Grinding of Riblets on Curved Paths

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Abstract. The grinding of riblets with multiple profiled grinding wheels is an efficient method to minimize the fluid friction on surfaces. In turbo machinery components, like pump impellers or compressor blades, the riblets must be ground with a curved tool path since the flow is rarely linear on such surfaces. This leads to angular errors in the generated riblet profiles and therefore requires the use of grinding wheels with smaller diameters. The tool wear increases due to lateral strain on the peaks of the grinding wheel. Consequently, the increased wear and the need of smaller tool diameters decrease the efficiency of the process. In this paper a structuring process with dicing blades was investigated in order to increase the economic viability of this process. A dressing operation for such tools is not necessary and thus reduces the non-productive time of the manufacturing process. Furthermore, profile tip wear has no negative effects on the aspect ratio of the generated riblets since the riblet geometry is determined by the thickness of the dicing blades.

Introduction

About a quarter of the 250 million MWh industrial energy demand per year in Germany is attributable to pump systems [1]. In some cases, the power consumption can be reduced by the usage of smaller pump systems or an optimized design of the operating point in order to get the demanded output [2]. However, when a large pumping capacity of several MW is required, those optimizations have already been made in most cases. Thus, new strategies for saving energy are required. Examples for the mentioned systems can be found in the areas of water supply and boiler feed pumps for power stations.

The largest loss of efficiency occurs as a result of the near-wall friction between the flowing medium and the pump surface. There are efficiency losses of up to 4.1 % that have been proven by these frictional losses [3, 4].

An approach from nature in order to minimize those friction losses is the skin structure of sharks. It has microscopic grooves that effectively reduce the flow resistance due to less occurring turbulences in the boundary layer transversely to the direction of flow. These structures are called riblets.

Therefore, riblets that are designed in direction of the flow can reduce the frictional resistance near the wall by up to 10 % [5, 6, 7] compared to a perfect smooth surface. Consequently, the pumping efficiency can be improved by up to 1.5 % [8]. However, the system efficiency is highly influenced by the geometry and dimensions of the riblet-structures. Experiments with different riblet-geometries at the German Centre for Aerospace have shown that an optimal aspect ratio of 0.5 riblet-height to riblet-width should be used [5]. The optimal dimensions of the riblets are furthermore affected by the velocity and viscosity of the flowing medium [9]. However, compressor blades of a gas turbine need suitable riblets with widths between 20 µm and 120 µm since flow conditions vary along the compressor blade. The optimal width of these structures can, due to a higher viscosity, be up to 200 µm if water is used as fluid [10, 11, 12]. Thus, manufacturing technology has to achieve a reliable, fluid adjusted and economically sustainable riblet structuring process for different riblet dimensions. Hereby, the present paper investigates the particular manufacturing process of impellers that are commonly used for power plant pumps.
Grinding of curved paths

The riblets are applied concentrically on the impeller using a surface grinding process. However, angular errors occur on the flanks of ground riblets due to the particular process kinematics between the grinding wheel and the material. When the grinding wheel is moved along a circular path the resulting contact line leaves its ideal path as it runs in parallel to the grinding wheel and does not follow the circular path (Fig. 1). Thus, material outside the desired contour is removed. This leads during left-handed paths to an angular error on the right flank and decreases the aspect ratio.

Different experiments with varying path radius $r_{\text{path}}$ and grinding wheel diameter $D_t$ have been carried out in order to investigate their influence on the angular error. The results have shown a decrease of the angular error if the path radius is increased with a constant grinding wheel diameter. Furthermore it was shown that the angular error is too low for measurement, if a grinding wheel diameter of 80 mm and a path radius of 60 mm are used. Therefore, the manufacturing of curved riblet-geometries by grinding is basically possible.

The critical path radius, which describes the point of unmeasurable angular error, linearly increases with the tool diameter. However, the grinding wheel diameter needs to be adjusted to the specific application since the path radius of riblet-structures is predefined. An analysis of the necessary path radii on the impeller has shown that grinding wheel diameters of less than 100 mm must be used for a reliable manufacturing process of the impeller.

Influence of feed rate and cutting speed

For the goal of an economic riblet production the influence of the grinding parameters feedrate $v_f$ and cutting speed $v_c$ was analyzed in analogous tests on tempered test specimens made out of G-X9CrNi13 which is commonly used for impellers. The experiments were carried out on a Blohm Profimat MC 407 grinding machine with oil as cooling lubricant. As the patterning of riblets is concentrically ground on an impeller, the experimental tests were also performed using a curved toolpath. A corresponding sample is shown in Fig. 2.
Figure 2: Analogy test on impeller material

The grinding path is about 80 mm long whereas $\Delta h$ is defined by the difference between the ideal and the real depth of the generated riblets. Furthermore, the radial wear $\Delta r$ is defined as the difference between $\Delta h$ at the beginning and the end of the grinding process. The radial wear for 1 m grinding path is presented in Fig. 3.

Figure 3: Influence of the cutting speed $v_c$ and the feed rate $v_f$ on the radial tool wear

The mechanical stresses of the abrasive grains are reduced due to the decreasing chip thickness at higher cutting speeds. Thus, tool tip wear can be significantly reduced by an increase of the average cutting speed up to 90 m/s (Fig. 3). Cutting speeds above 90 m/s lead to thermal workpiece damage and therefore require a more effective cooling concept. Contrary, up to a cutting speed of 60 m/s the influence of the feedrate is relatively low. However, profile tip wear at a feedrate of 1200 mm/min
is still up to 88 µm per 1 m toolpath which leads to a continuously decreasing aspect ratio. This tool wear is too high for suitable structuring of larger areas, if impeller riblets with a desired depth of about 10-30 µm are investigated. With feedrates of 300 mm/min and below the tool tip wear can be reduced to 13 µm/m. This however, decreases the generated surface per time to an unacceptable level.

These results show that a productive manufacturing process of riblet-structures with common grinding wheels cannot ensure the required quality since riblets of several kilometers length are required for some components (e.g. Impellers). This issue becomes even more relevant if tools with a larger diameter are used since they cause significant angular errors in the generated riblet-profiles. This necessitates the use of tools with smaller diameters and thus inevitably leads to a reduction of the active abrasive surface and therefore to a substantially increased profile tip wear per mm toolpath. Consequently, a better tool concept is needed.

Metal bonded grinding wheels have also been investigated and seem to be better suited for the structuring of riblets as they show a lower profile tip wear per grinding path. However, due to the long lasting electric contact discharge dressing the nonproductive times increase significantly and therefore make the concept economically unsuitable.

**Alternative tool concept**

As an alternative for the manufacturing of riblets dicing blades can be used. These dicing blades are available with a minimum thickness of 15 µm and can be used directly for the structuring of the riblets because their shape corresponds to the negative of the riblet-profile. To compensate the occurring wear the depth of cut must be increased accordingly. No dressing process is needed so that the nonproductive times are reduced to a minimum.

In order to grind multiple riblets simultaneously the formerly used grinding wheels were dressed with up to 30 profiles next to each other in the abrasive coating. In Fig. 4 the used dicing blades are shown. To achieve a higher efficiency six dicing blades were combined to a single tool and consequently tested.

![parallel use of six dicing blades](image)

**Figure 4: Tool concept with dicing blades**

Fig. 5 shows the fully structured surface of an impeller with an associated profile scan of the created surface. The supernatant of the six dicing blades varies from 900 µm to 1200 µm. Therefore, it is hard to achieve a homogenous surface. The targeted dimensions of 40 µm width and 20 µm depth are partially achieved. The tool wear of the dicing blades is about 0,05 µm per 1 m
toolpath and thus significantly lower than with standard grinding wheels. This wear can easily be compensated with an increasing depth of cut.

![Riblet-structures](image)

**Figure 5: Machined riblet-structures**

**Process parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_t$</td>
<td>800 mm/min</td>
</tr>
<tr>
<td>$n_{dicing}$</td>
<td>28 000 min$^{-1}$</td>
</tr>
<tr>
<td>$a_e$</td>
<td>20 µm</td>
</tr>
</tbody>
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**Dicing blade**

- D4-6 nickelbond
- $d_e = 54$ mm
- $b_e = 30 - 35$ µm

**Measuring device**

- NanoFocus AG Optical Profilometer µScan®

**Summary and outlook**

In this paper it has been shown that an economic production of riblets with vitrified bonded CBN grinding wheels is not possible. The profile tip wear from 13 µm up to 88 µm per 1 m toolpath at cutting speeds of 90 m/s is too high in order to achieve an acceptable aspect ratio for long grinding paths. Curved paths require the use of grinding wheels with a smaller diameter and thus increase the problem. By using dicing blades a sufficiently high aspect ratio for long grinding paths can be achieved. The tool wear is about 0.05 µm per 1 m toolpath and thus significantly lower compared to the formerly used grinding wheels. The occurring wear can be compensated without redressing, which considerably reduces the non-productive times of the process.

In further research activities the increase of the process reliability of this novel structuring process will be investigated so that a homogenous and reproducible structuring of impellers becomes possible.

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![Federal Ministry of Economics and Technology](image)
References


