Journal of Machine Engineering, 2025, Vol. 25, No.4, 53–74
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received*: 15 September 2025* / Accepted: *21 November 2025* / Published online: *1 December 2025*

additive manufacturing,
rapid tooling,
abrasive processes,
technological effects

Dawid ZIELINSKI[1*], Sisay Workineh AGEBO[2],
Tesfaye Mengesha MEDIBEW[2], Karolina CHODNICKA-WSZELAK[1],
Mariusz DEJA[1]

RECENT RESEARCH PROGRESS AND FUTURE PERSPECTIVES OF ADDITIVELY FABRICATED ABRASIVE TOOLS

Additive technologies are becoming increasingly important in the fabrication of innovative tools. Currently, 3D printing methods based on flexible materials in various forms are being successfully used in the production of tools dedicated for precision abrasive machining, such as lapping, polishing or honing. This paper demonstrates recent research progress of additively fabricated abrasive tools made from metal and plastics powders, light-curable resins, as well as material in the form of filaments. The currently still existing limitations and further perspectives for the development of prototype tools are also indicated. Particular attention was paid to the discussion of the development of prototype tools based on PA12 polyamide powders and ABS filament material, which were used successively in precision abrasive machining of metal materials and technical ceramics with loose abrasive. The tested tools were made using SLS selective laser sintering and FFF/FDM thermoplastic extrusion methods. The presented technological effects concerning the process efficiency and the evaluation of the geometric structure of the surface of machined workpieces confirm the great potential of flexible abrasive tools. Another modern approach in the manufacture of abrasive tools is combining resin and metal bonds with abrasive grains. This type of innovative hybrid-bonded tools can be also useful in precision abrasive processes of specific materials, such as ultra-high molecular weight polyethylene.

1. INTRODUCTION

Abrasive processes are advanced finishing techniques used to enhance the surface quality, hardness, and wear resistance of materials, often employed in precision machining and surface engineering. These processes utilize abrasive particles to remove material and refine surface texture, which is critical for enhancing the durability and functionality of manufactured products. Magnetic Abrasive Finishing (MAF) and Magnetic Abrasive

---

[1] Department of Manufacturing and Production Engineering, Faculty of Mechanical Engineering and Ship Technology, Gdansk University of Technology, Poland
[2] Doctoral School at Gdansk University of Technology, Gdansk University of Technology, Poland
[*] E-mail: dawid.zielinski@pg.edu.pl
https://doi.org/10.36897/jme/214550

Machining (MAM) are notable methods that utilize magnetic fields to control abrasive particles for surface finishing purposes. MAF has been shown to significantly improve surface quality, with studies reporting reductions in surface roughness and improvements in surface finish for materials such as brass and stainless steel (SS-304) when using composite abrasives like SiC and Al_2O_3 under wet conditions [1,2]. MAM, a related process, uses magnetic abrasive particles and magnetic forces to achieve nanometer-range surface finishing, with key parameters such as electromagnet rotational speed, voltage, magnetic flux density, abrasive particle size, and working gap influencing material removal rate and surface roughness [3]. Abrasive Flow Machining (AFM) is another advanced technique that uses a flexible abrasive medium to polish complex free-form surfaces. AFM has demonstrated the ability to significantly reduce surface roughness, making it suitable for finishing irregular geometries where conventional methods are limited by machine movement constraints [2, 4]. The mechanism of abrasive flow involves particle collisions and plowing effects on the workpiece surface, which contribute to material removal and improvement of surface morphology, particularly in micro-hole machining applications [5]. Other finishing methods, such as Chemical Mechanical Polishing (CMP) and Ultrasonic Machining (USM), also contribute to surface engineering by enhancing hardness and wear resistance, respectively, through controlled material removal and surface modification [2].

Recent research on additively fabricated abrasive tools has highlighted their growing application in abrasive machining, particularly for hard and brittle materials, such as advanced ceramics. Additive manufacturing (AM) technologies enable the production of complex tool geometries and structures, which are difficult to achieve with conventional methods. This capability supports rapid tooling and rapid manufacturing, accelerating production processes and enabling the fabrication of fully functional machine parts and tools with tailored abrasive properties [6]. Such capabilities are particularly relevant in emergency scenarios, where additive manufacturing can support the rapid replacement of structural elements through customized geometries and tailored material properties [7].

Experimental studies have demonstrated the potential of polymer-based abrasive tools produced by fused filament fabrication (FFF) and selective laser sintering (SLS). For instance, acrylonitrile–butadiene–styrene (ABS) wheels reinforced with diamond grains have been tested in precision surface grinding, showing promising results in terms of material removal efficiency, surface finish, and tool wear resistance. Tools with serrated working surfaces exhibited improved performance compared to continuous surfaces, indicating the importance of tool surface design in additive abrasive tools [8]. Similarly, SLS-fabricated lapping plates from polyamide powders combined with diamond abrasives have been used for eco-friendly free abrasive machining, achieving effective material removal and surface finish improvement with minimal abrasive dosing [9]. Polymer-based abrasive tools and media are utilized in various advanced machining and finishing processes, particularly for materials that are difficult to machine or require precise surface quality improvements. One application involves abrasive flow finishing (AFF), where a polymer-based flexible medium embedded with abrasive particles serves as the finishing tool. The properties of this polymer medium, combined with process parameters, critically influence the final surface roughness of the workpiece. For example, a viscoelastic polymer abrasive medium was developed and studied for finishing micro-slots in surgical steel, resulting in a significant reduction in surface roughness from 3.54 μm to 0.21 μm, which demonstrates the medium's effectiveness in micro-feature finishing [10]. In the context of additive manufacturing, polymer-based abrasive media have been employed to improve the surface finish of parts produced by atomic diffusion additive manufacturing (ADAM). Here, a natural polymer-based abrasive medium was used in AFF to reduce the surface roughness of pure copper parts. The study investigated the impact of extrusion pressure, finishing cycles, abrasive particle concentration, and size on surface roughness reduction, with the number of finishing cycles being the most significant parameter. The abrasive medium consisted of abrasive particles dispersed in a polymer matrix, allowing for a controlled finishing action through reciprocating flow [11]. Regarding polymer composite materials, abrasive processing involves preparation steps where surface roughness is critical for subsequent operations such as gluing. The abrasive tools and processing modes are selected to achieve the necessary surface roughness for reliable adhesive bonding. The abrasive tools used in these processes are designed considering the characteristics of the polymer composite, and the abrasive processing is often hydroabrasive cutting, which involves polymer-based composites as the workpiece rather than the tool itself. The design methods for abrasive processing of polymer composite parts consider the surface quality requirements and tool selection [12]. No direct information on polymer-based abrasive tools, such as grinding wheels or impregnated abrasive tools, was found in the context, except for a study on grinding wheels impregnated with synthetic organosilicon polymers to improve the grinding of INCONEL® alloy, which is not polymer-based abrasive tools per se but rather polymer impregnation of abrasive tools [13].

Material development is another area of progress, with research focusing on photopolymer-abrasive composites containing silicon carbide abrasive fractions. These composites have been characterized for viscosity and structural properties, providing insights into their applicability for 3D printing of abrasive tools. Such developments suggest potential for customizing abrasive tool properties through composite formulation [14]. Despite these advances, limitations remain, including the need to optimize abrasive grain distribution, tool wear behavior, and the balance between tool hardness and flexibility. Future directions point toward further refinement of composite materials, hybrid manufacturing techniques that combine additive and subtractive processes, and sustainability considerations, such as reducing the carbon footprint through green manufacturing approaches [15]. Another trend involves the evolution of grinding and abrasive tools through various AM processes, which have been explored historically and continue to advance. Current research highlights the technological frontiers of different AM methods, identifying both existing capabilities and gaps that suggest directions for future development. This includes optimizing the material composition and structural design of grinding tools to enhance performance and durability [16]. In addition to tool fabrication, abrasive machining and finishing of additively manufactured metal parts represent a significant area of progress. Conventional abrasive methods such as grinding, polishing, and honing are adapted to address the unique surface characteristics and microstructural features of AM parts. Nonconventional techniques, such as abrasive flow machining (AFM), electrochemical machining, and magnetic abrasive finishing, are also gaining attention for their ability to handle the complex internal geometries and challenging material combinations typical of AM components. These approaches contribute to improving surface quality and mechanical properties, which are critical for the practical application of AM parts [17]. Specifically, AFM has been studied for its effectiveness in precise surface control, with research showing that initial surface textures and abrasive media characteristics significantly influence material removal efficiency and surface finish. This indicates a trend toward more detailed understanding and control of abrasive flow processes to optimize finishing outcomes for complex parts [18].

Additively fabricated abrasive tools hold significance in the industry due to their ability to meet the high requirements imposed by competitive manufacturing environments, particularly in machining hard and brittle materials, such as advanced ceramics. The use of additive manufacturing (AM) enables the production of abrasive tools with complex geometries and innovative constructions that are difficult to achieve with traditional methods, which can positively impact machining results and tool performance [6]. One significant advantage is the rapid production capability. Additive manufacturing enables the creation of abrasive tools without the need for mold opening, providing immediate availability and reducing lead times from months to potentially hours or days. This flexibility supports both small-scale and individual production, reducing costs and inventory requirements, and making it accessible to factories of all sizes as well as individual users [19]. The technology also facilitates the fabrication of tools with tailored working surfaces, such as those reinforced with diamond grains, which can improve material removal efficiency and surface finish quality in precision grinding operations. Experimental results have demonstrated that additively manufactured abrasive tools, including those produced by fused filament fabrication (FFF) and reinforced with abrasive particles, can exhibit low wear rates and perform effectively in industrial applications [8]. Furthermore, additive manufacturing supports rapid tooling and rapid manufacturing processes, accelerating the overall production cycle by integrating software automation and tool involvement. This integration can enhance the manufacturing process by enabling the production of fully functional machine parts and tools directly from digital models [6]. Moreover, post-processing techniques, which are crucial for enhancing the surface finish and functional performance of AM parts, also present challenges when applied to abrasive tools. While various finishing methods exist, including mechanical abrasion and chemical or laser finishing, their effectiveness varies depending on the complexity of the tool geometry and material type. The inability of some post-processing methods to adequately finish intricate internal surfaces or complex freeform cavities limits the practical application of additively manufactured abrasive tools. Hybrid post-processing approaches may offer solutions but require further exploration to overcome individual process limitations [20, 21].

The integration of AM with abrasive tool production aligns with trends in green manufacturing and hybrid manufacturing processes, which aim to reduce the carbon footprint of machining operations. These hybrid processes, including ultrasonic-assisted machining and textured cutting inserts, are discussed as part of broader efforts to adopt sustainable manufacturing practices by minimizing resource use and enhancing tool life. The ability of AM to rapidly produce tools tailored to specific applications also supports resource efficiency by reducing the need for excess material and enabling rapid tooling, which shortens production cycles and lowers energy consumption [22]. Post-processing techniques for additively manufactured parts, including the use of abrasive tools, also contribute to sustainability by enhancing the properties and lifespan of the parts, thereby reducing the frequency of replacement and associated material waste. Mechanical, chemical, electrochemical, and thermal post-processing methods can improve surface quality and durability, which are critical for sustainable tool use [23]. Furthermore, metal additive manufacturing combined with surface treatment technologies offers potential for remanufacturing, which supports circular economy principles by restoring worn parts instead of discarding them. This approach can reduce waste and resource consumption, although challenges remain in scaling these processes cost-effectively and optimizing materials and parameters for specific applications [24].

The objective of this article is to provide a comprehensive review of recent progress in the development of additively manufactured abrasive tools, to highlight unresolved challenges and knowledge gaps, and to define future research directions with particular emphasis on sustainable applications and the capability of AM to support the emergency replacement of structural elements.

2. CHARACTERISTICS OF ABRASIVE TOOLS BASED ON AM TECHNOLOGIES

A review of current research works indicates the growing importance of additive technologies in the fabrication of abrasive tools. Currently, it is possible to build tools with strictly defined external and internal geometries from different types of materials. The main groups of materials used include powders of metals and their alloys and plastics, liquid resins, as well as materials in the form of filaments. Additively fabricated tools find application in various abrasive technologies, such as grinding, lapping, polishing or honing. The following section will discuss in detail the main groups of tools based on additive technologies and include laser powder bed fusion, liquid resins as well as extrusion-based methods.

2.1. POWDER BED FUSION METHODS

2.1.1. METAL-BONDED TOOLS

The production of metal-bonded abrasive tools involves embedding hard abrasive materials, such as diamond or CBN, into metallic materials, including bronze, nickel, steel, and aluminium alloys, as shown in Figure 1. The metallic matrix in these tools maintains abrasive grain retention through mechanical bonding and chemical attachment. The tools demonstrate outstanding wear resistance and high strength, which enables them to handle demanding grinding operations on ceramic materials, glass, and hardened steel. However, the conventional manufacturing processes for metallic-bonded abrasive tools through brazing and hot pressing and sintering create dense materials with no porosity. The production methods fail to create the necessary open pores which limit coolant delivery and swarf removal efficiency in machining operations, according to Kishore et al. [25] and Pratap et al. [26]. The technology of additive manufacturing serves as a vital solution to overcome these production challenges. The laser powder bed fusion (LPBF) process enables designers to create complex structures with controlled porosity and customized abrasive arrangements which solve the problems of traditional manufacturing methods [27]. The process starts with specific requirements for feedstock preparation. A uniform mixture of spherical metal powders (Cu, Ni-Cr, AlSi10Mg, tool steels) with irregular abrasive grains is essential to stop segregation from occurring during recoating.

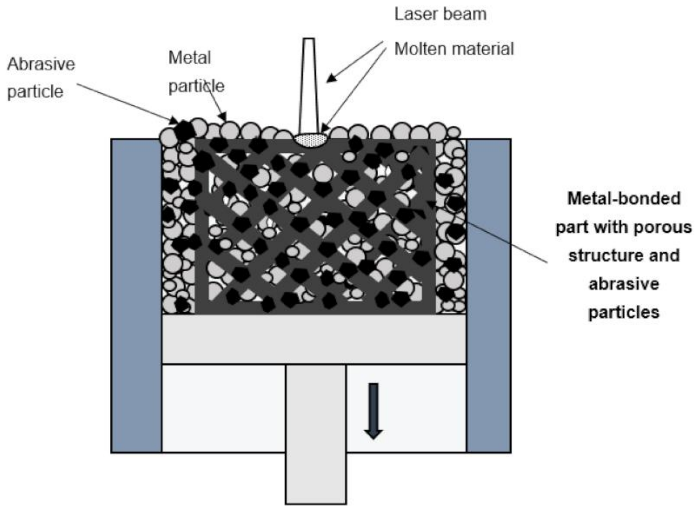

Fig. 1. Schematic illustration of the SLM process used to produce porous metal-bonded grinding tools incorporating abrasive particles [6]

The initial research in this domain proved that the concept was workable. The researchers at Maekawa et al. [28] created a polishing tool with austenitic stainless-steel mirror finish capabilities through green-tape laser sintering (GTLS) of copper-based tape containing cubic boron nitride (CBN) abrasives. Yang et al. [29] created a laser-based system to produce a diamond cup wheel with fine abrasive grains. In their study, they initially sprayed a mixture of Ni-Cr alloy powder and diamond grains uniformly onto the ASAI 1045-steel substrate using feeding devices. Afterward, the CO2-CNC laser machine was used to sinter and melt the Ni-Cr powder with the metal binder as material was deposited in the course-prescribed manner as shown in Fig. 2a. The diamond grinding grains were later sintered onto the alloy with the binder, both done with particular accuracy commanded by the computer program. To achieve a grinding wheel with diamond grains distributed in a regular pattern, any surplus grains were eliminated through the utilization of airflow (Fig. 2b). This process ensured the production of a grinding wheel with a consistent distribution of diamond grains, as illustrated in Fig. 2c. A key innovation was the use of airflow to remove excess grains, ensuring a highly uniform distribution. While these studies validated the core AM approach, they relied on specialized, non-standard equipment, highlighting an initial barrier to widespread adoption. A significant advancement was the introduction of architectured porous structures, moving beyond simple stochastic porosity. For instance, the research team of Tian et al. [30–32] developed triply periodic minimal surfaces (TPMS) through Selective Laser Melting (SLM) of AlSi10Mg alloy with diamond abrasives. This design strategy created complex, interconnected channels and pores, allowing for precise control over coolant flow and grinding performance. Crucially, the LPBF process with an AlSi10Mg matrix provides exceptional chemical bonding and grain retention for diamond abrasives. Research has indicated that this strong retention, which allows for the effective machining of challenging materials like quench-hardened Cr4W2MoV cold die steel [33], results from the formation of a stable aluminium carbide (Al_4C_3) layer at the diamond-bond interface during the high-temperature manufacturing process [34]. This secure chemical bond is a fundamental advantage over purely mechanical retention methods. The architecture grinding wheels made from LPBF technology showed more than 80% abrasive retention during grinding tests on BK7 glass while Wang et al. [35] demonstrated that these wheels reduced specific grinding energy by 78.1% when compared to electroplated wheels. The LPBF-manufactured tools demonstrate consistent performance on optical glasses according to Han et al. [36], who measured a standard composite mixture surface roughness of Ra = 0.76 μm on BK7 glass. The octahedron lattice structure developed by Tian et al. [37] enabled precise control of porosity and created surface discontinuities for intermittent grinding which resulted in better grinding forces and lower specific energy and maintained surface quality. The study on crystal-structured compliant tools demonstrated material efficiency through their ability to increase specific surface area by 295–409% while using only 29–36% of the material and introducing beneficial microscopic compliance anisotropy. Furthermore, the structural design capabilities of AM technology allow users to create new material combinations. Material compatibility stands as the most important factor because LPBF parameters need precise adjustment to achieve complete metal matrix density while protecting abrasive materials from thermal damage since diamond becomes graphitic and CBN undergoes an unwanted phase transition, according to Petrusha, I. A. [38]. Denkena et al. [39] used Laser Powder Bed Fusion (LPBF) to create NiTi-diamond composite tools with specifically designed cavities. Their work showed that pre-alloyed NiTi powder works better than elemental blends yet diamond abrasives require different LPBF parameters which may cause overheating and crack attraction problems that do not occur when processing the metal by itself.

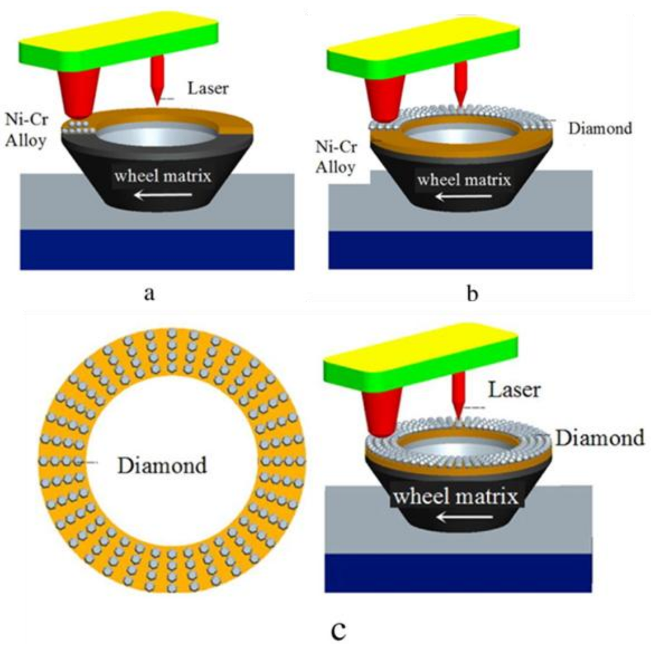

Fig. 2. 3D printing process of diamond grinding wheel with regularly distributed grains [5]. a) Ni based binder 3D printer; b) Uniform spray of diamond grains; c) Regular distribution of grains

2.1.2. POLYAMIDE-BONDED TOOLS

Polyamide is a widely used thermoplastic known for its chemical stability, mechanical performance, and great electrical and thermal resistance. Based on their monomer, polyamides occur in a variety of forms including PA6, PA66, PA11, PA12, and PA46. Polyamides, as major engineering polymers, are widely utilized in the oil and gas industry, automobile industry, marine, electronics, medical devices, household appliances, and others [40, 41]. Polyamide material has recently become increasingly important in a variety of applications, including the manufacture of advanced abrasive tools. The most often used technology for fabricating these tools was SLS additive manufacturing, which involves sintering the polyamide material, which comes in powder form. Fig. 3 depicts the fabrication of lapping tools using the SLS 3D printing process, which involves designing the tool, converting it into STL file and generating G-codes, transferring to the machine, preparing orientation and parameters, 3D printing, and post-processing with sandblasting. This tool can be used directly by assembling it into the machine setup and machining occurs via a three-body abrasion mechanism, which removes material from the workpiece through the interaction of the polyamide tool, abrasive grains, and the workpiece [42]. However, these tools are highly recommended for use in a variety of abrasive operations under light load settings [6].

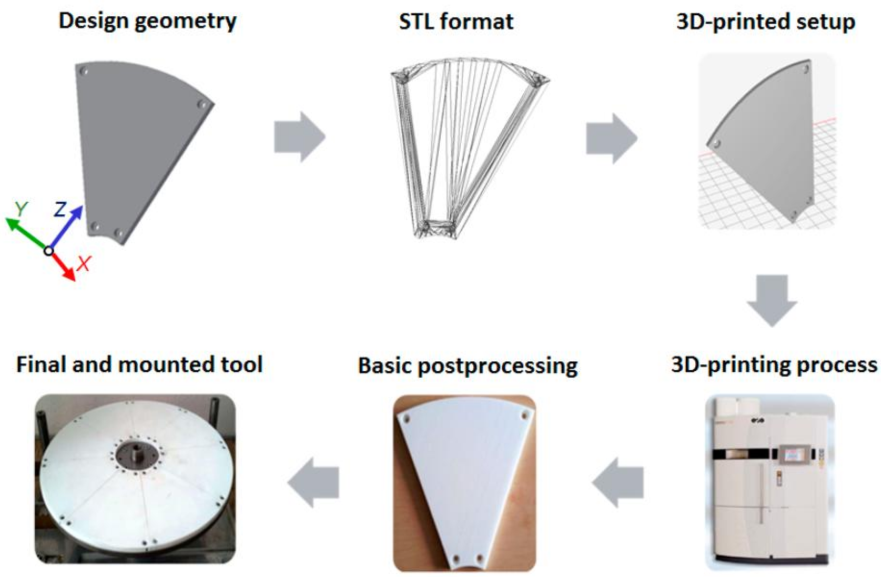

Fig. 3. Fabrication of polyamide-based lapping tool using selective laser sintering 3D printing process [42]

Du et al. [43] fabricated resin bond diamond grinding wheels with internal cooling holes using PA2200 polyamide material, glass bubbles, white corundum, and diamond abrasive materials (Fig. 4a). The tool was improved surface roughness of the glass and cemented tungsten carbide samples up to 2–4 μm. Furthermore, as reported, increasing the number of internal cooling holes reduced the grinding forces on the samples. Henkel et al. [44] used the filament-based material extrusion (MEX) technique to fabricate diamond-based ultra-fine grinding tools out of a composite material made of polyamide 12 (PA 12), zirconium oxide particles, and diamond grains (Fig. 4b). The tool was shown to improve the surface roughness of fused silica planer samples (Rq range from 10 to 14 nm). As shown in Fig. 4c, a pilot research was carried out utilizing an SLS-fabricated tool made of polyamide PA2200 while free abrasive machining Al_2O_3 ceramics.

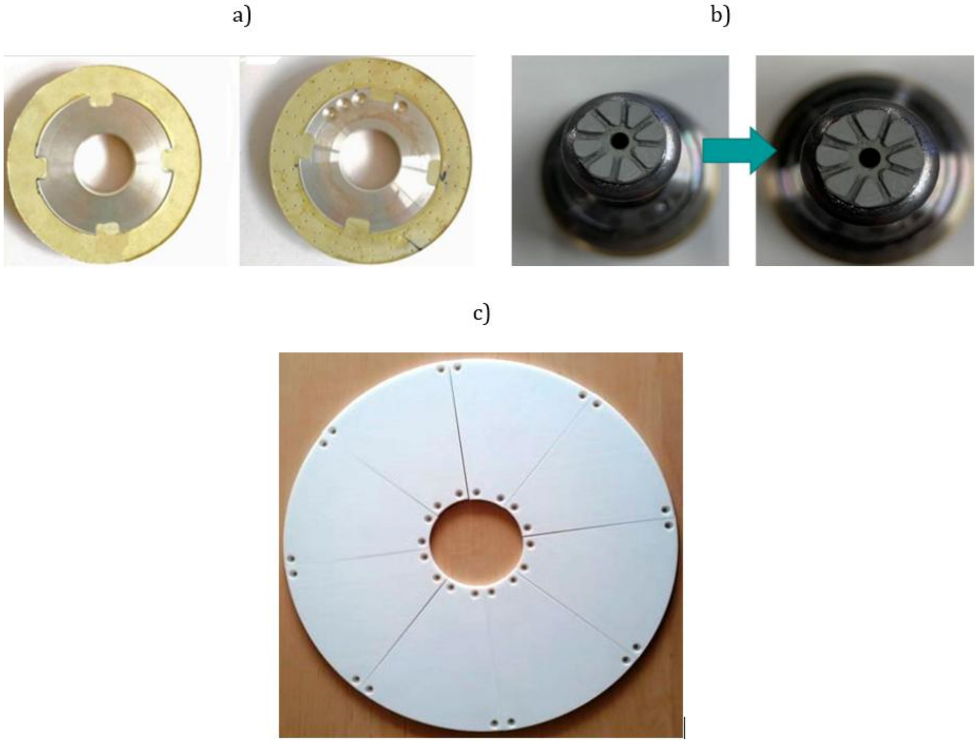

Fig. 4. Polyamide based abrasive tools: a) resin bonded diamond-grinding wheel without cooling and cooling holes [43], b) material extrusion based grinding tool before and after ultra-fine grinding [44], c) segmented single-sided lapping wheel [42]

The lapping tool was built from eight distinct segments and found improving the surface quality and material removal of Al_2O_3 ceramic samples, resulting in a much lowered wear rate [42]. The wear characteristics of a polyamide lapping tool fabricated from PA2200 by selective laser sintering were investigated experimentally following long-last machining of Al_2O_3 ceramic samples utilizing contact and non-contact based equipment's. The tool's straightness error was examined using least squares (LSQ) and the control line rotation scheme (CLRS), revealing the highest, middle, lowest, and non-contact zones on the tool's active surface. The experimental results verified the modelling, demonstrating that the most wear occurs toward the inner tool radius. After 840 minutes of machining a difficult-to-machine material, a lapping tool was demonstrated to have improved technical impacts such as material removal and surface roughness, as well as considerably lower wear [45]. In study [46], the potential of two distinct optical devices, such as a 3D laser scanner and an optical profilometer, was assessed while analysing the wear characteristics of polyamide PA2200 lapping tools using novel measurement approaches. The wear evaluation procedures and instruments were proven to be useful in assessing the straightness error of an additively fabricated lapping tools. In another research [47], the effect of process parameters on the wear characteristics of lapping tools was investigated using a PS/DK 23 experimental design while taking into account unit pressure p, velocity v, and machining time t at two different levels: higher (+) and lower (–). Higher parametric settings were observed to increase the material removal and enhance surface roughness of ceramic samples, but also resulted in more tool wear when compared to lower parametric values. In addition, a mathematical model was proposed to accurately predict the values of technological effects such as material removal and surface roughness within the defined range of machining parameter settings. Furthermore, the influence of three-body abrasion kinematics on the wear characteristics of a polyamide lapping tool was assessed using a series of experiments that included both co- and counter-rotational kinematics. As reported, the counter-rotational kinematics arrangement resulted in higher material removal from ceramic Al2O3 samples while increasing wear rate along the radial axis of the lapping segments. In contrast, the co-rotational kinematics configuration was shown to significantly enhance the roughness and surface height distribution of ceramic samples [48]. In overall, the present studies on fabricating abrasive tools based on polyamide material is deemed progressive, and it will give insights for future research efforts in the development of abrasive tools using additive manufacturing.

2.2. RESIN-BONDED TOOLS

Resin is a liquid photopolymer material that comes in a range of varieties, such as tough, standard, and flexible, depending on its intended application. This material is light sensitive, thus when exposed to UV light, it hardens, allowing for the creation of detailed objects. As illustrated in Fig. 5, the resin material was employed to create a lapping tool using the spin-coating procedure. The procedure entails mixing the abrasive grains with the resin material according to the necessary mixing ratio, applying the combination to the cast iron plate using a spin-coating process, and curing by exposing the applied mixture to UV light [6]. The fabrication of resin-bonded abrasive tools through additive manufacturing depends on vat photopolymerization techniques, which include Digital Light Processing (DLP) and stereolithography (SLA) for curing a photopolymer resin mixture with abrasive grains and functional fillers [49, 50]. This method surpasses the geometric limitations of conventional hot-pressing, enabling the fabrication of tools with complex internal architectures, such as integrated cooling channels, which are critical for performance but impossible to achieve with traditional methods [51]. The primary challenge in this manufacturing process is developing printable feedstock with high abrasive levels without compromising either the resin structure or material consistency.

The research field has tackled this problem through new material science developments. The research by Meng et al. [52] shows that UV-curable diamond-resin composites for DLP printing require precise control of diamond concentration levels and curing duration to achieve optimal material properties, including mechanical strength and cutting performance. Barmouz et al. [53] showed that the combination of resins with different viscosities prevents sedimentation problems while enabling the production of tools with high abrasive content (31.25 vol%).

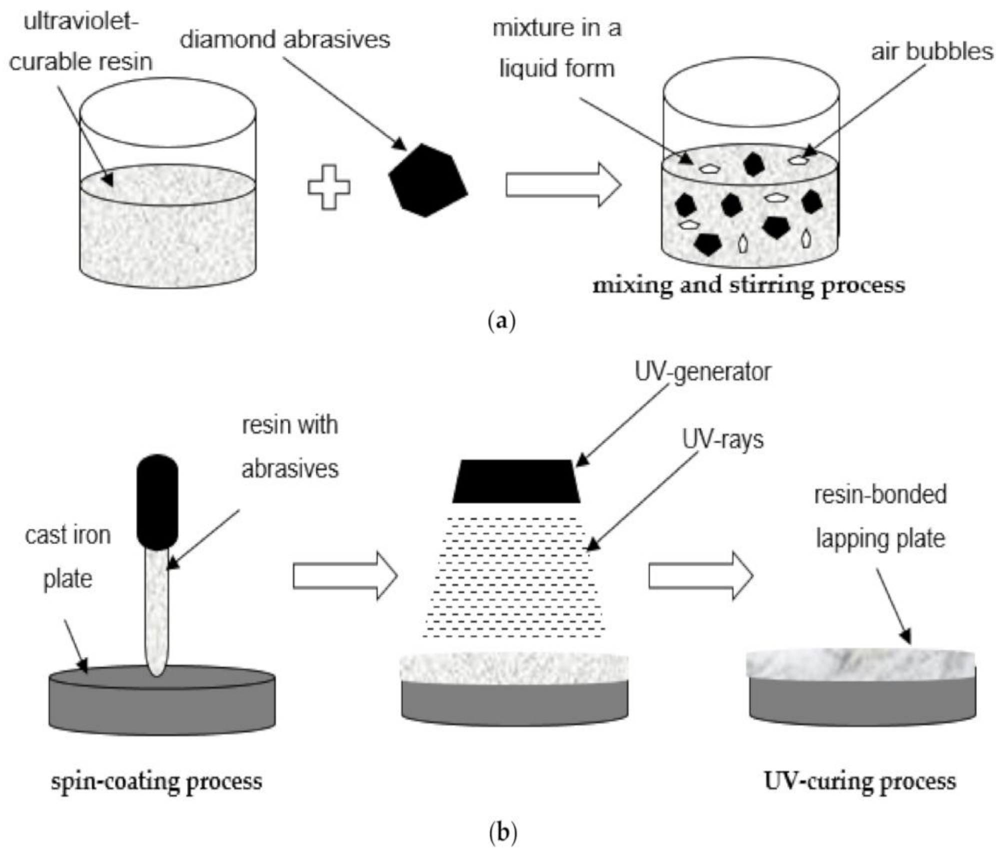

Fig. 5. Fabrication of resin-based lapping tool: (**a**) mixing the resin with abrasives grains, (**b**) spin-coating and UV curing process [6]

The optimized bond formulation resulted in improved surface quality, a substantial 33–50% decrease in grinding forces, and a 2–3 times longer tool lifespan which proves how resin rheology directly affects tool performance. The fundamental characteristics of the base resin determine its suitability for grinding operations since acrylate-based systems provide exceptional strength and thermal resistance and hardness properties [50]. The process of adding reinforcement phases to the resin matrix represents a standard approach for enhancing mechanical characteristics. Qiu et al. [54] performed an extensive study on additive particles and determined that Al_2O_3, SiO_2, and SiC particles decrease shear strength but a 15 wt.% Al_2O_3 addition led to tensile strength increasing from 15.17 MPa to 25 MPa and substantially better diamond retention force. The addition of Al_2O_3 to the wheel resulted in enhanced grinding performance since it extended the tool service life to 115 minutes while improving both material removal rates and surface quality. Habel et al. [55] added various additives to phenol resin and found that glass fibres brought the most significant advantages which resulted in a 50% increase in mechanical strength and a 75% improvement in wear resistance along with an 11% better dimensional accuracy. The authors have extensively tested the grinding performance of these tools produced through AM technology. The grinding tests performed by Ai et al. [51] proved that SiC wheels made through DLP technology with built-in coolant channels dramatically reduced tool deterioration and prevented loading while processing hardened steel by using 50 wt.% abrasives that resulted in a 50% better surface quality and thirty times less wear. The internal feature design of these tools received further development from Barmouz et al. [49] who implemented Venturi-shaped hydrodynamic cooling channels. The researchers showed that the new design achieved its best results by combining surface slots (VCP+S) with hydrodynamic coolant flow acceleration, which required no external pressure increase. The experimental results showed that the tool design achieved the most notable performance benefits through a 15% reduction in grinding forces, a 13-fold decrease in radial wear, and a 12× higher G-ratio than solid wheels. Barmouz and Azarhoushang [56] developed the first method to manufacture DLP hybrid resin-bronze bonds by increasing metal and abrasive components which enhanced tool life by 28% and improved profile accuracy by 44% and surface finish quality. The implementation of designed helical grooves reduced cutting forces by 60% which proves that AM technology enables the creation of multi-material functionally graded grinding tools that exceed traditional manufacturing capabilities.

2.3. EXTRUSION-BASED TOOLS

Extrusion-based abrasive tools are polymer-bonded, characterised by a composite matrix such as ABS, PA12, TPU reinforced with abrasive particles like diamond or zirconia to form flexible, low-cost grinding or polishing tools. They offer inherent elasticity, good damping, and easy customisation but exhibit lower thermal stability and wear resistance than metal- or resin-bonded counterparts. As shown in Fig 6, the production process involves a simple, direct, and affordable fabrication of these composite tools from abrasive-filled filaments.

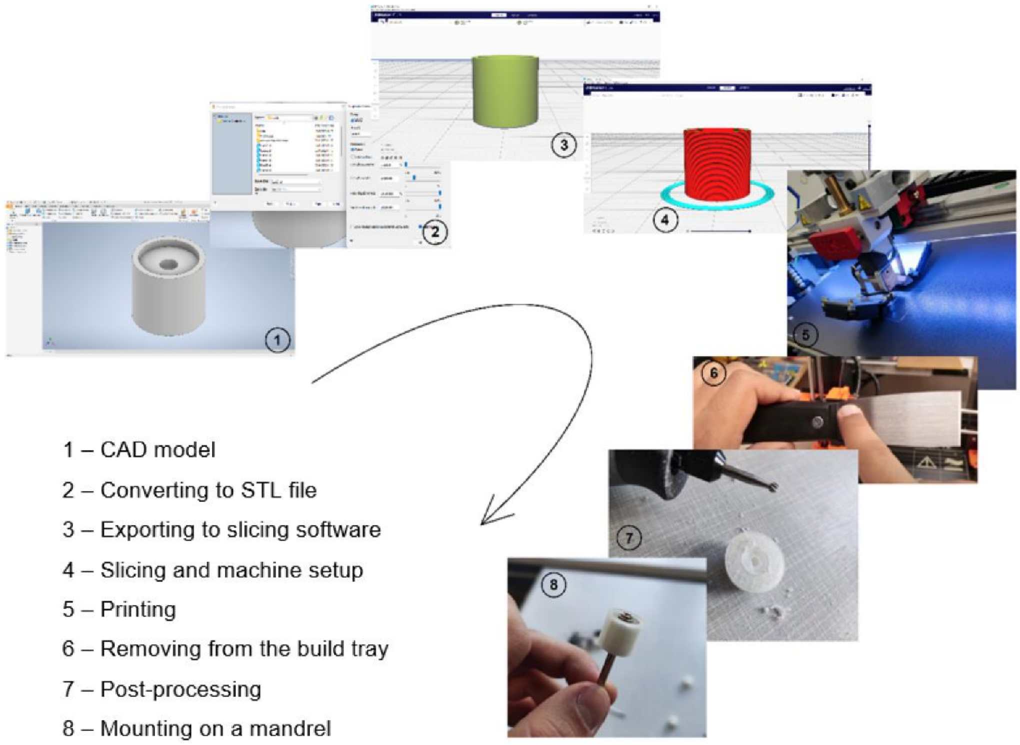

Fig. 6. The fabrication process of abrasive tools using material extrusion-based additive manufacturing [8]

Material extrusion-based additive manufacturing (MEAM) tools have become a choice of current investigation to be used as a new tool manufacturing method. Material Extrusion (MEX) through Fused Filament Fabrication (FFF) provides an easy approach to creating abrasive tools for manufacturing. The MEX process builds tools from scratch through sequential thermoplastic material layer deposition using a heated nozzle [6]. MEX provides users with simple operation, fast production, affordable costs, and flexible tool design capabilities, which make it suitable for rapid prototyping and custom tool creation [57]. Typically, it employs composite filaments where a thermoplastic polymer—such as Acrylonitrile Butadiene Styrene (ABS), Thermoplastic Polyurethane (TPU), or Polyamide (Nylon, PA)—is reinforced with abrasive grains (like diamond or ZrO_2) and other functional fillers to produce a versatile, printable feedstock [58–60]. The application of MEX extends beyond the direct fabrication of end-use abrasive tools to the production of rapid tooling for manufacturing processes like injection moulding and sheet metal forming.

Strano et al. [61] demonstrated this versatility, using MEX to produce polymeric rapid tools. The printing of tooling inserts for bending and injection molding applications uses high-performance polymers such as PEI (ULTEM) and PLA which maintain their functionality through multiple production runs [61]. The main difficulty when using MEX for precision tooling involves dealing with the natural geometric variations that occur during the manufacturing process. Polini & Corrado [62] solved this problem through their virtual Design for Additive Manufacturing (DfAM) tool which combines simulation software to forecast MEX-printed part errors including flatness and cylindricity of features. The researchers validated their model for ABS parts with lattice structures through experimental measurements which showed prediction accuracy between 1.3% and 3% [62]. The model serves as a vital tool for testing MEX-fabricated components before production and determining their manufacturing tolerances. Research has demonstrated that both commercially available and specially formulated filaments are effective. For instance, standard ABS filament-based affordable printers have successfully created prototype grinding tools, which an investigation showed that the shape of the printed tool directly influences material removal rates and the surface quality of steel workpieces [8]. The tools become more effective when designers apply proper material design techniques. A key approach is to optimize filament composition, for example, reinforcing ABS with zirconium oxide (ZrO_2) particles, which improves the tool's performance. Optimization, including balancing filler loading and processing parameters, resulted in tools with a 32% increase in wear resistance compared to pure ABS, highlighting how fillers can boost the matrix's durability [58]. The potential of MEX for high-precision applications is especially notable, and thus, a major development involved creating a custom diamond-impregnated polyamide 12 (PA12) filament, further reinforced with ZrO_2. The tools produced from this composite material served for ultra-fine grinding operations on fused silica, which represents a hard, brittle material used in optical components. The MEX-fabricated tools produced outstanding results because they reached surface roughness (*Rq*) values between 10.5–13.5 nm which represented a 97–98% improvement from the original state [59, 61]. The MEX tools demonstrated performance levels that were equal to or superior than those of standard resin-bonded tools thus showing MEX can produce tools for both precise finishing tasks and heavy-duty prototyping applications. However, the advantages of design freedom offered by AM do not automatically guarantee superior performance in all applications. A numerical study by Lieber et al. [63] into using metal AM for plastic extrusion dies serves as a critical counterpoint. The researchers used CFD to analyse a U-channel profile and found that the AM-optimized streamlined die design performed similarly to the traditional subtractively manufactured design, which indicates that AM benefits need individual assessment through advanced simulation tools [63]. However, the MEX process for abrasive tools does face challenges. The moisture content of filament material causes dimensional inaccuracies because it produces outgassing and voids when printing. Additionally, the thermoplastic matrix has inherent limitations in thermal resistance, which can cause blunting and thermal wear during grinding, ultimately reducing tool life compared to thermoset or metal-bonded tools [59]. The manufacturing process of tools with integrated cooling channels from digital models provides a major benefit despite facing these technical problems [61]. Material Extrusion functions as an operational technology that produces affordable, customized, complex abrasive tools that provide enhanced performance for applications requiring detailed designs and precise surface finishes.

3. DISCUSSION

A summary of the discussed groups of tools based on AM, along with their characteristics and the main machining effects obtained, is provided in Table 1. The indicated examples of tools demonstrate the great potential of AM printed tools used in precision abrasive machining of various materials, including difficult-to-cut materials such as ceramic materials, hardened steel or titanium alloys. A crucial aspect of evaluating abrasive tools is the possibility of their practical use in the abrasive machining, along with a comprehensive analysis of the obtained technological effects. So far, the amount of experimental data related to the performance of systematic studies is still limited and refers mainly to laboratory conditions. Particularly in the case of metal-bonded abrasive tools, the high cost of manufacturing tools significantly limits the possibility of performing systematic tests. Another challenge is the possibility of properly producing tools that are a mixture of metal powders and abrasives with assumed and reproducible characteristics. When machining with loose abrasives, among others in lapping technology, the use of flexible materials such as polyamide powders and resins allows significantly faster and cheaper production of tools. Thus, it is possible to conduct more extensive studies related to the evaluation of machining effects, along with an analysis of the influence of the type of tool geometry and the machining process parameters. Table 2 provides a concise comparison of different types of additively fabricated tools considering their main advantages and disadvantages as well as future application.

Most of the analysed works indicated in Table 1 focus on the evaluation of the main machining effects based on the surface quality of machined workpieces, determined most often by Ra and Sa parameters, as well as the efficiency of the machining process, determined by the amount of mass loss of machined samples. Nevertheless, another crucial aspect of precision abrasive process is the analysis of tool wear, especially for newly developed tools based on additive technologies.

Table 1. Comparison and characteristic of the main groups of abrasive tools based on AM technologies

Group of abrasive tools based on AM	AM method and material used to fabricate the tool	Characteristic of the tool	Machined workpiece	Main machining results: material removal; surface roughness, tool wear	Reference
Powder bed fusion	Selective laser sintering SLS and polyamide powder	Lapping segments used to conduct free abrasive machining with abrasive suspension containing SD 28/20 abrasive paste and D107 loose diamond grains	Ceramic material Al_2O_3	Δm = 4041 mg; dm = 33.68 mg/min; Ra = 0.46 µm; Sa = 0.5 µm; Tool wear based on profile error of ~200 µm	[Zieliński, Deja, Grzesik and Żak 2025]
	Selective laser sintering SLS and mixture of nylon PA2200, glass bubble K46, white corundum 500# and diamond W40	Grinding wheels with arrayed internal cooling holes containing diamond grains W40 and others: glass bubble K46 or white corundum 500#	Glass (BJ32) and cemented tungsten (YG15)	Surface roughness varying from 2.0 to 4.0 µm	[Du et al., 2019]
	Multi jet fusion MJF and thermoplastic polyurethane TPU material	Grinding tools consist of TPU body and abrasive layer in the form of 120 mesh diamond belt	Titanium alloys TC4	Maximum material removal rate MRR = 0.14 g/s; Ra = 1.53 µm – 1.96 µm	[Li et al., 2024]
	Selective laser melting SLM and mixed composite powder of AlSi7Mg and diamond particles	Grinding wheels fabricated from the mixture of AlSi7Mg powder with particle size of 15–53 µm and diamond particles with size of 38–45 µm and the volume ratio of abrasive grains 15 %	BK7 glass	Ra = 0.76 µm	[Han, G., Xu, Y., Huang, G., Yang, Z., & Ren, C. 2025]
Resin-bonded	Digital light processing DLP and blend of acrylic resins (28 W% resin A +72 W% resin B)	Honing stones printed from the mixture of blend acrylic resins and 50 wt% silicon carbide (SiC-320F)	Hardened steel	Ra ~ 0.5 µm; Sa ~ 0.3 µm	[Barmouz, M., & Azarhoushan g, B. 2025]
	Customized ultraviolet curing system and mixture of liquid epoxy resin Dymax425 and diamond grains	Lapping segments fabricated from the mixture of resin and diamond abrasives average sized 15 µm	Ceramic material Al_2O_3	Δm = 122 mg; Ra = 0.18 µm	[Gou et al., 2019]
	Digital light processing DLP and two acrylic resins	Grinding wheels printed from the mixture of acrylic resins and abrasive grains of	Hardened steel	Lowest surface roughness Ra ~ 0.5 µm and Sa ~ 0.4 µm	[Barmouz, M., Steinhäuser, F., &

		silicon carbide (SiC F220) and diamond with average diameter 64 µm			Azarhoushang, B. 2024]
Extrusion-based	Fused filament fabrication FFF and ABS filament	Grinding wheels with continuous and serrated working surfaces	41Cr4 alloy steel	Δm = 0.058 g; Ra ~ 0.3 µm	[Zieliński, D., Deja, M., & Zator, M. 2024]
	Material extrusion filament-based (MEX) process	Diamond-based ultra-fine grinding tools fabricated from hybrid filament containing polyamide 12, tetragonal zirconium dioxide (ZrO_2) and diamond grains with an average grain size of 15 µm	fused silica “HPFS 7980 5F”	Maximum material removal height ~ 30 µm Lowest surface roughness Rq ~ 10 nm	Henkel, S., Knauf, M., Katzer, F., Wille, T., Barz, A., Boeckh, T., Gerhardt, M., Kerber, A., Rädlein, E., & Bliedtner, J. (2025)
Hybrid-bonded (metal-resin)	Digital light processing DLP and sintering process and printed composition of bronze powder, abrasive grains, photopolymer and anti-sediment agent	Hybrid resin-metal bond grinding wheel fabricated from the composition of silicon carbide abrasive grains F220 (60-70µm), photopolymer used as a print bond, anti-sediment agent and bronze powder with 45 µm diameter used as a wheel bond	Al 7075	Lowest surface roughness Ra ~ 1 µm	[Barmouz, M., & Azarhoushang, B. 2025]
	Digital light processing DLP and sintering process and printed composition of bronze powder, abrasive grains, photopolymer, anti-sediment agent and glass fiber	Glass fiber reinforced metal bond grinding wheel fabricated from the composition of silicon carbide F220 (60-70µm), photopolymer used as a print bond, anti-sediment agent, glass fiber with 12 mm length and bronze powder with 45 µm diameter used as a wheel bond	UHMWPE – ultra-high molecular weight polyethylene	Lowest surface roughness Ra ~ 2 µm and Sa ~ 5 µm	[Barmouz, M., Steinhäuser, F., & Azarhoushang, B. 2025]

*Table 1 continued

For this purpose, it is necessary to use appropriate measurement techniques and methods for analysing the data obtained. Currently, in most research papers, authors mainly focus on the evaluation of tool wear conducted on the basis of microscopic observations. Unfortunately, the amount of quantitative and numerical data determining the value of wear is still limited. Due to the high roughness and irregular surface structure, especially for laser powder bed fusion abrasive tools from metals and their alloys, the use of conventional contact methods is difficult and in some cases impossible to use.

Therefore, proposed by the authors of the study [46] method for evaluating the shape and wear of polyamide abrasive tools is based on non-contact measurements conducted using an optical profilometer and a 3D scanner. The obtained data and the developed methodology for their analysis allowed the determination of profiles defining the shape and wear of abrasive segments based on the Wt parameter. In addition, surface topography analysis also provides important information related to the wear mechanism of tools made from polyamide powders. The shape of the obtained profiles and the value of wear are similar to those determined by measurements made with a coordinate measuring machine. This confirms the possibility of performing fast and accurate wear measurements of flat lapping wheel surfaces, especially for additively fabricated tools.

Table. 2. Comparison of different types of AM-fabricated tools

Group of additively manufactured abrasive tools	Advantages	Disadvantages	Future potential
Metal-bonded	- construction of tools with complex internal and external geometries, including tools with regular and irregular arrangements of abrasive particles, as well as grinding wheels with increased porosity; - significant reduction in the roughness of machined surfaces	- high material and tool fabrication costs; - possibility of defects occurring, including cracks as well as graphitization of diamond grains	The possibility of effective machining of a wide range of materials, including hard and brittle materials, using high process parameters.
Polyamide-bonded	- low tool wear enabling long-term machining tests; - use of the minimum dose of abrasive suspension; - significant improvement in the quality of machined surfaces; - a relatively simple and inexpensive method of tool production, including the fabrication of a set of tools in a single 3D printing process;	- possibility of defects and deformations, especially in the fabrication of tools with large and flat surfaces; - limited range of machining parameters due to sintered polyamide powders	The possibility of effective and economical machining of various materials, including difficult-to-cut materials such as ceramic materials, confirmed by systematic experimental tests of free abrasive machining.
Resin-bonded	- relatively low material costs and high precision of fabricated tools; - significant improvement in the quality of machined surfaces with limited possibilities for effective machining of hard and brittle materials, including ceramics	- high wear rate limiting the range of parameters used and types of materials machined; - time-consuming fabrication process involving the preparation of a mixture of resin and abrasive grains, and then the process of curing them with UV light	Production of precision abrasive tools enabling significant improvement in the surface quality of different materials.

Extrusion-based	- fast and inexpensive process of manufacturing tools with strictly defined geometries and without the necessity of long post-processing; - the possibility of using various materials with different properties, including composite materials;	- significant tool deformation, especially during machining of hard materials; - the necessity of continuously providing a fresh dose of abrasive slurry directly to the machining zone	Modification of the surface of workpieces, including surfaces that have previously undergone other abrasive machining processes, with limited possibilities for effective machining of hard and brittle materials.
Hybrid-bonded	- the possibility of obtaining high mechanical properties allowing for machining with high cutting parameters; - combining the advantages of flexible and hard materials in a prototype abrasive tool	- a complex and expensive manufacturing process involving the development of composite materials and the use of different additive processes; - limited amount of experimental data requiring systematic machining tests along with an evaluation of the technological effects obtained and tool wear characteristics	The possibility of effective machining of a wide range of materials, including those with specific properties used, among others, in the aerospace and automotive industries.

*Table 2 continued

Another modern approach is the development of hybrid-bonded grinding tools based on resin-metal materials. In the case of the group of abrasive tools indicated in Table 1 and described as hybrid-bonded, compositions containing not only a mixture of abrasive material and metal powder, but also photopolymer serving as abrasive tool bond material are used. Therefore, the process of producing such tools considers first the use of a digital light processing (DLP) technique, and then the sintering process. The possibility of utilizing the unique properties of flexible resin and durable metal binder can lead to positive results in precision abrasive machining of difficult-to-machine materials, but still requires the performance of further and systematic tests.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

The most important findings based on the revised current research works are drawn as follows:

- Additive manufacturing has a great potential in the fabrication of abrasive tools from different types of materials and different internal and external geometries. Nowadays, the main groups of abrasive tools based on AM include powder bed fusion from metals and polyamide, resin- and extrusion-based tools, as well as hybrid-bonded grinding wheels.
- Abrasive tools based on AM are used in machining a wide range of materials, including difficult-to-cut materials such as ceramics, titanium alloys or hardened steel and usually causing a significant reduction in the roughness of their surfaces.
- Polyamide abrasive tools fabricated by selective laser sintering can be used in the efficient and economical free abrasive machining of hard and brittle ceramic materials. The

prototype lapping segments retain high cutting properties after a single dosing of the abrasive suspension containing loose diamond grains, enabling effective material removal for 120 minutes and even more, as well as significantly improvement in surface finish. Soft and porous structure of sintered polyamide enables effective penetration of grains into the active surface of the tool, resulting two- and three body abrasion.

- One of the basic machining effects analysed using additively fabricated tools is the surface finish of the workpieces. Although AM-fabricated tools enable to decrease the surface roughness parameters, the amount of quantitative data obtained, especially related to tool wear, is still limited. Therefore, in the near future conducting more and systematic tests may enable wider application of the tools, including industrial conditions.
- The fabrication of tools based on extrusion from basic filaments is much faster and cheaper compared to other AM methods, especially laser powder bed fusion. A wide range of possible feedstock materials with different properties, as well as different designs of tools make this group of tools also suitable in precision machining.

Possible future perspectives in the development of additively fabricated tools mainly concern:

- Conducting further and systematic experimental tests using different process parameters and type of abrasive material with detailed analysis of technological effects.
- Development of tools with different external and internal geometries.
- Comprehensive characteristics of tool wear using modern measurement methods based on optical profilometers and 3D scanners as well image analysis.
- Development of new hybrid materials and tools fabricated from hybrid materials containing abrasive grains.
- Possibility of tool regeneration, especially for flat and precision abrasive processes such as lapping.

REFERENCES

[1] RAMPAL R., WALIA A.S., SOMANI N., GOYAL T., GUPTA N.K., 2025, *Enhancing Precision Machining: Evaluation of Magneto-Rheological Abrasive Finishing (MAF) for Brass and SS-304 Material Using Composite Abrasives*, International Journal on Interactive Design and Manufacturing, 19/6, 4471–4485, https://doi.org/10.1007/s12008-024-02101-9.

[2] GUPTA G., KUMAR P., KUMAR K., SRILATHA A.S.C., 2025, *Advanced Finishing Processes for Enhanced Surface Engineering*, Bobba P.B. (Ed.), AIP conference proceedings 3157/1, American Institute of Physics, https://doi.org/10.1063/5.0271286.

[3] KHATTRI K., CHOUDHARY G., BHUYAN B.K., SELOKAR A., 2018, *A Review on Parametric Analysis of Magnetic Abrasive Machining Process*, IOP Conference Series, Materials Science and Engineering, 330,1, 12105, https://doi.org/10.1088/1757-899X/330/1/012105.

[4] KUMAR M., ALOK A., KUMAR V., DAS M., 2022, *Advanced Abrasive-Based Nano-Finishing Processes: Challenges, Principles and Recent Applications*, Materials and Manufacturing Processes, 37/4, 372–392, https://doi.org/10.1080/10426914.2021.2001509.

[5] LI J., ZHU Z., HU J., ZHOU Z., ZHANG X., ZHAO W., 2020, *Particle Collision-Based Abrasive Flow Mechanisms in Precision Machining*, International Journal of Advanced Manufacturing Technology, 110/7-8, 1819-1831, https://doi.org/10.1007/s00170-020-05974-8.

[6] DEJA M., ZIELINSKI D., KADIR A.Z.A., HUMAIRA S.N., 2021, *Applications of Additively Manufactured Tools in Abrasive Machining-A Literature Review*, Materials, 14/5, 1318, https://doi.org/10.3390/ma14051318.

[7] JASINSKI K., MURAWSKI L., KLUCZYK M., et al., 2023, *Selected aspects of 3D printing for emergency replacement of structural element*s, Advances in Science and Technology Research Journal, 17/1, 274–289. https://doi.org/10.12913/22998624/158486.

[8] ZIELINSKI D., DEJA M., ZATOR M., 2024, *A Comparative Study of Precision Surface Grinding Using Additively Fabricated Acrylonitrile-Butadiene-Styrene (ABS) Wheels with Continuous and Serrated Working Surfaces*, Materials, 17/23, 5867, https://doi.org/10.3390/ma17235867.

[9] ZIELINSKI D., DEJA M., GRZESIK W., ZAK K., 2025, *High Performance Eco-Friendly Free Abrasive Machining Using an Additively Fabricated Tool and PCD Based Slurry*, Scientific Reports, 15/1, 30960, https://doi.org/10.1038/s41598-025-16363-0.

[10] SINGH S., SANKAR M.R., 2020, *Rheological Study of the Developed Medium and Its Correlation with Surface Roughness During Abrasive Flow Finishing of Micro-Slots*, Machining Science and Technology, 24/6, 882–905, https://doi.org/10.1080/10910344.2020.1771570.

[11] SHAIK M.B., MAMILLA R.S., NASINA V., 2025, *Experimental Investigation and Prediction of Surface Roughness in Abrasive Flow Finishing of Additive Manufactured Pure Copper*, Progress in Additive Manufacturing, 10/4, 2133–2160, https://doi.org/10.1007/s40964-024-00741-7.

[12] TAMARKIN M., TISHCHENKO E., AZAROVA A., BUTENKO V., 2020, *Surface Quality Formation at Polymer Composite Details' Abrasive Processing. IOP Conference Series*, Materials Science and Engineering, 918/1, 12114, https://doi.org/10.1088/1757-899X/918/1/012114.

[13] KAPLONEK W., NADOLNY K., ROKOSZ K., MARCIANO J., MIA M., PIMENOV D.Y., KULIK O., GUPTA M.K., 2020, *Internal Cylindrical Grinding Process Of INCONEL® Alloy 600 Using Grinding Wheels with Sol-Gel Alumina and a Synthetic Organosilicon Polymer-Based Impregnate,* Micromachines (Basel), 11/2, 115, https://doi.org/10.3390/mi11020115.

[14] GOLOBURDIN D., KOZLOV A., KOZLOV A.V., 2022, *Development of a Photopolymer-Abrasive Composite For 3D Printing Tools*, Voronezh Scientific-Technical Bulletin, 4–10, https://doi.org/10.34220/2311-8873-2022-4-10.

[15] SHARMA V., PANDEY P.M., 2023, *Additive and Subtractive Manufacturing Processes: Principles and Applications*, Sharma V., Pandey P.M., Eds.; 1st ed., 1, CRC Press. https://doi.org/10.1201/9781003327394.

[16] BORGES D.J.A., SOUZA A.M., DA SILVA E.J., 2023, *A Review on the Production of Grinding Tools Through Additive Manufacturing Processes: from Current Possibilities to Future Perspectives*, Machining Science and Technology, 27/5, 472–530, https://doi.org/10.1080/10910344.2023.2253027.

[17] MEDIBEW T.M., ZIELINSKI D., AGEBO S.W., DEJA M., 2025, *Recent Research Progress in the Abrasive Machining and Finishing of Additively Manufactured Metal Parts*, Materials, 18/6, 1249, https://doi.org/10.3390/ma18061249.

[18] WANG H., GUO Y., WANG X., GAO H., 2024, *On Surface Texture Evolution in Abrasive Flow Machining*, Materials and Manufacturing Processes, 39/13, 1894–1909, https://doi.org/10.1080/10426914.2024.2368550.

[19] LUO MIOU., 2015, *Abrasive Tool Manufacturing Method Based on 3D Printing*, Patent CN104924499, https://worldwide.espacenet.com/publicationDetails/biblio?FT=D&date=20150923&DB=EPODOC&CC=CN&NR=104924499A#.

[20] SYRLYBAYEV D., SEISEKULOVA A., TALAMONA D., PERVEEN A., 2022, *The Post-Processing of Additive Manufactured Polymeric and Metallic Parts,* Journal of Manufacturing and Materials Processing, 6/5, 116, https://doi.org/10.3390/jmmp6050116.

[21] DE OLIVEIRA D., GOMES M.C., DOS SANTOS A.G., RIBEIRO K.S.B., VASQUES I.J., COELHO R.T., DA SILVA M.B., HUNG N.W., 2023, *Abrasive and Non-Conventional Post-Processing Techniques to Improve Surface Finish of Additively Manufactured Metals: A Review*, Progress in Additive Manufacturing, 8/2, 223–240, https://doi.org/10.1007/s40964-022-00325-3.

[22] SHARMA V., PANDEY P.M., 2023, *Additive and Subtractive Manufacturing Processes: Principles and Applications*, Sharma V., Pandey P.M., Eds.; 1st ed., Vol. 1, CRC Press, https://doi.org/10.1201/9781003327394.

[23] ALAM Z., IQBAL F., KHAN D.A., 2024, *Post-Processing Techniques for Additive Manufacturing,* Iqbal F. Z. Alam, Khan D.A, Eds.; 1st ed., Vol. 1, CRC Press. https://doi.org/10.1201/9781003288619.

[24] KAHHAL P., JO Y.-K., PARK S.-H., 2024, *Recent Progress in Remanufacturing Technologies Using Metal Additive Manufacturing Processes and Surface Treatment*, International Journal of Precision Engineering and Manufacturing-Green Technology, 11/2, 625–658, https://doi.org/10.1007/s40684-023-00551-2.

[25] KISHORE K., SINHA M.K., SINGH A., ARCHANA GUPTA M.K., KORKMAZ M.E., 2022, *A Comprehensive Review on the Grinding Process: Advancements, Applications and Challenges,* Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 236/22, 10923–10952, https://doi.org/10.1177/0954406222111078.

[26] PRATAP A., PATRA K., DYAKONOV A.A., 2019, *A Comprehensive Review of Micro-Grinding: Emphasis on Toolings, Performance Analysis, Modeling Techniques, and Future Research Directions*, The International Journal of Advanced Manufacturing Technology, 104/1, 63–102.

[27] LI X., WANG C., TIAN C., FU S., RONG Y., WANG L., 2021, *Digital Design and Performance Evaluation of Porous Metal-Bonded Grinding Wheels Based on Minimal Surface and 3D Printing.* Materials & Design, 203, 109556.

[28] MAEKAWA K., YOKOYAMA Y., OHSHIMA I., 2001, *Fabrication of Metal-Bonded Grinding/Polishing Tools by Greentape Laser Sintering Method*, Key Engineering Materials, 196, 133–140.

[29] YANG Z., ZHANG M., ZHANG Z., LIU A., YANG R., LIU S., 2016, *A Study on Diamond Grinding Wheels with Regular Grain Distribution Using Additive Manufacturing (AM) Technology*, Materials & Design, 104, 292–297.

[30] TIAN C., LI X., CHEN Z., GUO G., WANG L., RONG Y., 2020, *Study on Formability, Mechanical Property and Finite Element Modeling of 3D-Printed Composite for Metal-Bonded Diamond Grinding Wheel Application*, Journal of Manufacturing Processes, 54, 38–47.

[31] TIAN C., WAN Y., LI X., RONG Y., 2023, *Permeability Design and Assessment of the Additively Manufactured Metal-Bonded Diamond Grinding Wheel Based on TPMS Structures*, International Journal of Refractory Metals and Hard Materials, 114, 106237.

[32] TIAN C., WAN Y., LI X., 2024, *The Influence of Diamond Content on the Formability and Mechanical Properties of Additively Manufactured Metal-Bonded Diamond Tools*, The International Journal of Advanced Manufacturing Technology, 131/9, 4649–4661.

[33] TIAN C., LI X., ZHANG S., GUO G., WANG L., RONG Y., 2018, *Study on Design and Performance of Metal-Bonded Diamond Grinding Wheels Fabricated by Selective Laser Melting (SLM)*, Materials & Design, 156, 52–61.

[34] TIAN C., LI X., ZHANG S., GUO G., ZIEGLER S., SCHLEIFENBAUM J.H., RONG Y., 2019, *Porous Structure Design and Fabrication of Metal-Bonded Diamond Grinding Wheel Based on Selective Laser Melting (SLM)*, The International Journal of Advanced Manufacturing Technology, 100/5, 1451–1462.

[35] WANG C., WANG D., TIAN C., WANG L., RONG Y., LI X., 2021, *Grinding Performance Evaluation of 3D-Printed Porous Metal-Bonded Grinding Wheel in BK7 Glass Grinding*, The International Journal of Advanced Manufacturing Technology, 117/5, 1445–1457.

[36] HAN G., XU Y., HUANG G., YANG Z., REN C., 2025, *Compression, Permeability and Grinding Properties of Selective Laser Melted Porous Metal-Bonded Diamond Grinding Tools*, Journal of Manufacturing Processes, 136, 177–191.

[37] TIAN C., WAN Y., LI X., RONG Y., 2023, *Study on the Additively Manufactured Porous Metal-Bonded Grinding Wheel Designed by Octahedron Lattice Structure*, The International Journal of Advanced Manufacturing Technology, 125/3, 1743–1756.

[38] PETRUSHA I.A., 2000, *Features of a Cbn-to-Graphite-Like BN Phase Transformation Under Pressure*, Diamond and related materials, 9/8, 1487–1493.

[39] DENKENA B., KRÖDEL A., HARMES J., KEMPF F., GRIEMSMANN T., HOFF C., KAIERLE S., 2020, *Additive Manufacturing of Metal-Bonded Grinding Tools*, The International Journal of Advanced Manufacturing Technology, 107/5, 2387–2395.

[40] HUANG W., HU X., ZHAI J., ZHU N., GUO K., 2020, *Biorenewable Furan-Containing Polyamides*, Materials Today Sustainability, 10, 100049, https://doi.org/10.1016/j.mtsust.2020.100049.

[41] SANJAY KRISHNA I., SREEDHAR CHETAN M., PATEL, 2021, *Molecular Dynamics Simulation of Polyamide-Based Materials - A Review*, Computational Materials Science, 200, 110853, https://doi.org/10.1016/j.commatsci.2021.110853.

[42] DEJA M., ZIELINSKI D., 2021, *A Pilot Study on Machining Difficult-To-Cut Materials with the Use of Tools Fabricated by SLS Technology*, Materials 14, 5306, https://doi.org/10.3390/ma14185306.

[43] DU Z.J., ZHANG F.L., XU Q.S., HUANG Y.J., LI M.C., HUANG H.P., WANG C.Y., ZHOU Y.M., TANG H.Q., 2019, *Selective Laser Sintering and Grinding Performance of Resin Bond Diamond Grinding Wheels with Arrayed Internal Cooling Holes*, Ceram. Int., 45, 20873–20881.

[44] HENKEL S., KNAUF M., KATZER F., et al., 2025, *Development and Application of Material Extrusion Produced Ultra-Fine Diamond Grinding Tools for Machining Hard Brittle Materials*, Int. J. Adv. Manuf. Technol. 139, 4631-4650, https://doi.org/10.1007/s00170-025-16121-6.

[45] DEJA M., ZIELINSKI D., AGEBO S.W., 2024, *Study on the Wear Characteristics of a 3D Printed Tool in Flat Lapping of Al2O3 Ceramic Materials*, Wear 556, 205515.

[46] AGEBO S.W., ZIELINSKI D., DEJA M., 2025, *Comparison of Different Optical Measurement Methods in the Evaluation of the Wear of SLS-Fabricated Tool Used for Free Abrasive Machining*, The International Journal of Advanced Manufacturing Technology, 1–18.

[47] ZIELINSKI D., AGEBO S.W., DEJA M., 2025, *Effect of Process Parameters on the Wear Characteristics and Lapping Performance of SLS-Fabricated Polyamide Tools*, Wear, 574–575, 206093, https://doi.org/10.1016/j.wear.2025.206093.

[48] AGEBO S.W., ZIELINSKI D., DEJA M., 2025, *Influence of the Three-Body Abrasion Kinematics on the Surface Characteristics of an SLS-Fabricated Tool During Machining of Ceramics*, Sci. Rep. 15, 19786, https://doi.org/10.1038/s41598-025-02692-7.

[49] BARMOUZ M., AZARHOUSHANG B., ZAHEDI A., RABIEI F., STEINHÄUSER F., 2023, *Progress in Grinding Performance by Additive Manufacturing of Grinding Wheels Integrated with Internal Venturi Cooling Channels and Surface Slots*, Journal of Manufacturing Processes, 99, 485–500.

[50] BARMOUZ M., STEINHÄUSER F., AZARHOUSHANG B., KHOSRAVI J., 2024, *Influence of Bond Thermal and Mechanical Properties on the Additively Manufactured Grinding Wheels Performance: Mechanical, Wear, Surface Integrity, and Topography Analysis*, Wear, 538, 205215.

[51] AI Q., KHOSRAVI J., AZARHOUSHANG B., DANESHI A., BECKER B., 2022, *Digital Light Processing-Based Additive Manufacturing of Resin Bonded Sic Grinding Wheels and Their Grinding Performance*, The International Journal of Advanced Manufacturing Technology, 118/5, 1641–1657.

[52] MENG X, YANG W, DENG X., 2021, *Research on 3D Printing Process and Properties of Diamond-Resin Composites Based on Digital Light Processing*, Diam. Relat. Mater. 120: 108715.

[53] BARMOUZ M., STEINHÄUSER F., AZARHOUSHANG B., 2025, *Correction: Tailored Bond Characteristics in Additively Manufactured Resin Bond Grinding Wheels: Achieving Optimal Performance, High Abrasive Concentration, and Cost Efficiency*, Progress in Additive Manufacturing, 10/4, 2053–2053.

[54] QIU Y., HUANG H., XU X., 2018, *Effect of Additive Particles on the Performance of Ultraviolet-Cured Resin-Bond Grinding Wheels Fabricated Using Additive Manufacturing Technology*, Int. J. Adv. Manuf. Technol. 97, 3873–3882.

[55] HABEL A., BARMOUZ M., STEINHÄUSER F., AZARHOUSHANG B., 2024, *Influence of Additives on Grinding Performance of Digital Light Processing-Printed Phenol Bond Grinding Wheels*, Applied Sciences, 14/17, 7711.

[56] BARMOUZ M., AZARHOUSHANG B., 2025, *Additive Manufacturing of Hybrid Bond Grinding Wheels Via Digital Light Processing: Performance Enhancement Through Composition Alteration and Groove Incorporation*, Results in Engineering, 105808.

[57] COOGAN T.J., KAZMER D.O., 2020, *Prediction of Interlayer Strength in Material Extrusion Additive Manufacturing*, Additive Manufacturing, 35, 101368.

[58] RANJAN N., TYAGI R., KUMAR R., KUMAR V., 2024, *On Fabrication of Acrylonitrile Butadiene Styrene-Zirconium Oxide Composite Feedstock for 3D Printing-Based Rapid Tooling Applications*, Journal of Thermoplastic Composite Materials, 37/2, 692–712.

[59] KNAUF M., KATZER F., HENKEL S., WILLE T., BLIEDTNER J., GERHARDT M., KERBER A., 2024, *Development of Individually Designed, Additively Manufactured Fine Grinding Tools with a Hybrid Bond for Processing Inorganic, Non-Metallic Materials*, Eleventh European Seminar on Precision Optics Manufacturing, 13221, 96–98, SPIE.

[60] HENKEL S., KNAUF M., KATZER F., WILLE T., BARZ A., BOECKH T., BLIEDTNER J., 2025, *Development and Application of Material Extrusion Produced Ultra-Fine Diamond Grinding Tools for Machining Hard Brittle Materials*, The International Journal of Advanced Manufacturing Technology, 1–20.

[61] STRANO M., RANE K., FARID M.A., MUSSI V., ZARAGOZA V., MONNO M., 2021, *Extrusion-Based Additive Manufacturing of Forming and Molding Tools*, The International Journal of Advanced Manufacturing Technology, 117/7, 2059–2071.

[62] POLINI W., CORRADO A., 2024, *A Design for Additive Manufacturing Tool for Parts Obtained Through a Material Extrusion Process*, Progress in Additive Manufacturing, 9/2, 285–298.

[63] LIEBER S.C., VARGHESE A.P., TARANTINO R., TAFUNI A., 2023, *Additive Manufacturing for Plastic Extrusion Die Tooling: A Numerical Investigation*, CIRP Journal of Manufacturing Science and Technology, 41, 401–412.