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Production and characterisation of batch manufactured flexible micro-grinding tools for finishing metallic surfaces

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Abstract

In this study, we report on batch production and use of flexible micro-grinding tools for finishing metallic surfaces. By using photo-structurable polyimide as a matrix material, many similar heads of these grinding tools can be produced at once using a photolithography process. The abrasive (silicon carbide) is easily integrated into the matrix by dispersing it into the polymer before applying the polyimide-abrasive-suspension (PAS) to the substrate. By varying the process parameters of batch production and the weight fractions of PAS, the layer thickness and material properties like the Young's modulus are adjusted in order to optimize the grinding performance in a given application. After separation, the tool heads are bonded to the tool shafts. Due to the two-part construction, the heads can be easily exchanged after wear and the shafts can be reused. In addition, the diameter of the tool shafts is tuned to standardized collets. This allows the use of the grinding tools in conventional machine tools, which enables easy integration into existing manufacturing cycles. The flexibility of the micro-grinding tools allows high precision machining of metallic surfaces, which will be shown for copper. The comparison of the infeed and the material removal shows the high flexibility of the tool. The grinding is followed by a roughness analysis of the surface. Single grinding processes are compared to multi grinding processes and it is shown that multiple steps halve the surface roughness in this grinding procedure. The tool wear is measured as well. First, we observe a high initial tool wear by a dressing process and after that it reduces to under 1 µm for each further grinding step with a tool path length of 42 mm.

Keywords: Precision engineering, micro-grinding, high precision machining, micro production technology

1. Introduction

Nowadays, micromachining is an important tool for the production of microsystems and can be divided into physical, chemical and mechanical machining [1]. The field of mechanical machining includes precision grinding. Some grinding tools can be used in CNC machine tools, which offers the possibility to grind more complex surfaces and thus to achieve a higher surface quality right in the areas where it is needed.

A low surface roughness or high surface quality is important in many fields, since it determines, among other things, the properties of a component [2]. For example, lenses used in micro-optics should have a very low surface roughness so that less light is scattered [3], and in medical technology, surface roughness of an implant can lead to different reactions in the body [4].

In order to achieve a particularly low surface roughness, micro-grinding tools with a flexible bond matrix are suitable, as the bond matrix yields during the grinding process, the material removal is thus reduced and only the roughnesses on the surface are levelled. The structural accuracy is maintained [5].

Polyimide, which is characterized by high thermal and chemical resistance properties, can be used as such a flexible bonding matrix. Abrasive particles can be stirred into the polyimide during the manufacturing process. On basis of such a polyimide-abrasive-suspension (PAS), macroscopic grinding tools have already been produced [6]. However, it is not possible to machine microstructures on this scale.

For this purpose, a process must be found that enables the structuring of the PAS. Photolithography is a suitable method, which also has the advantage that batch production of several hundreds of similar grinding heads is possible.

2. Experimental procedures

The following section is divided in two parts. First, the manufacturing process of the micro-grinding tools is described, which include the batchprocessing of the tool heads, the milling process of the tool shafts and the bonding process of both parts. Second, the CNC aided grinding process on copper surfaces is characterized.

2.1. Manufacturing and characterisation process of micro-grinding tools

The manufacturing of the tool heads starts with a photolithography process. Silicon carbide (SiC) with a grain diameter of around 4 to 6 µm is used as abrasive grains and a polyimide as flexible binding matrix. A silicon wafer with a thickness of 500 µm is used as substrate. The PAS is spin coated onto the substrate, followed by a softbake, an exposure step, a development of the non-exposed areas and a hardbake. A variation of the mass percentage of silicon carbide (0,8-25 wt% while mixing manually), the speed while spin coating (1 000-2 000 rpm) and the hardbake temperature (200-350 °C) should reveal the influence on the layer thickness. Measurements were performed tactile, a first time after the development step and a second time after the hardbake. The produced grinding heads have a diameter of around 1 mm.

The photolithography process is followed by deep reactive ion etching to increase the possible depth of grinding to around 250 µm. Then the tool heads can be separated by dicing into squares with an area of 1.2 x 1.2 mm². With the actual design, 236 grinding heads are manufactured out of one substrate with high potential for optimizing the mask design to produce more tool heads at a time.

Furthermore the influence of curing temperature and abrasive content on the Young's Modulus was measured on free standing films of the functional layer by tensile testing. In order to obtain free standing films, samples in the form of a flat specimen with a geometry of 50 x 6 mm were produced as described above. They were then anodically removed from the substrate. The analysis were performed with the test tool until the sample broke.

Simultaneously the tool shafts are milled in a 5-axis CNC milling machine (C5, Datron). As material aluminium is used for its great machinability. The shaft diameter is tuneable for standardized collets. For the investigations, a diameter of 4 mm is chosen. The top is structured with a milled circular bag in the middle so the tool heads auto align in the centre.

A two component epoxy resin adhesive (Plus Endfest 300, UHU) is used for bonding manually, its curing is aided by temperature (150 °C, 5 min). The placement is done manually. To test the adhesion strength, shear tests are performed. For this purpose, the grinding heads are exposed to different temperatures (50-400 °C, for 30 min) in order to investigate the influence of possible heat development during grinding and to test the maximum heat resistance of the glue. Furthermore, the influence of the cooling lubricant used (Pro Cut 200, Datron) is investigated with exposure times up to 60 min and a combination of cooling lubricant and heat treatment (100 °C, 30 min) is investigated. Additionally thermal shock tests are carried out (low temp. -20 °C, high temp. 220 °C, 20 cycles of 60 s). For each experimental set-up, five samples are prepared, from which the mean value for the adhesion strength is calculated. Furthermore, five reference specimens are prepared to compare the adhesion strength of untreated and treated samples.

2.2. CNC grinding on copper surfaces

To test the functionality, the micro-grinding tools with 25 wt% abrasive are used on prepared copper surfaces. The copper workpieces are face milled and grinded with FEPA P 1200 grinding paper to generate a comparable surface for every experiment. The parameters are a cutting speed of about 62 m/min, a feed rate of 100 mm/min and an infeed of 5 µm. The analysis of the surface roughness of grinded spots is performed optically in two different areas by confocal microscopy. The mean roughness R_a and the mean roughness depth R_z are recorded. The result after grinding is compared with the surface roughness before grinding. A comparison of single step grinding with multi step grinding is done as well. Multi step grinding is done with 4 or 7 steps of grinding the same area with the same tool. For each step an area of 12,57 mm² is ground with a tool path length of 42,14 mm After every grinding step, the tool wear is measured, so that the machine can correct the infeed with the tool wear. Besides that, a tactile measurement of the height difference between the grinded area and the original surface takes place to analyse the flexibility of the micro-grinding tool by the comparison of infeed and material removal. Every grinding approach is carried out three times.

3. Results and discussion

Experimental results are described and discussed below. These are divided into the analysis of the manufacturing process, the characterization of the adhesion strength and the evaluation of the grinding tests.

3.1. Influence of manufacturing parameters on tool heads

The influence of the manufacturing process parameters on the resulting layer thickness of the PAS is analysed as described above. The coating thickness is higher with increasing abrasive mass fraction and with decreasing rotation speed and hardbake temperature. Thus, the highest film thickness of 66.9 µm was detected at the lowest rotation speed of 1 000 rpm, the highest mass fraction of 25 wt% and the lowest hardbake temperature of 200 °C. Furthermore, it was observed that the hardbake resulted in a shrinkage of the film thickness. This can be explained by an increased polymerization of the polymer and a stronger outgassing of solvent, monomers and oligomers remaining in the PAS after softbake. Since a higher mass percentage for grinding experiments later on was used, a high temperature for the hardbake step was selected for the further grinding tests in order to ensure the strongest possible linkage and thus incorporation of the abrasive grains into the bond matrix. This should lead to a lower outbreak of the grains out of the bond matrix prematurely, thus minimizing tool wear but it also increases the chance that the grains will not break out soon enough and become dull. The grinding performance would thus be greatly reduced.

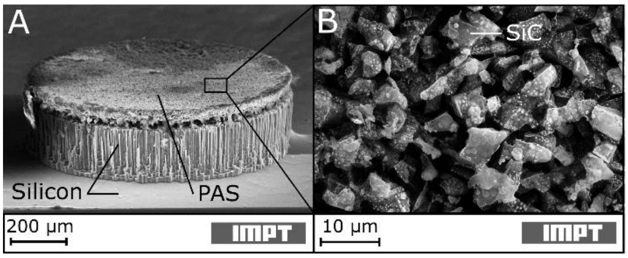

Figure 1. SEM pictures of the side view of a ready to use micro-grinding tool head (A) and the top view (B)

Figure 1 shows scanning electron microscopy (SEM) pictures of a grinding head that is ready to use. In the side view (Fig. 1 A), the PAS layer adhering to the etched silicon base can be seen very clearly. In addition, a magnified top view image (Fig. 1 B) clearly shows the SiC grains. Only a small amount of bonding matrix can be seen, which was reset by the etching process due to the significantly higher etch rate of polyimide compared to SiC. This is advantageous because the grains have thus been uncovered before the first grinding process. It can be seen as a kind of conditioning of the grinding head. However, a disadvantage is that the grains are more likely to break out due to poor anchoring in the matrix.

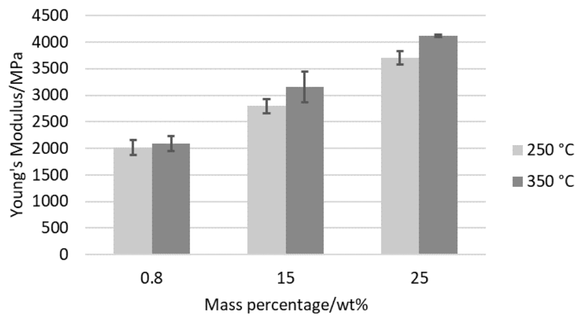

Figure 2. Results for Young's Modulus after tensile tests with different abrasive mass percentage and hardbake temperatures

The parameters selected during the manufacturing process also have an influence on the mechanical properties of the grinding tool heads. Especially the Young's modulus is of interest. The results of the tensile tests are shown in Figure 2. They show that the hardbake temperature has very little effect, provided that the same baking duration is kept. In contrast, a higher abrasive content shows a significant rise of the Young's modulus. Here, a particle reinforcement occurs to the composite material consisting of polyimide and silicon carbide. Compared to a mass fraction of 0.8 wt%, the Young's modulus increases by a factor of approximately 2 at the highest mass fraction of 25 wt%. This can have a negative effect on the flexibility of the grinding head. However, a higher mass fraction of abrasive can also lead to an increased metal removal rate due to an increased number of cutting abrasive grains on the surface.

3.2. Shear strength of epoxy resin adhesive

In order to characterize the assembly process, the bond strength was investigated by shear tests. Initially, untreated joints were examined in a first test. Here, five samples yielded a mean bond strength of 47.7 MPa and a standard deviation of 7.5 MPa. This shows exceptionally high adhesion strength of the tool heads to the tool shafts.

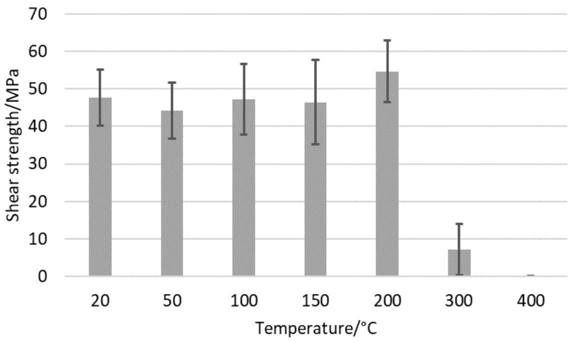

Figure 3. Shear strength between tool head and tool shaft by shear tests after heat treatment for 30 min at different temperatures

Subsequently, the grinding tools were exposed to higher temperatures. After an effective time of 30 min, shear tests were carried out immediately. The results can be seen in Figure 3. The measured values at 20 °C represent the untreated reference samples. Up to a temperature of 200 °C, no effect on the bond strength could be detected. Above 300 °C, there were already two failures that no longer showed any adhesion. However, the remaining three specimens also showed a significantly reduced value down to a bond strength of only 15 % in comparison to the reference samples. At a specific point, which seems to be between 200 °C and 300 °C in this case, the molecular structure can not withstand such high temperatures. This leads to chemical rearrangements and so to a change in mechanical properties. After the treatment at 400 °C, bonded joints could no longer be detected. The influence of cooling lubricant and temperature shock tests was also tested as described above. These showed no change in adhesion strength for the used time intervals compared to the reference samples. Also no decrease in bond strength could be detected when the tools were treated with a combination of cooling lubricant and a temperature of 100 °C for 30 min.

The results show a high resistance of the adhesive joint to temperature and cooling lubricant. The grinding experiments, which will be discussed below, confirm the suitability of the adhesive during the use of the tools.

3.3. Grinding Process on copper surfaces

The surface quality after grinding describes the functionality of the tool. An improvement of the roughness values compared to the unground surface is expected. For this purpose, the grinding tests are carried out as described and the roughness values R_a and R_z are compared before and after grinding.

An example of a comparison before and after the grinding is shown in Figure 4. In this example an unground (reference) surface is compared to a seven times grinded one to see how good the surface quality can get.

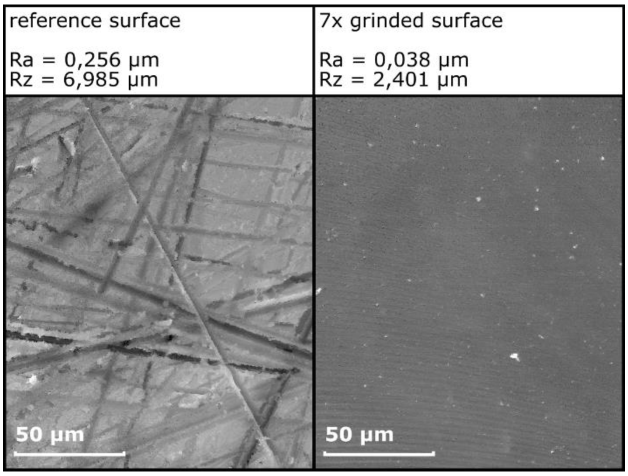

Figure 4. Analysis of surface roughness with confocal microscopy for reference surface and a seven times grinded surface.

On the left, deep furrows in the surface can be seen in the height profile before grinding, which lead to high roughness values. On the right, the surface that has been ground seven times, shows no more deep scratches, but smaller punctual heights (white). This is also reflected in the roughness values. In comparison, R_a decreases to 15 % and R_z to 34 % of the original values. The local heights are presumably remnants of the silicon carbide that have splintered off from grains or have completely detached from the bonding matrix. This is supported by energy-dispersive X-ray spectroscopy (EDX), by which particles on the workpiece surface could be identified as silicon carbide. Since they can still be detected on the surface despite the cleaning process after grinding, it can be assumed that they were pressed into the soft surface of the copper by the contact pressure between the tool and the workpiece. Despite the negative effect of the remaining grains on the roughness values, a strong improvement in the surface finish can be seen.

The following investigations should reveal the influence of the number of repetitions of the grinding process on the roughness values and the tool wear. Figure 5 shows the influence of the multi step grinding process on the surface roughness and as it can be seen, the surface quality improves with each further repetition of the grinding process. However, the highest improvement were already achieved after the first grinding step, where the R_a and the R_z values are approximately halved. One factor for this is the more exposed abrasive grains, which lead to a higher metal removal rate in the first repetitions. The further improvement is significantly smaller. Depending on the application, single step grinding processes could therefore already provide sufficient surface quality, but more iterations are recommended for the highest surface quality with mean values of R_a = 0.038 µm and R_z = 2.4 µm after seven repetitions.

For tool usage, the tool wear plays a major role. The first two grinding steps showed the highest impact on the tool wear. On average, the tool loses approximately 5.1 µm of length here. Subsequently, the tool wear is significantly lower, on average a tool wear of 0.9 µm is detected for the iterations three to seven.

This can be explained by the etching process. The resulting conditioning leave the uppermost grains exposed and decrease their contact area with the binding matrix as can be seen in Figure 1B. Besides the advantageous higher number of cutting edges the grains break out easier, resulting in increased tool wear. The newly exposed grains are integrated stronger into the binding matrix and the tool wear decreases. This is supported by the SEM images in Figure 5 compared to Figure 1B. Already after the first grinding step, for the most part only strongly integrated abrasive grains can be observed. This intensifies after four and seven repetitions. Nevertheless, the analysis of the grinding tests and the steady improvement of the surface roughness indicate that sufficient new cutting abrasive grains are exposed. This can be described as a kind of self-conditioning of the grinding tool. However, this should be investigated in more detail in connection with the maximum tool life.

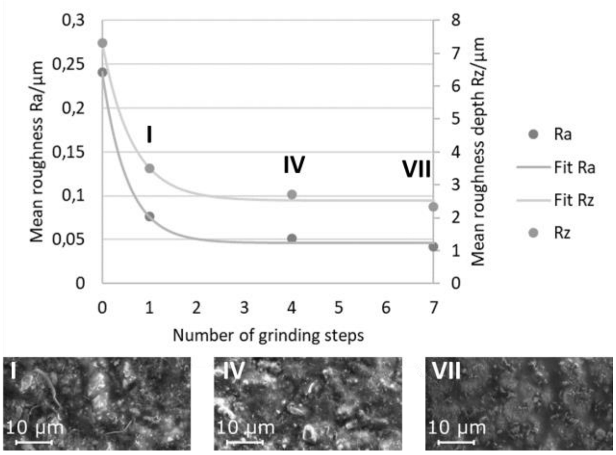

Figure 5. Comparison of surface roughness for R_a and R_z after no grinding (0), single step grinding (1), four iteration multiple grinding (4) and seven iteration multiple grinding (7). SEM pictures of the tool head surface added for every grinding strategy showing the difference in topography. Compared to Fig. 1B, a higher proportion of binding matrix can be seen and the grains are more integrated in it.

Another aspect to be investigated is the flexibility of the tools. For this purpose, the height difference between the ground surface and the original surface were compared. The infeed of the machine tool was 5 µm. For all specimens, the measurements showed significantly smaller height differences. On average, these were slightly less than 1 µm. Only a marginal difference could be detected between single step and multi step grinding. Presumably, the largest cutting effect occurs during the first iteration. Here the abrasive grains are strongly exposed from the bond matrix as said before. Subsequently, the surface tends to be levelled instead of being cut deeply, which is an advantage because the structural accuracy remains. However, by comparing removed material and infeed, it can be assumed that the micro-grinding tools are flexible to a certain extent. Further investigations are necessary regarding possible plastic deformations and the maximum usable contact pressure.

Furthermore, copper could be observed on the tool surface at about half of the tools after the grinding process. The detected copper was confirmed by EDX images. This could indicate an insufficient coolant supply or poor accessibility of the tool surface for the coolant. It should be investigated further to see if it is a problem for the self-conditioning of the grinding tool.

4. Conclusion

This work shows that hundreds of flexible micro-grinding tool heads can be produced by batch production. Therefore, polyimide was used as a binding matrix mixed with SiC abrasive grains. The investigations show that the mixing ratio in particular plays a major role for the properties of the final tool. Specimens produced with a higher mass percentage of abrasive have a higher PAS layer thickness of up to 66.93 µm in total and also a higher Young's modulus in the range of 4 000 MP, which is twice as high as for samples with lowest abrasive mass percentage. To have enough abrasive edges for grinding, a ratio of 25 wt% of SiC grains was used for mechanical processing of copper workpieces. After that, the grinding tool was bonded on an aluminium shaft with a two component epoxy resin adhesive proved to be very resistant to temperature up to 200 °C, rapid temperature changes (-20 °C to 220 °C), the used cooling lubricant and a combination of cooling lubricant and heat treatment. Only longer exposure to higher temperatures (> 200 °C) caused the adhesive to fail. However, subsequent grinding tests showed that the shear strength of the bond was more than adequate for the application with mean values between 44.3 MPa and 54.7 MPa for the given temperature range. Analysis of the ground copper surfaces showed that the surface roughness decreased significantly after the first grinding step, and the values for R_a and R_z were halved. Further iterations of a multi-step grinding process showed less serious improvement, but an improvement in surface finish was also evident after the seventh iteration. Tool wear showed a similar behaviour. Initially, the tool length decreased by several micrometres per grinding step after the first two iterations, but afterwards the wear reduced to less than 1 µm on average per iteration. This can be attributed to some kind of conditioning of the grinding tool. The uppermost abrasive grains have a poorer integration into the binding matrix because of the etching step and break out easier. Finally, the flexibility was investigated. It could be demonstrated on the basis of the ratio of material removal and infeed (different by a factor of about 5). Thus, it could be shown that the developed micro-grinding tools fulfil the demand of mechanical stability, grinding properties and flexibility. However, further analyses are still pending. In the future, the grain size and tool head diameter will be. The maximum tool life has yet to be determined. Additionally, the developed process chain can be used with other abrasive grain types, such as cBN or diamond. Furthermore, copper is more difficult to machine than its oxides, so prior oxidation of the areas to be machined could also lead to a better grinding result.

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References

[1] Brinksmeier E and Preuss W 2012 Micro-machining *Phil. Trans. R. Soc. A* **370** 3973-3992
[2] Aurich J C, Schneider S, Mayer P, Kirsch B and Hasse H 2017 Oberflächenerzeugungs-Morphologie-Eigenschafts-Beziehungen *ZWF* **111** 213-216
[3] Germar T A 1997 Angular dependence and polarization of out-of-plane optical scattering from particulate contamination, subsurface defects, and surface microroughness *Appl. Opt.* **36** 8798-8805
[4] Guehennec L L, Lopez-Heredia M-A, Enkel B, Weiss P, Amouriq Y and Layrolle P 2008 Osteoblastic cell behaviour on different titanium implant surfaces *Acta Biomaterialia* **4** 535-543
[5] Heintze S D, Forjanic M and Rousson V 2006 Surface roughness and gloss of dental materials as a function of force and polishing time in vitro *Dental Materials* **22** 146-165
[6] Asadi E, Hockauf R, Denkena B, Grove T and Wurz M C 2018 Flexible mono- and multilayer micro grinding tools for ultra-high precision processing and micro machining *euspen 18th Venice Italy*