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Grinding of riblets with "beaver tooth" multi-layer tools

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Abstract

To reduce friction in turbo machinery components, riblets are induced on compressor blades or pump impellers. Here, the grinding process enables a higher productivity in machining of riblet structures compared to knurling, laser or milling operations. Usually, profiled grinding tools are used to create such structures inspired by sharkskin. Unfortunately, conventional grinding tools have to be dressed continuously to keep the desired profile in the circumferential surface. To avoid the time-consuming dressing process and to enable a self-sharpening effect, an innovative multi-layer tool concept is developed. The tool consists of two types of thin polyimide layers. The first type contains abrasives and the second is a support layer without abrasives. These layers are piled alternately in a special manufacturing process and act like a monolithic tool in grinding process.
The aim of the investigations presented in this paper is to find an optimal parameter setting to produce riblet structures productively by using the self-sharpening effect. The optimal setting allows a grinding process without any dressing process by using a large part of the grinding tool volume. At first, the manufacturing process is focused to create clearly divided support and abrasive layers of the grinding tool. Furthermore, the investigation shows the relationship between grinding parameters and the setback of the supporting layer in the middle of the tool. This setback is important for the creation of riblet structures in the surface of AISI 420 workpieces.

Keywords: multi-layer tool, micro machining, riblet;

1. Introduction

The functionalization of surfaces is a key technology to increase the performance of technical components in the next decades [1]. Especially the reduction of friction in tribological contact is the main task for automotive industry and the entire transport and energy sector. In the field of fluid dynamics, the prevention of turbulences of near surface flow plays an enormous role. To reduce friction, avoid turbulences and decrease the emission of greenhouse gases, the field of bionics offers promising solutions. Sharkskin e.g. is composed of little rips or riblets, which reduce turbulence and support laminar flow [2]. For technical systems like pumps and turbo engines, the wall friction on compressor blades or pump impellers is a huge factor to increase the efficiency. Due to the usage of riblets, the wall friction is decreased by 0.2 percent in turbo engines and up to 1.5 percent in pumps. By the reduction of wall friction by only one percent, the emission of CO_2 of the operation of a centrifugal pump of a power plant could be reduced by 100 t per year [3, 4]. The dimension of the beneficial riblets depends on the viscosity and the flow speed of the fluid.

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Due to the complex geometry of flow related components and their small tolerances, the machining of riblet structures is challenging. These free formed and curved topographies can be structured by micro milling, micro eroding or with laser ablation, which is highly time consuming [5, 6]. A more economical process is peripheral grinding with profiled grinding wheels. Wang used grinding tools with a ceramic bonding and silicon carbide (grain size 16 µm) to induce riblets with a minimum height of 10 µm and a line distance of 20 µm. An optimal height-distance-ratio of triangular riblets is 1 [7]. He applied a profiled diamond dressing wheel to create the riblet structure in the grinding wheel by axial offset and grooving operations [8]. As well as Hahmann and Krawczyk, Wang used a copper wire to dress metal bonded grinding wheels by eroding every single riblet structure in the circumference of the tool [9, 10, 13]. This is more flexible compared to a dressing wheel, but both dressing concepts are extremely time consuming. Furthermore, between the dressing processes the riblet profile of the grinding wheel is constantly changing. That means, in a profile grinding process a self-sharpening effect cannot be reached.

To reach a self-sharpening grinding process an innovative multi-layer tool concept is developed. This concept was initially proposed by Denkena et al. [11]. They used conventional dicing blades and polymeric spacers to receive cutting and supporting layers in one grinding tool. The concept is also known as beaver tooth principal. The rodent front tooth consists of two different layers, a thin hard in the front and a softer one in the back of the teeth. During gnawing, the softer part is set back and the harder part wears more slowly. Thereby a self-sharpening, sharp edge results [12]. Similar to nature, the supporting layer of the grinding tool acts like the softer part of the beaver teeth. A self-sharpening effect results, if the right process parameters can be found to constantly wear down the supporting part of the tool. By using this tool concept, only an initial dressing step is needed and 95 percent of dressing time compared to a profiled grinding wheel is saved. The productivity of the structuring process of compressor blades with riblets is improved more than 15 times. Unfortunately, the manufacturing process for these tools is not optimized jet and resulting in poor accuracy. It is therefore difficult to create the same riblet structures again [11].

The aim of the current investigations is the development of a flexible tool concept, which enables the targeted description of cutting and wear behavior of the abrasive and support layer. In the next section the new tool concept and its manufacturing procedure is explained.

2. Manufacturing of multi-layer tools

The new multi-layer tools are manufactured via spin coating thin film technology in the clean room of the Institute of Micro Production Technology - IMPT. Figure 1 describes the full manufacturing process. In a first step, a silicon wafer is laminated with Kapton®. The silicon wafer functions as carrier for the emerging micro-grinding tool. Kapton® is a polyimide foil with a silicone-containing adhesive. In this case, the foil and the adhesive have a thickness of about 25 µm each. In preparation of the spin coating, liquid polyimide in form of

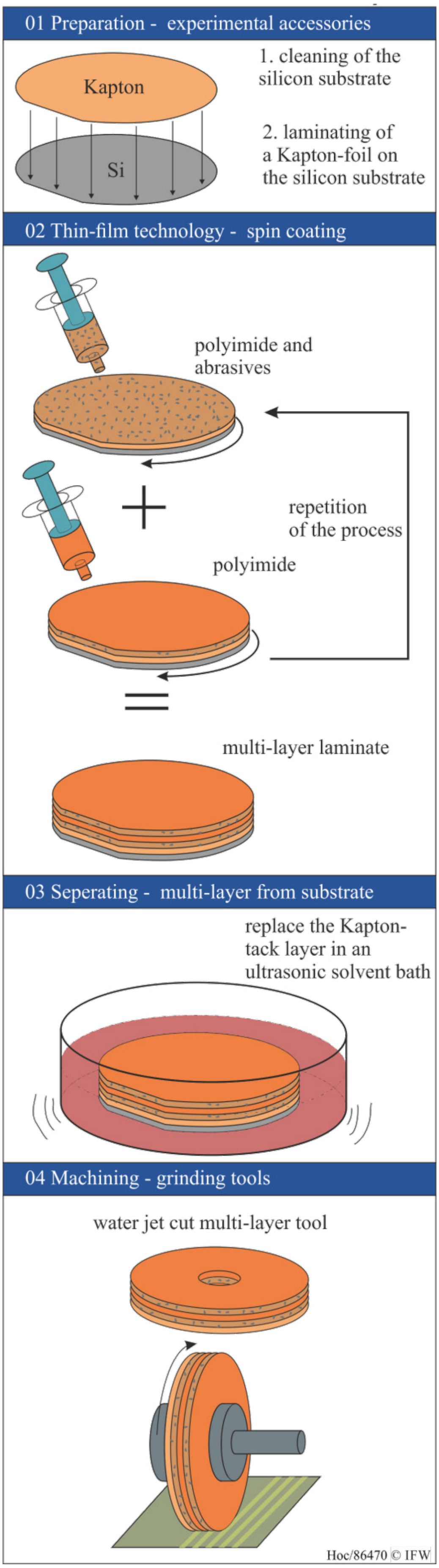

Fig. 1. Manufacturing process of multi-layer tools

a photosensitive photoresist is mixed with abrasives. After polymerization, the photoresist has a high thermal stability, mechanical strength as well as beneficial wear resistance. For the first investigations, 4 g of silicon carbide with a size of 600 mesh (about 23 µm grain size) are mixed with 40 ml of polyimide. The silicon carrier with the Kapton layer is placed on a rotary table and the mixture is applied. The table is turned until a uniform layer occurs. The thickness of the layer depends on the rotary speed and the size as well as the number of grains. For the described prototype, a layer of 45 to 50 µm is achieved. After the application, the polyimide-abrasive-layer is dried in a soft baking process at 100°C and exposed to UV light to polymerize the layer. On top of the abrasive layer, a layer with clear polyimide is applied in the same way. This procedure is repeated two times so that a five-layer system occurs. Finally, the whole laminate received a hard bake at 200°C. With the conclusion of the spin coating process, the laminate is released from the silicon carrier in an ultrasonic solvent bath. The solvent only dissolve the silicon-containing adhesive. Figure 2 shows a cross sectioning of the final laminate with a total width of about 215 µm. It can be seen that due to the slightly thinner Kapton layer below, the laminate is not symmetrical. The monolithic tool has no boundaries between the abrasive and support layer and the SiC grains appear white under the microscope.

Fig. 2. Micro section of the five-layer laminate

After the manufacturing process, the laminate is clamped between two aluminum plates and cut by water jet cutting with a natural cutting abrasive consisting of SiO_2, Al_2O_3 and FeO and a jet pressure of 4000 bar. The finished multi-layer tool has dimensions of Ø52 mm x Ø40 mm.

3. Experimental Setup

The prepared multi-layer ring is clamped in a conventional flange for dicing blades with an outer diameter of 49 mm. Therefore, the protrusion of the tool is 1.5 mm. The flange is fixed on a HSK E-40 shrink chuck with an adapter. This tool is clamped in the five-axis high-precision milling machine Röders RFM 600 DS. Prior to the grinding experiments, the multi-layer tool needs pre-treatment. Figure 3 shows two microscopic pictures recorded with the Keyence VHX 500 incident light microscope. The layers of the tool are still connected and it shows a brittle material removal behavior (figure 3a). To achieve a tool without runout and a uniform surface the tool is dressed. The dressing process is necessary for the reproducibility of the initial condition of the tool and the comparability between two parameter settings. The tools are dressed in several cycles with a ceramic bonded sharpening stone with a grain size of 9 µm and the parameters in table 1.

Table 1: dressing parameters.

dressing speed [m/s]	feed speed [mm/min]	axial feed per loop [µm]
50	60	80

After dressing, all five layers have the same radius around the circumference. The surface is smooth and the grains within the abrasive layers are visible (3 b).

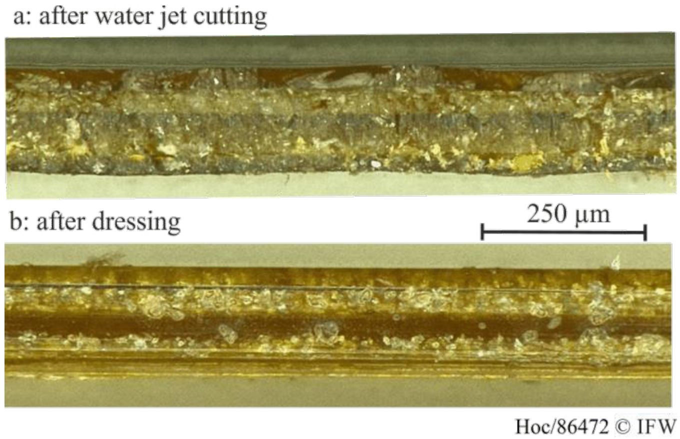

Fig. 3. (a) Laminate after water jet cutting; (b) Laminate after dressing

The rectangular-shaped workpieces are made of AISI 420 and the investigated surface is wet ground in six and polished in two further steps until a reflecting surface below Ra = 0.1 µm is reached. Only in this way, it is ensured that the influence of the grinding tool on the surface generation can be evaluated. In the next step, the specimen is clamped in the machine vise and adjusted with a digital 3D measuring probe.

4. Grinding investigations

The prepared multi-layer tool is used for the investigation of two parameter settings (table 2). Five paths are ground with the first setting before the explained dressing procedure is repeated.

Table 2. grinding parameters.

Setting	grinding speed [m/s]	feed speed [mm/min]	axial feed per loop [µm]
A	30	60	20
B	60	240	20

4.1 Grinding tool wear behavior

To investigate the alteration of the multi-layer tool, the 3D visualisation of the Keyence VHX5000 is used. All test with confocal devices or laser triangulation sensors fail due to the flexibility and width of the tool. However, figure 4 enables an evaluation of the tool wear behavior. It shows the tool profiles in direction of tool width after grinding.

After grinding with parameter setting A, small chips can be determined on the abrasive layers. The supporting layer on the right and the Kapton layer are set back, but the support layer in the middle has nearly the same height as the abrasive layers.

After grinding with setting B, the central support layer is set back significantly and the riblet structure can be visualized. A high number of chips is located on the abrasive layer. The reason for this is the equivalent chip thickness heq. The grains of the multi-layer tool in setting A have a heq of 40 µm whereas the grains in setting B have a heq of 80 µm. Due to the higher chip thickness, the supporting layer is set back and the grains are still cutting. Test with even higher heq caused a delamination for this tool specification.

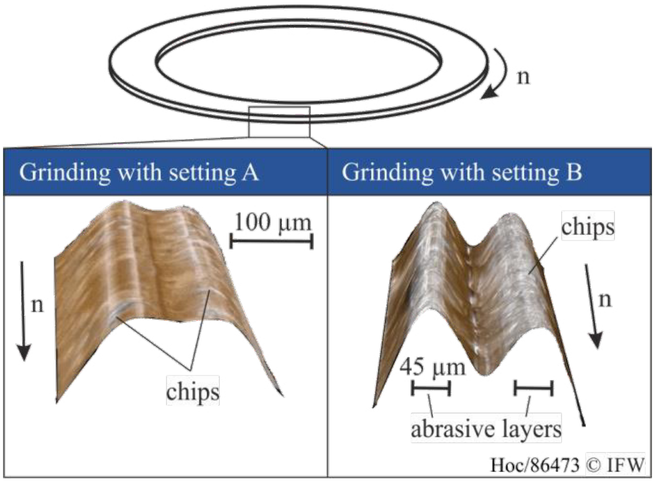

Fig. 4. Tool profiles in width direction after grinding AISI 420

4.2 Generation of riblet structures

The structured workpieces are measured with the 3D profilometer µscan of the company nano focus.

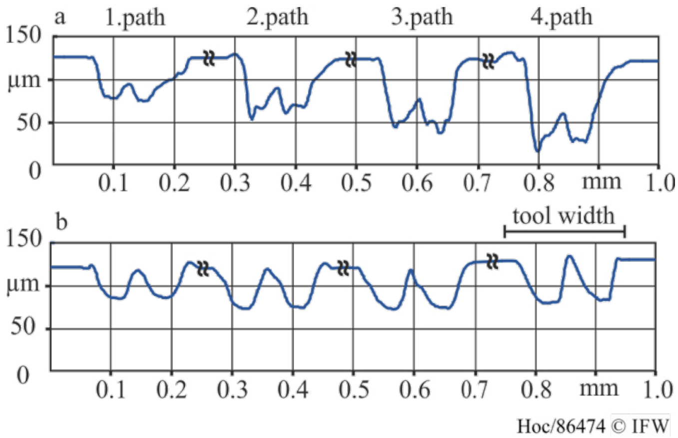

Fig. 5. Generated riblet profiles with parameter setting (a) A and (b) B

As figure 5 shows, the riblet structures created by setting A have an increasing depth. This is caused by a crooked workpiece surface. Apart from that, the single riblet of each path has a height of approximately 30 µm and a height-distance-ratio of 0.6. The riblet structures created by setting B have an average height of 50 µm, a height-distance-ratio of 1.1 and are significantly more uniform. This fact corresponds to the qualitative assessment of tool wear in Figure 4. According to Lietmeyer this height-distance-ratio is extremely beneficial to surface near flows [7]. Besides the presented parameter setting, investigations with a significant lower and higher equivalent chip thickness were conducted. So far, higher chip thicknesses result in delamination of the Kapton layer, layer breaks or a total failure of the multi-layer tool. Lower chip thicknesses cause a high process temperature and a melting of the tool in the subsurface. In this case, the tool is rubbing on the workpiece and no riblets are generated.

5. Conclusion and Outlook

In conclusion, the manufacturing of a flexible multi-layer tool is possible as well as the modification of layer thickness and grain concentration. Furthermore, process parameters for the new tool were found to generate riblets with an average height of 50 µm. Consequently, the new tool concept enables a more beneficial height-distance-ratio of riblets than profile grinding.

The presented novel grinding process needs further investigation and optimization. The next step will be the replacement of the Kapton layer by a metal coating. Similar to the adhesive layer this metal coating can be dissolved and future laminates will be symmetrical. In addition, the application of shadow masks is used to control the exact tool geometry during the exposure. After a detailed investigation of effects by cutting and feed speed as well as the depth of cut, different tool specification will be examined. In this process, the measurement of process forces, temperatures in the subsurface and variation of riblet structures will be examined. After this, the initial dressing step will be waived. Furthermore, the valuation of the tool behavior will be supported by SEM images.

The last step should be the modelling of the tool wear behavior and an adaption of the tool path to ensure an exact riblet height over a bigger surface. To improve the productivity the maximal number of layers will be investigated too.

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