

A feasibility study on selective laser sintering-fabricated polyamide tools in double-sided precision machining of technical aluminum oxide ceramics

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ABSTRACT

The significance of the lapping process lies in its ability to achieve precise surface quality and dimensional accuracy on the workpiece. Apart from multiple controlled and uncontrolled process factors, the lapping tool type and its characteristics play a critical role in the process efficiency. Additive manufacturing (AM) recently attracted considerable attention in precision machining environments due to its design flexibility and customization of the fabricating tool structure. This paper presents an experimental demonstration of additively fabricated tools by the SLS method in the double-sided lapping process of Al_2O_3 ceramic samples. The experimental investigations have been carried out to evaluate the attained technological effects on ceramic samples, such as surface roughness (S_a) and material removal rate (MRR). Additionally, the wear mechanism of the lapping wheel was assessed based on global map observation using a 3D laser scanner and the radial axis profile using a 3D optical profilometer. The results of the first experimental study showed significant improvement in the surface quality of ceramic samples with 68.75% reduction of the initial surface roughness within 10 minutes of machining time from S_a 1.6 μm to 0.5 μm . Moreover, the enhancement of the surface quality of ceramics samples was attained with the removal rate of 91.2 mg/min. Furthermore, the radial axis profile of tools, surface topographies, and global map observations indicated the potential of the polyamide tool by resulting in relatively lower wear conditions with the grooves formed on the tool surface. The research revealed considerable promise of SLS-printed lapping wheels in double-sided precision machining of a difficult-to-cut Al_2O_3 ceramics while achieving favourable technological effects and minimum wear condition.

Keywords: abrasive machining, double-sided lapping, selective laser sintering, ceramic samples.

INTRODUCTION

Ceramic materials are widely used in various areas of industry, including the automotive, tooling and electronics sectors. The high hardness,

the tendency to crack and the formation of surface defects during machining require the use of suitable methods and abrasive tools for this type of material [1, 2]. Abrasive processes, such as grinding and lapping, are still one of the most popular

methods for mechanical parts finishing, including difficult-to-cut materials. However, obtaining high accuracy in shape and dimensions, as well as low surface roughness, requires consideration of the appropriate parameters and conditions of planarization processes [3]. Lapping with grinding kinematics and double-sided lapping or double face grinding with planetary kinematics enable significantly more efficient processing of brittle ceramic materials, such as technical oxide ceramics Al_2O_3 , compared to conventional one-sided lapping. In particular, double-sided lapping is a promising process for machining flat and parallel surfaces of ceramic components, e.g., sealing discs or bearing rings [4]. Currently, one of the developments of the indicated processes is the production of new tool designs based on different additive methods and hybrid materials.

Additive manufacturing (AM) methods, also commonly referred to as incremental manufacturing or 3D printing, enable the fabrication of components with complex geometries, including tools and production tooling components – Rapid Tooling. Additive manufacturing processes recently attracted considerable attention in various abrasive tools fabrications, including metal-bonded, polyamide-based, resin, and material extrusion, as well as hybrid-based [5].

The application of powder bed fusion 3D printing methods has been pointed out in [6, 7] as one of the solutions for the fabrication of elastic abrasive tools with strictly defined internal and external structure. Nowadays, metal powder 3D printing methods are successfully used to produce grinding wheels with porous structures [8, 9]. For softer tools used in lapping or polishing, it is possible to use a mixture of liquid resins and loose abrasive grains cured by laser or UV light [10]. Material extrusion additive manufacturing (MEAM) based on virgin or hybrid materials containing some fillers, can be used to produce prototype grinding wheels. For example, Zieliński et al. [11] developed an abrasive tool with a strictly defined working surface geometry from a commercially available ABS filament. Abrasive paste containing diamond grains was applied to the tool surface only before the machining tests began. Nevertheless, effective machining of ceramic materials requires the use of diamond or boron carbide grains. Henkel et al. [12] evaluated the performance of ultra-fine grinding tools made through the material extrusion AM process using a novel composite

material consisting of diamond grains, zirconium oxide particles, and polyamide 12 materials. By using the developed tools, the roughness of fused silica samples was observed with values of R_q ranging from 10 to 14 nm, attaining a 97% reduction from the initial surface condition. In the study [13], various AM technologies were used to fabricate abrasive tools for the grinding purpose of 41Cr4 alloy steel samples. The study considered mSLA with resin materials, material extrusion with ABS and TPU materials, and SLS with PA12 powder material. Among the investigated grinding tools, the research reported that TUP-made tools were found to have great potential by enhancing the quality, whereas PA12 tools delivered superior material removal, while resin-made tools resulted in excessive wear. Authors in [14] evaluated the performance of a high-porosity vitrified grinding wheel made through a vat photopolymerisation AM process. The 3D-printed vitrified grinding wheel performed well at a 25 μm depth of cut compared to a lower depth of cut at the same material removal rate, showing lower wear, better surface finish, and minimal wheel loading. The study at [15] presented a customized honing tool made through DLP AM process using an engineered polymeric resin blend and silicon carbide (SiC-320F) abrasive grains for the stones. The tool was used for the purpose of finishing internal cylindrical surfaces, and the results showed the tool's high performance by reaching a roughness level of $S_a \approx 0.3 \mu m$ and $R_a \approx 0.5 \mu m$ while significantly improving the load-bearing capacity of the surface. Additionally, prototype tools made from polyamide powders using the SLS method have been found promising for the abrasive machining process. The elimination of support structures and significantly less complicated post-processing compared to metal powder bed fusion leads to considerable cost and time saving in the fabrication of soft tools, which are intended for grinding and lapping, among other things. For example, the authors of paper [16] used the SLS method and a mixture of PA 2200 polyamide powder with W40 diamond grains to produce a prototype grinding wheel with cooling holes. The inclusion of additional cooling holes in the tool geometry allowed for direct supply of coolant to the machining zone, thus reducing cutting forces. Deja and Zieliński [17] successfully used tools fabricated by SLS technology for machining technical oxide ceramics

Al_2O_3 . An abrasive suspension containing D107 diamond grains was applied to the flat surface of the printed tool before machining tests. The soft and porous structure of the sintered PA 2200 polyamide and the adopted set of lapping parameters enabled the effective reinforcement of the wheel surface with abrasive grains, which consequently affected the efficient removal of material from the ceramic samples, as well as a significant reduction in the roughness parameters R_a and waviness W_a of their surfaces. The tool tested not only allowed for obtaining positive technological effects but was also characterised by low wear [18]. The effective machining time of the plate was significantly longer compared to resin-bonded wheels, as well as electroplated tools used in lapping with grinding kinematics. This demonstrates the great potential of flexible materials such as polyamide to produce novel abrasive tools. Despite the positive results of polyamide tools in the single-sided lapping process, so far, there was no systematic investigations related to the use of SLS-printed tools in the double-sided lapping process.

Therefore, this study aimed to investigate the machining performance and wear characteristics of 3D printed polyamide tool in double-sided precision machining of a difficult-to-cut Al_2O_3 ceramics. The scientific novelty of this work is the development and fabrication of prototype segmented tools using the selective laser sintering (SLS) method, which have been successfully used in the double-sided precision machining of Al_2O_3

technical oxide ceramics. The study assessed the potential of the tool considering machinability metrics, such as using surface roughness parameters (S_a , S_v , S_p , and S_z) and material removal rate (MRR). Additionally, the wear characteristic and mechanism of the tool were further evaluated based on surface global map observation using a 3D laser scanner and radial axis profile by employing 3D optical profilometer. The presented results of the first experimental tests showed the potential of flexible SLS-printed polyamide wheels in double-sided lapping of technical oxide ceramics Al_2O_3 by effectively embedding them with boron carbide abrasive grains during the machining process and indicated the future possible directions for further systematic work.

MATERIALS AND METHODS

The lapping tools

Prototype lapping wheels with a segmented construction were made by the SLS method from polyamide PA 2200 powder using the EOS Formiga P100 3D printer and the set of parameters given in Table 1. After the fabrication process, abrasive segments were only cleaned of unused powder as a basic post-processing (see Figure 1a). Abrasive segments were then tightly clamped to the machine body. The segments have indicated a good clamping force and cannot be moved on the base body. Moreover, the holes in the segments on the upper wheel matched the holes for the coolant supply in the base body. This demonstrates that the proposed geometry of the individual segments and the obtained dimensional and shape accuracy after the AM process enabled stable mounting of the segments to the machine tool body. Finally, the lower and upper lapping wheels with outer diameter $d_o = 451$ mm and inner diameter $d_i = 199$ mm were composed of eight independent abrasive segments that form a uniform flat surface of the tools – Figure 1b.

Experimental setup

The experimental investigations were carried out on a double-sided lapping machine of the type Peter Wolters AL 00-1L of Lapmaster Wolters GmbH, Rendsburg, Germany, at the IWF TU Berlin – Institute for Machine Tools and Factory Management, Technische Universität

Table 1. 3D printing process and machining parameters

3D printing process parameters	Value
Thickness of a single layer	100 μm
Laser type	CO_2
Power of laser	30 W
Length of a laser beam	10.2–10.8 μm
Printing speed	10 mm/s
Printing resolution	0.005 mm
Printing orientation	vertical
Machining parameters	Value
Grain	Boron carbide
Grain size	F120
Mixing ratio	35 g / 500 ml
Speed ratio	0.5
Pressure	60 daN
Process time	10 min

Berlin, Germany. Cylindrical Al_2O_3 ceramic samples ($\text{HV}_{10} = 1.100 \text{ MPa}$) with an outer diameter $d_{\text{wo}} = 30 \text{ mm}$, an inner diameter $d_{\text{wi}} = 18 \text{ mm}$, and an initial height $h_w = 3 \text{ mm}$ were used as workpieces. The lapping parameters are given in Table 1. A total of 24 ceramic samples were distributed within the four leading rings placed on the flat surface of the lower lapping wheel, as shown in Figure 1c. The lapping suspension was gradually added during the lapping process. After the machining, the roughness of the upper and lower surfaces of the samples was measured using an S neox Sensofar 3D optical profilometer according to the ISO25178 standard. SensoMAP premium 9.1 software was used to analyse the obtained surface topographies. The topography of the ceramic samples was measured using a Nikon EPI 20X objective and a confocal measurement technique with a confocal fusion algorithm. The analysed measurement field size was $840.42 \times 702.42 \mu\text{m}$. The analysis considered three measurements for the selected sample, including each

surface before and after the lapping process. In the case of segment surface measurements, the confocal technique and the confocal fusion algorithm were also used, along with a Nikon EPI 5X objective with a pixel size of $2.76 \mu\text{m}/\text{pixel}$. Depending on the type of measurement, the field size was $3.36 \times 2.81 \text{ mm}$ or $118.40 \times 5.33 \text{ mm}$. The evaluation of the wear of selected segments after the experimental tests was performed based on measurements carried out with a HANDYSCAN 3D 700 Elite 3D scanner and dedicated VXelements™ software by Creaform Inc, as well as S neox Sensofar optical profilometer.

RESULTS AND DISCUSSION

Surface topography of Al_2O_3 ceramics

The surface structure is one of the crucial technological effects of the lapping process. Therefore, a non-contact method was used in

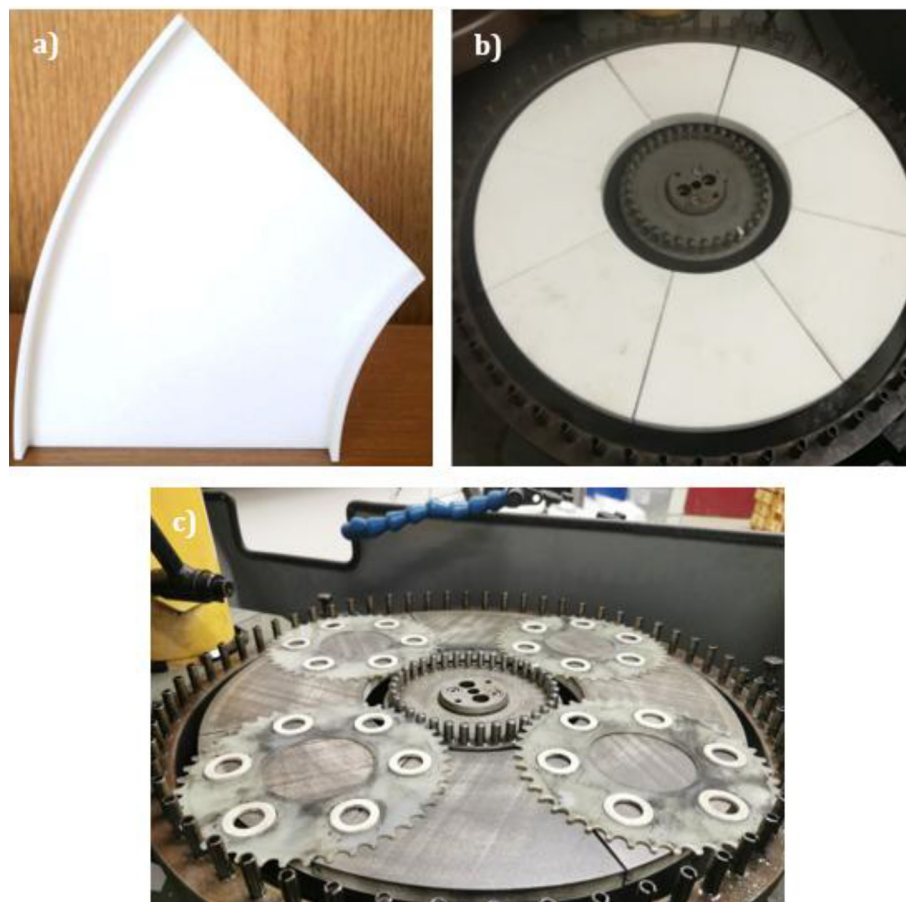


Figure 1. Double-sided lapping experiments setup: a) the single SLS-printed abrasive segment; b) assembled segments of the lower disc on the base body; and c) lower lapping wheel with Al_2O_3 samples placed inside the leading rings after machining

a comprehensive way to evaluate the quality of flat surfaces of ceramic workpieces. The results of upper- and lower-surface roughness measurements on ceramic samples are presented in Figures 2 and 3. As a result of the lapping process, a significant reduction in the values of the roughness parameters was achieved for both the lower and upper surfaces of the machined ceramics. For example, the initial value of the parameter $S_a \approx 1.6 \mu\text{m}$, similar for both surfaces, was reduced to $S_a \approx 0.5 \mu\text{m}$ and $S_a \approx 0.7 \mu\text{m}$ for upper and lower surfaces, respectively. The use of S_a -value as a reference parameter was due to its wide practical application in the evaluation of the geometric structure of the surface of mechanical parts. Meanwhile, the values of the individual parameters, as well as the shape of the topography, are similar for both surfaces. The determined values for the extracted profiles from the surface topography

confirmed a significant reduction in roughness. Moreover, exemplary surface topographies also highlighted material defects resulting from the machining of hard and brittle technical ceramics, Figure 3b. The differences observed in the roughness parameter values between the lower and upper surfaces of the samples could result directly from the nature of the double-sided lapping process. As shown in the diagram in Figure 4, the downward force is applied via the upper wheel, which leads to variations in the force exerted on the upper and lower surfaces. The downforce can then significantly influence the intensity of grain embedding into the individual surfaces of the flexible tools, consequently leading to the predominance of two- or three-body abrasion mechanisms. Therefore, this issue may significantly influence the characteristics and wear mechanisms of flexible tools made from polyamide powder. For this reason, it will be

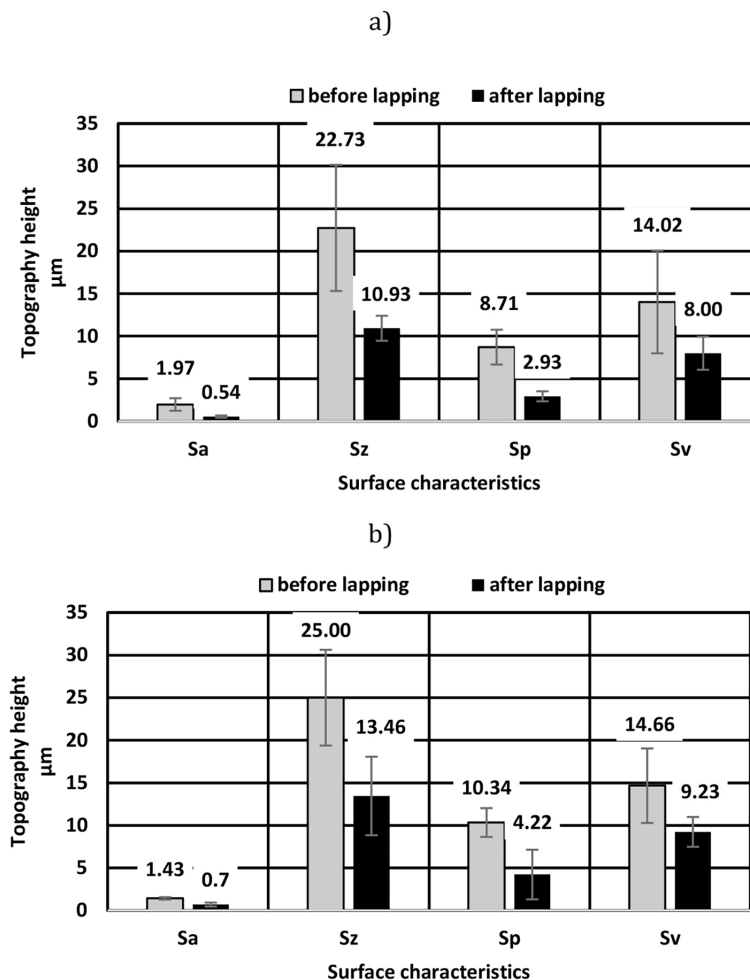


Figure 2. Values of selected surface roughness S parameters after double-sided lapping of technical oxide ceramics Al_2O_3 for the upper (a) and lower (b) surfaces; error bars show $\pm$ standard deviation calculated from three measurement points of upper and lower lapping wheels

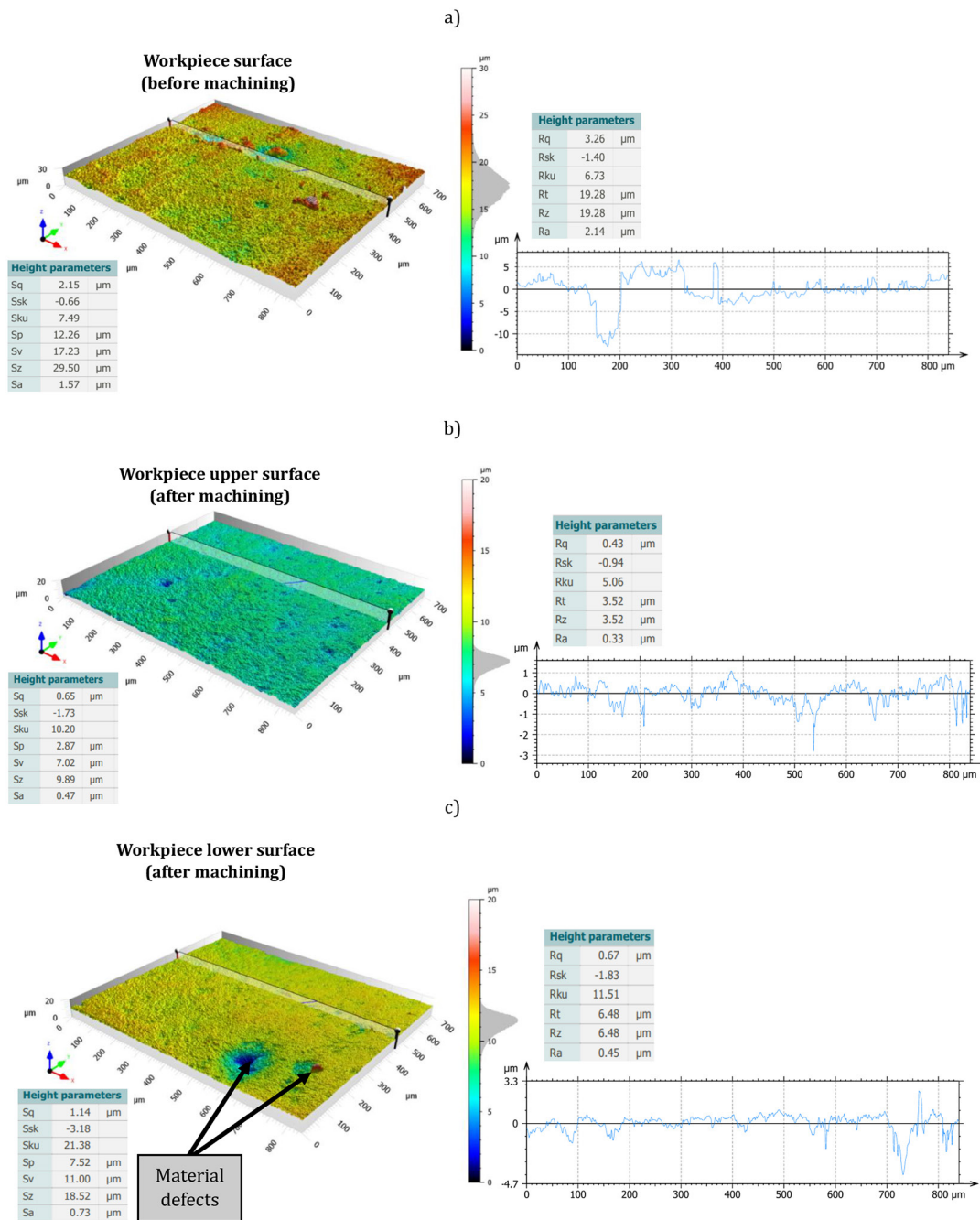


Figure 3. Examples of surface topographies of Al_2O_3 ceramic samples before (a) based on lower surface and after (b, c) lapping tests with selected height parameters and extracted profiles

analysed in more detail in future work, considering longer machining test times.

Material removal rate and mechanism

Material removal is considered a key performance metric during the abrasive machining process, and the efficiency is mainly influenced by various process-induced factors, including the kinematic configuration, process parameters, size and quantity of abrasive grains, and the unit

pressure applied on the workpiece. In this experimental study, the removal of material from the Al_2O_3 ceramic samples takes place mainly due to the three-body abrasion mechanism that occurs between the polyamide tool, boron carbide grains, and the workpiece. However, during machining the action of three-body abrasion makes a transition to the combination of three- and two-body abrasion due to abrasive grains embedment in the tool surface, and this facilitates the material removal process (Figure 4). As

shown in the topographic observation of Figure 5, during the lapping process, the softest nature of an SLS-printed polyamide tool enabled some of the abrasive grains to partially or fully embed on the tool surface and act as a fixed abrasive grain to perform the material removal action in the form of chips. Therefore, the boron carbide grains protruding above the surface of the tool enabled the cutting of hard and brittle ceramics. The results showed good performance of the tool by removing a total of 912 mg of material from Al_2O_3 ceramic samples during 10 minutes of machining, indicating the removal rate of 91.2 mg/min. Aside from the benefit of abrasive embedment, the action of abrasion of abrasive grains caused the tool surface to experience grooves with varying depths of cut along the active regions of the tool due to the grains' rolling and sliding mechanism during the process.

Wear characteristics of the tool

Another important aspect of abrasive machining processes is the control and monitoring of the tool shape. Macroscopic observations after the experimental tests did not indicate excessive wear on the prototype tools, which could be used for further tests after cleaning from the abrasive

slurry. Non-contact methods based on 3D optical profilometers and 3D scanners can be used for the evaluation of the wear of AM-fabricated wheels [19]. The use of a 3D scanner allowed comparing the geometry of selected abrasive segments of the upper and lower lapping wheel after machining tests with their 3D CAD models, and then to determine the shape deviations in selected tool areas – Figures 6a and b. The designated blue areas define the largest deviations between the actual segment geometries after machining and their 3D CAD models, with an assumed tolerance of $\pm 20 \mu\text{m}$, indicating the areas of greatest segment wear. The adopted tolerance value allowed indicating a general view of the wear of lapping wheels after the machining process. Therefore, further and more detailed analysis was carried out based on measurements realised with an optical profilometer along the centrelines of the lapping wheels. By employing a confocal 5X magnification scale and applying a Gaussian filter with a cut-off 0.80 mm, radial axis waviness profiles of lower and upper lapping segments were extracted and used to evaluate the wear characteristics. As seen in Figures 6c and d, the highest wear resulted near the inner and outer radii of the lower and upper segments, with the maximum height of $W_t = 156.20 \mu\text{m}$

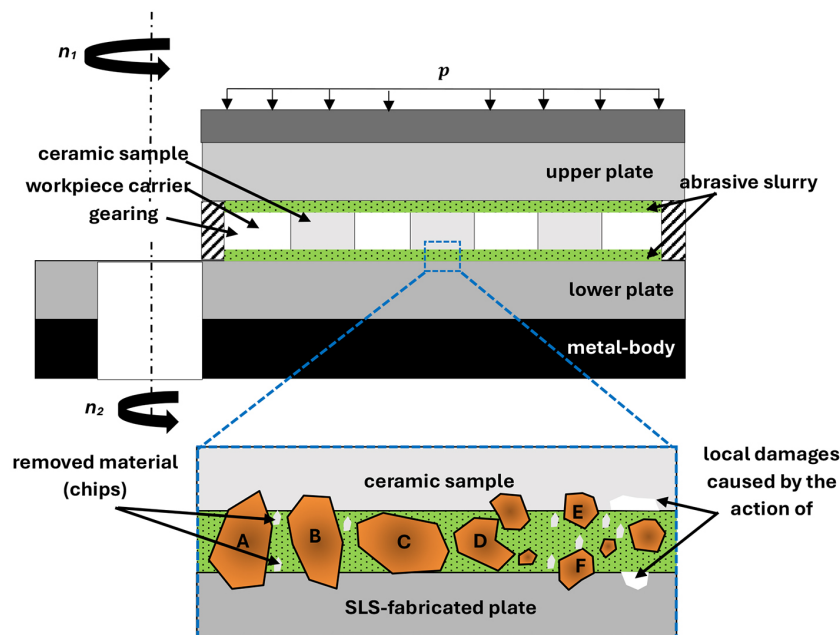


Figure 4. General scheme of free abrasive machining using SLS-fabricated lapping wheels; where n_1 – rotational speed of a upper tool, n_2 – rotational speed of a lower tool, p – unit pressure, A and B – abrasive grains embedded in the surfaces of the plate and the sample, C – abrasive grain rolling between surfaces of the plate and the sample, D – crashed abrasive grain, E and F – abrasive grains embedded in the surface of the sample and plate, respectively

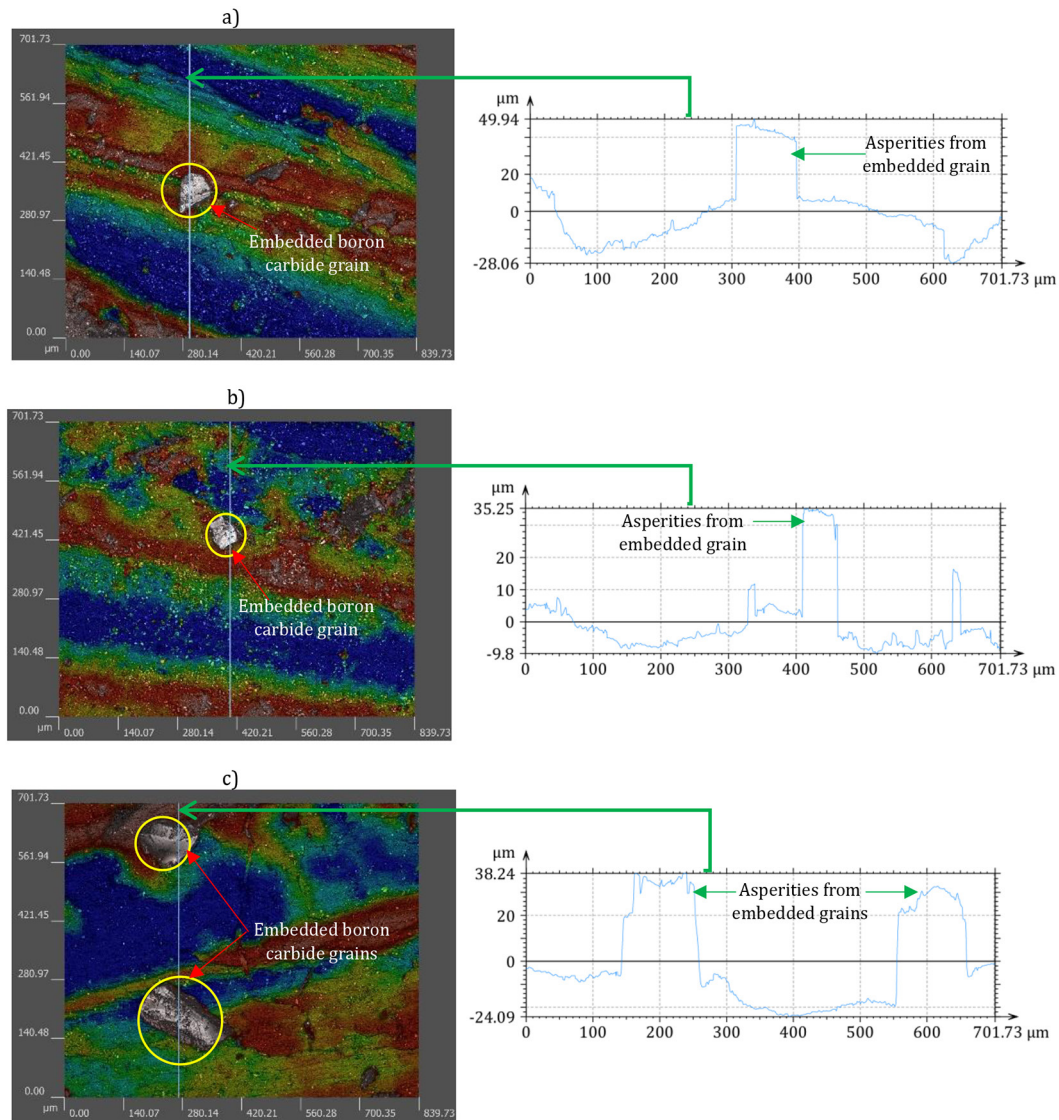


Figure 5. An exemplary topography and profile of the abrasive grains embedment mechanism on the tool surface: (a-b) topography and profile taken from the lower segment, (c) topography and profile taken from the upper segment

and $W_t = 198.49 \mu\text{m}$, respectively, along the profile. Thus, this confirms the results obtained with the use of a 3D scanner. The surface topography at a specific radius of the tool showed that the wear was mostly caused by abrasion of boron carbide grains, which made the surface of the segments wear, creating grooves and embedding particles. The obtained results indicate relatively low and similar wear of both abrasive segments. At the same time, the segment shape errors are also due to the 3D printing process itself. Therefore, in future works, the analysed geometries will be compared not only to the 3D CAD computer models of the tools, but also to their actual shapes obtained directly after their fabrication process on the 3D printer. The proposed lapping

wheels produced by 3D printing technology and based on polyamide powder have been successfully used in machining difficult-to-cut ceramic material. As a result of lapping, the roughness parameters were significantly reduced, obtaining values similar to those using electroplated tools in double-face grinding [20, 21], as well as SLS-printed tools in one-sided lapping [18]. Basic investigation related to shape and profile analysis of single segments indicated similar and relatively low values of tool wear. Thus, the first experimental studies have indicated the great potential of SLS-fabricated polyamide wheels in double-sided lapping of ceramic workpieces.

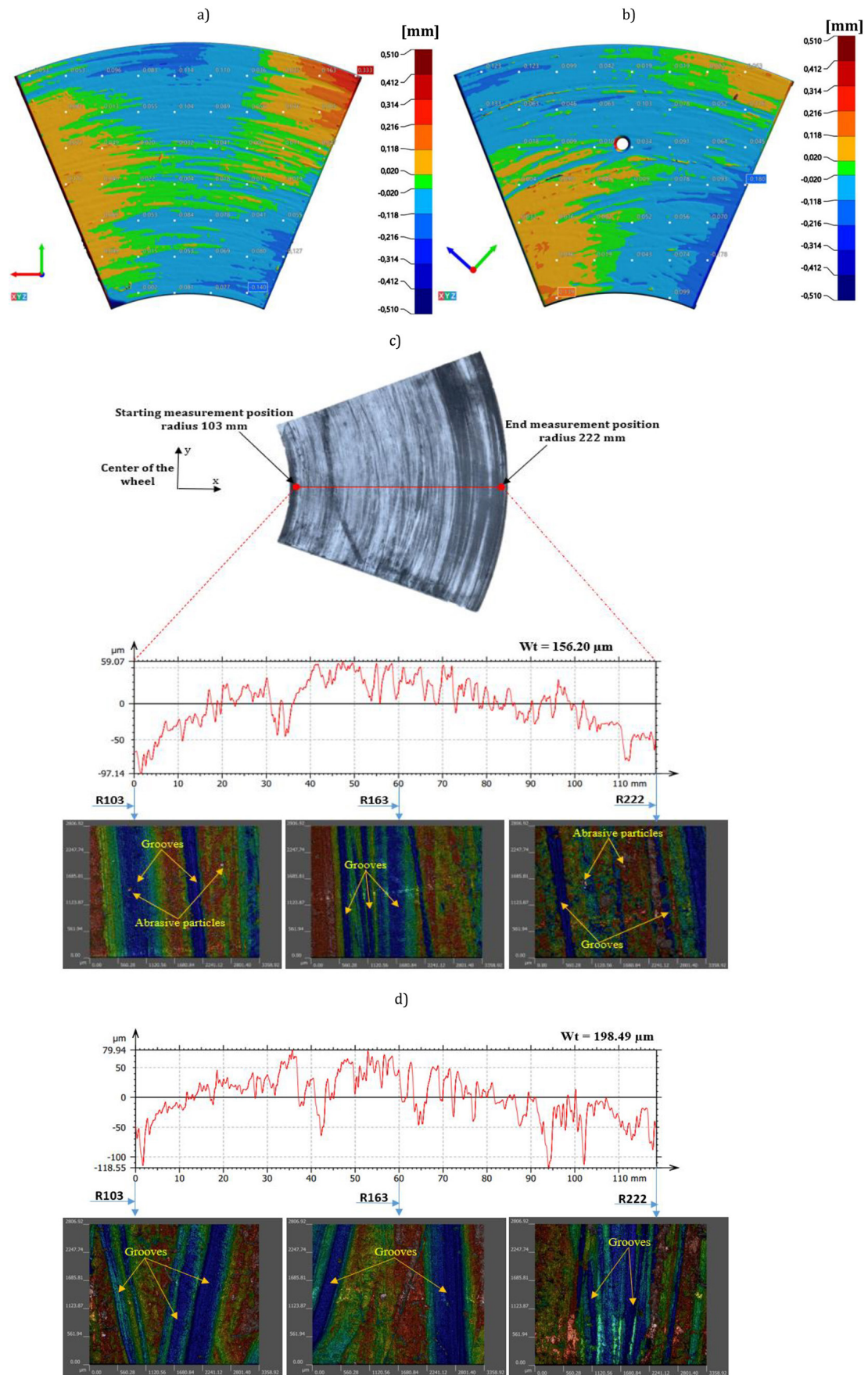


Figure 6. Wear analysis of SLS-fabricated wheels based on an example color-coded deviation map demonstrating the areas of tool wear (marked in blue) on the lower (a) and upper (b) segment, and radial axis waviness profiles with selected topography of lower (c) and upper (d) segment

CONCLUSIONS

The additive manufacturing (AM) process is increasingly being applied in the production of various precision machining tools. In this research, novel additively fabricated tools by the SLS method were successfully used in double-sided lapping of a difficult-to-cut Al_2O_3 ceramics. Following the first and pilot experimental investigations on the performance and wear characteristics of polyamide tools in the precision machining process, the following conclusions are drawn:

- The proposed method, based on polyamide powder, made it possible to fabricate the segments forming the upper and lower lapping plates with the assumed dimensions and without the need for extra post-processing. Moreover, it is possible to produce all segments in a single printing process.
- The results of the first experimental tests indicated a significant reduction in the values of the roughness parameters for both side surfaces of the ceramic samples, from the value of the parameter $S_a \approx 1.6 \mu\text{m}$ up to the value of $S_a \approx 0.5 \mu\text{m}$. Moreover, some surface defects typical of machining hard and brittle materials were also observed on selected surface topographies.
- The material removal mechanism of the process is mainly controlled by the three-body abrasion occurring between the tool, abrasive grains, and workpiece. The tool's surface was observed with some abrasive particles embedded along the active region, suggesting a favourable effect of grain embedment in the achieved material removal rate of 91.2 mg/min. This suggests the occurrence of a transition of three-body abrasion to a combination of three- and two-body abrasion during the machining process.
- Macroscopic observations and measurements using a 3D scanner and an optical profilometer did not indicate excessive wear on the lapping wheels, which allows them to be reused in the next machining process. Moreover, the radial axis profile of tools indicated the highest tool wear based on maximum height $W_t \sim 200 \mu\text{m}$.

Overall, the study revealed a potential of SLS-fabricated tools in double-sided precision machining of Al_2O_3 ceramics while achieving favourable technological effects and minimal wear. A future study will focus on more experimental studies,

along with a statistical analysis of the obtained results. In addition, a detailed evaluation of the surface topography of the machined samples as well as the flat surfaces of the abrasive segments will be carried out, together with the analysis of the amount and characteristics of wear and shape-error.

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