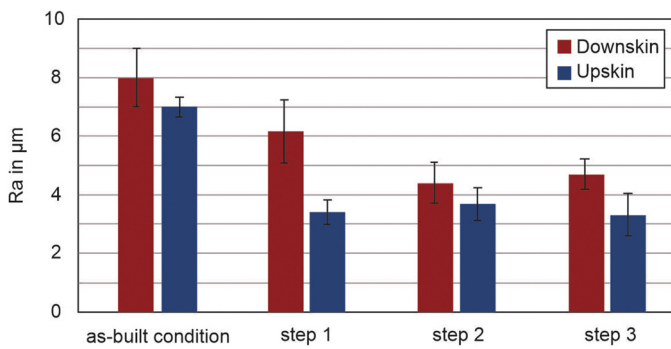


Fig. 29. Surface results (R_a values) after different processing steps for downskin (red) and upskin (blue) surfaces. [courtesy of OTEC GmbH].

component, which must be considered in applications. For the upskin surface, Step 1 already removes most of the AM-typical, loosely adhered particles and the dominant surface peaks. The remaining texture is governed by the layer-wise topography rather than removable asperities. Consequently, Steps 2 and 3 provide marginal additional roughness reduction and may be omitted when the goal is time-efficient processing without compromising the achieved surface state.

8. Open research questions/research directions

The wider industrial adoption of precision components produced by AM hinges not only on advances in process scalability and repeatability but also on the effectiveness and efficiency of post-processing operations. Among these, abrasive finishing processes are critical enablers for achieving the demanding surface quality and component precision required in aerospace, biomedical, and energy applications. Traditional subtractive methods such as machining remain prevalent, but they are increasingly insufficient, particularly for freeform and internal geometries, making abrasive post-processing a necessary complement. The distinct microstructures generated by AM, characterized by heterogeneous grain morphologies, melt-pool boundaries, residual-stress profiles, and inherent porosity, substantially influence material removal behavior. These microstructural features can lead to uneven or unpredictable abrasion. In AM steels, the role of non-metallic inclusions also remains an important open question, since oxygen level, inclusion type, inclusion morphology, and inclusion chemistry may significantly affect abrasive tool wear. Current studies are often difficult to reproduce due to insufficient disclosure of critical parameters such as media type, process conditions, or pre-treatment steps. This lack of systematic studies hampers model development and process standardization, making it difficult to generalize findings across different AM materials or geometries.

A key challenge lies in developing robust, multi-stage process chains tailored to the surface condition of as-built AM parts. Initial machining is often necessary to eliminate macroscopic waviness or support structures, followed by progressively finer abrasive steps to reduce surface roughness. Some abrasive finishing techniques are particularly advantageous for processing internal and freeform structures, where rigid tools cannot reach.

Modelling of abrasive processes remains an important enabler for optimizing processing conditions and predicting finishing responses [94]. Although that discussion did not specifically address AM materials, it highlighted that the main limitations of such models lie in the constitutive descriptions and in the identification of reliable model parameters. In this respect, the key issue for AM components is not the need for new process models, but the need to represent AM-specific workpiece states with sufficient fidelity. Established models remain applicable, provided they incorporate representative descriptions of anisotropy, defect population, near-

surface condition, and local mechanical response. Approaches from machining with geometrically defined cutting edges provide an indication of how such adaptation can be achieved. For example, physics-based flow-stress models have been adapted to AM microstructures by explicitly incorporating descriptors such as grain size, crystallographic texture, dislocation density, and precipitate size and volume fraction, derived from EBSD and thermodynamic simulations, and then used as input to FE-based simulations [110]. Comparable microstructure-sensitive models are, however, still largely unavailable for abrasive processes, where corresponding developments remain an open research need.

The time-intensive nature of many abrasive processes remains a bottleneck. Attempts to directly apply abrasive processes to rough as-built surfaces with R_a values ranging between 10–50 µm have resulted in excessive processing times, often extending into days rather than hours. Consequently, process chains combining subtractive and abrasive steps, are likely to be required for both technical and economic feasibility. It is therefore becoming increasingly clear that post-processing considerations must be embedded already in the design phase of AM components. Designing for tool accessibility and reducing surface variability are crucial, particularly in repair applications, which represent a growing and highly relevant use case. Importantly, this does not imply that abrasive finishing must be reinvented for AM; rather, established processes remain applicable when AM-induced surface states and geometrical constraints are considered in process, tool, and parameter selection.

For complex free-form surfaces where a non-conforming grinding wheel limits access, compliant tool concepts such as SAG provide a practical extension of conventional finishing by enabling conformal contact and improved reach, bridging motion-copying and pressure-copying processes. Despite its technical potential, the industrial implementation of SAG remains limited, largely due to the need to integrate process models with CAM data, and to establish robust, experimentally validated process windows. Other hybrid approaches are also emerging, such as combining electropolishing with mass finishing or integrating abrasive jet and chemical polishing methods. These processes aim to exploit the complementary strengths of multiple techniques, although they still suffer from a lack of process windows, scalability, and cost-efficiency at the industrial scale.

In addition to have complex geometries and rough surfaces, AM components are occasionally porous and have partially melted powder particles that adhere to the component surfaces. Therefore, careful cleaning (i.e., removing residual abrasive, chips, and powder from the finished surfaces) is essential to avoid contamination. Research on surface-cleaning technology after abrasive finishing is another needed research direction.

While the technical aspects of surface roughness improvement are often emphasized, the performance of a component is more strongly governed by the integrity and functionality of the surface. Fatigue performance, for instance, is closely linked to surface morphology and subsurface residual stress states. Although smoother surfaces generally correlate with improved fatigue life, this improvement is conditional on the minimization of surface and subsurface defects. AM microstructures often contain features that act as crack initiation sites, including lack-of-fusion defects, unmelted particles, and oxide inclusions. Abrasive processes must therefore be carefully selected and sequenced to target not only the visible topography but also the near-surface microstructure. Corrosion and wear resistance are similarly influenced by surface chemistry and grain structure, which can be significantly altered during post-processing.

Building on AM-specific challenges (e.g., high initial roughness, limited accessibility), a further research direction concerns the environmental and economical footprint of abrasive finishing within AM process chains. In many AM applications, these surface/geometry constraints necessitate multi-step post-processing and

long cycle times, which can make media, fluid, and energy consumption in finishing a dominant contributor to cost and environmental impact, potentially offsetting material efficiency benefits of AM. Future work should therefore couple process design with life-cycle assessment/cost modelling under AM boundary conditions, while also reducing the need for finishing through AM-aware design/build strategies that minimize surface variability and improve accessibility.

An increasingly vital enabler of future progress in this field is the integration of digital technologies, aligned with the principles of Industry 4.0 across the additive-abrasive process chain. AM build data (e.g., orientation, scan strategy) together with pre-finishing metrology should be used to generate feature- and location-specific finishing strategies (tool/media selection, toolpaths). During finishing, real-time monitoring of process signals (e.g., forces, temperature) can enable closed-loop control by continuously updating a local material-removal model and adapting process inputs to compensate for AM-typical surface variability and accessibility constraints. Coupling these data streams with data-driven models enables parameter selection that is conditioned on AM-specific surface state, thereby reducing over-processing and improving reproducibility. Digital twins could therefore link AM build, heat treatment, and finishing, allowing virtual validation of process sequences, and minimizing experimental costs.

Taken together, the path forward in abrasive post-processing of AM components lies in a deeper understanding of microstructural interactions, the development of efficient and adaptable multi-step process chains, the design of component geometries for accessibility, and the integration of sustainable practices and digital technologies. Future finishing approaches will need to shift from generalized surface quality targets to function-driven strategies, focusing on the specific surfaces and features that influence component performance most. This is especially important in repair and remanufacturing scenarios, where targeted finishing can enable performance restoration while minimizing material removal and processing time.

9. Concluding remarks

The evolution of AM from a prototyping technology to a viable route for producing precision components has brought abrasive finishing into focus as an enabler of functional performance. This keynote has presented a comprehensive analysis of abrasive post-processing methods, spanning grinding, abrasive fine-finishing, and mass finishing, in the context of their interaction with AM-specific surfaces, microstructures, and geometries. Through a synthesis of fundamental studies, and industrial demonstrations, it is evident that abrasive finishing not only removes the limitations of the as-built state but also shapes the mechanical, tribological, and dimensional properties that define component reliability in service. In terms of scope, this work primarily addressed abrasive finishing of metal AM components (with emphasis on PBF-LB, PBF-EB, and DED-LB), while selected ceramic and multi-material examples were included to illustrate broader material classes where finishing requirements are especially stringent.

A central outcome of this work is the recognition that the main challenge in abrasive finishing of AM components is not the validity of established finishing principles, but the AM-specific surface and subsurface conditions that govern their application. AM can produce surface topographies with staircase features, partially fused particles, and localized melt-pool artefacts, alongside microstructures with strong anisotropy; and defect populations, such as near-surface porosity, that are rarely present in traditional manufacturing routes. These features govern how abrasive tools interact with the surface, dictate achievable removal rates, and influence the evolution of surface integrity. Consequently, meeting functional-surface requirements for AM components requires AM-aware

selection of abrasive-finishing process, tool system, and operating conditions based on the known outcomes of the respective AM route rather than conventional manufacturing solutions. While abrasive finishing is a key enabler for functional AM components, it is not universally applicable without adaptation. In particular, AM parts may exhibit reduced local load-bearing capacity due to near-surface porosity, or lack-of-fusion defects, such that the mechanical loads introduced by abrasive contact can cause local plastic deformation, or crack initiation. In addition, processes with high frictional heating (e.g., grinding) can locally raise temperatures, alter residual-stress states, and promote thermally induced damage, thereby negating performance. Understanding these limitations is therefore essential for selecting a suitable finishing route and for defining AM-specific process windows.

Across the processes reviewed, one consistent message emerges: no single finishing method is universally optimal. The achievable balance between removal rate, surface quality, and geometric conformity depends strongly on the interplay between process kinematics, tool compliance, and accessibility to the surface features of interest. Fixed-abrasive methods such as grinding excel at rapidly reducing roughness on accessible external surfaces while imparting beneficial compressive stresses, but they are inherently limited on complex freeform geometry or in confined passages. Loose-abrasive and conformable-tool processes, including AFM and MAF, offer access to intricate geometries and internal channels, though often at lower removal rates and with greater sensitivity to media behavior and process control.

Importantly, the role of abrasive finishing in AM extends beyond achieving a target roughness value. Surface integrity encompasses multiple scales: from the statistical distribution of peaks and dales that governs friction, wear, and fluid retention, to the subsurface microstructural state that determines fatigue resistance and corrosion behavior. This keynote has highlighted examples where modifications to skewness, kurtosis, and residual stress state have had a more decisive impact on component performance than reductions in R_a or S_a alone. This finding reinforces the need for multi-parameter characterization in both research and industrial qualification.

The review has also demonstrated the importance of integrating abrasive-finishing considerations early in the AM process chain. In turn, finishing choices affect the viability of later steps, such as coating, assembly, or in-service repair. For maximum efficiency, abrasive finishing should be co-designed with AM build strategies and any intermediate machining or heat-treatment steps. This holistic approach not only improves technical performance but also reduces lead time, media/tool consumption, and overall cost.

From an industrial perspective, abrasive finishing is emerging as a critical enabler for AM adoption in aerospace, medical, and energy applications where surface-sensitive performance is paramount. Advances in adaptive tooling, in situ metrology, and closed-loop control will be decisive in this regard.

Ultimately, the integration of AM and abrasive finishing constitutes a distinct and evolving manufacturing paradigm. The interplay between AM-specific surface and microstructural features, process-dependent material removal mechanisms, and the resulting surface integrity characteristics should be treated as a dedicated field of research. Continued progress will rely on expanding the mechanistic understanding of these interactions, refining combined and adaptive processes to address complex geometries, and embedding finishing steps into digitally driven, closed-loop AM workflows. Establishing robust, standardized, and scalable abrasive finishing strategies will be essential to enable the reproducible production of AM components that meet the stringent dimensional, functional, and reliability requirements of industrial precision applications.

Nomenclature

ABS	Acrylonitrile-butadiene styrene
AFM	Abrasive flow machining
AM	Additive manufacturing
Ba	Bagnold number
BJT	Binder jetting
CFD	Computational fluid dynamics
CM	Chemical milling
CMP	Chemical-mechanical polishing
CP	Chemical polishing
CVI	Chemical vapor infiltration
DED	Directed energy deposition
DED-EB	Electron-beam based directed energy deposition
DED-LB	Laser-based directed energy deposition
DEM	Discrete element method
EP	Electropolishing
FDM	Fused deposition modelling
HCAF	Hydrodynamic cavitation abrasive finishing
HEA	High-entropy alloy
HIP	Hot isostatic pressing
LOF	Lack of fusion
LP	Laser polishing
MAF	Magnetic field-assisted finishing
MEX	Material extrusion
MJT	Material jetting
PBF	Powder bed fusion
PBF-EB	Electron-beam based powder bed fusion
PBF-LB	Laser-based powder bed fusion
PECM	Pulsed electrochemical machining
PLA	Polylactic acid
PM	Particulate matter
R_a	Arithmetic mean height
R_{ku}	Kurtosis
R_q	Root mean square height
R_{sk}	Skewness
R_z	Maximum Height
S_a	Arithmetic mean height (areal)
SAG	Shape-adaptive grinding
SB	Sandblasting
SCC	Stress corrosion cracking
SHL	Sheet lamination
Sk	Core height
Spk	Reduced peak height
Sq	Root mean square height (areal)
Svk	Reduced pit depth
UCAF	Ultrasonic cavitation abrasive finishing
VG	Vibratory grinding
VP	Vibratory polishing
VPP	Vat photopolymerization
WEDM	Wire electro-discharge machining

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Jan C. Aurich: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Peter Krajnik:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal

analysis, Data curation, Conceptualization. **Hitomi Yamaguchi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Eraldo da Silva:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Jacques Platz:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization.

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