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Tools and strategies for grinding of riblets on freeformed compressor blades

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Abstract

A major goal in the design of turbomachinery is the increase of efficiency. To attain this increase, the flow losses must be reduced. A substantial proportion of the losses is generated by skin friction between compressor blades and working fluid. With respect to smooth surfaces, micropatterns (riblet-structures) reduce skin friction in turbulent flow by up to 10 %. Grinding with multiprofiled wheels is an effective method for the manufacturing of riblet-structures on large plane surfaces. However, the grinding wheel wear affects the accuracy of the riblet geometry and the efficiency of the manufacturing process. Therefore, this paper shows the potential of different grinding wheel types for the manufacturing of riblet structures on an industrial scale with regard to tool wear. The results show that vitrified bonded tools are not suitable for the structuring of compressor blades. Here, axial forces lead to high profile wear. In contrast, grinding wheels with a metal bond are more wear resistant. However, the dressing process of metal bonded tools is time-consuming and causes 80% of the total machining time. As a consequence, just one blade can be structured per day. To increase the efficiency, a new grinding wheel was developed, which is bionically inspired by beaver teeth. The tool is constructed of alternating layers consisting of metal bonded diamonds and pure resin respectively. With this layer-by-layer setup, the tool does not have to be dressed and enables structuring of up to 50 compressor blades per day.

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Keywords: grinding, micro pattern, grindind wheel design, riblets

1. Introduction

Bionic structures have exceptional properties. For example, lotus leafs are dirt-repellent due to micro patterns on their surface (lotus effect) [1]. Geckos have branched nanohairs on the feet to cling on virtually any surface (gecko effect) [1]. Another important micro pattern, which can be used in the industry, can be found on shark skin. The skin of a shark is not smooth. Due to small ribs, called riblets, the skin feels rough. Investigations show that ideal riblets reduce skin friction up to 10 % [1,2]. Skin friction limits the efficiency of different continuous-flow machines like pumps or turbines [3]. Therefore, the use of riblets structures in the industry has great potential (fig. 1). For example, ideal riblets with an aspect ratio of 0.5 and a width between 20 µm and 60 µm can improve the efficiency of a turbine by about 0.2% [4]. As a result, about 400,000 t kerosene can be saved per year. The benefit of riblets in pumps is even higher. Here, riblets increase the efficiency about 1.5 %. Pumps are the largest energy consumers in industry [5].

Nomenclature

a_e	depth of cut
b_s	width of the grindig profile
CBN	cubic boron nitride
F_a	axial force
h	riblet-heigth
l_{max}	maximum contact length
$r_{eq,max}$	maximum equivalent grinding wheel radius
R_{max}	maximum grinding wheel radius
R_{path}	tool path radius
R_{WZ}	workpiece radius
R_{WS}	grinding wheel radius
s	riblet-width
SIC	silicon carbide

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v_c	cutting speed
v_f	feedrate
X	axis
X_L	length in X direction
Z	axis
Z_B	width in Z direction
α	angle
Δr_{sw}	radial profile wear
Δr_0	radial profile wear after 0 mm grinding length
Δr_{1300}	radial profile wear after 1300 mm grinding length
σ_{max}	maximum stresses

To use the potential of micro patterns, manufacturing processes are required, which economically generate micro patterns in a high quality. Compared to laser machining, EDM, micro milling and micro planing, grinding with multi-profiled wheels has been established as an effective method for generating riblet-structures on large scale surfaces [6]. So far, riblet-structures with an aspect ratio of 0.5 and a width of 60 µm have been ground on single curved NACA6510 profiles whereby a reduction of the near wall friction of about 4 % has been achieved [7]. In contrast to NACA-profiles actual compressor blades have double curved or freeform surfaces. These surfaces have to be machined employing a five-axis-grinding process. Therefore, additional requirements on the grinding process (such as complex contact conditions) have to be considered [8]. For example, the tool paths have to be curved in order to follow the curved stream flow. Such complex tool paths were used for example for belt-grinding in mould manufacturing [9].

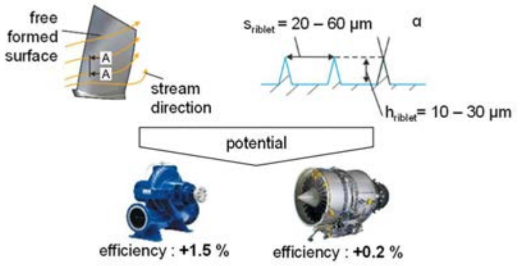
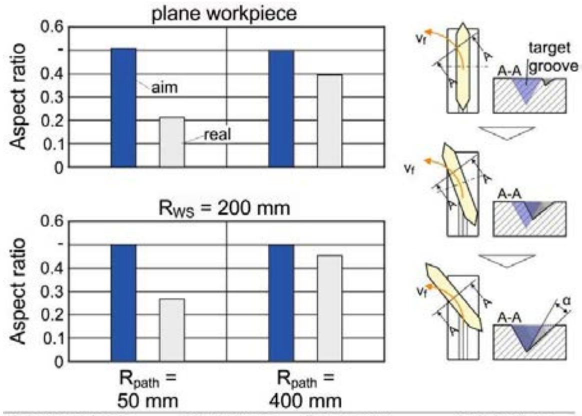


Fig. 1. Benefits of riblet-structures

The effect of five-axis motion on the ground riblet-structures is unknown. To close the research gap in structuring of freeform surfaces, the relevant influencing factors on the accuracy of the riblet-geometry in five-axis-grinding of riblet structures on double curved compressor blades are investigated. Thus, this paper considers the potential of different grinding wheel specifications for the manufacturing of riblet structures on an industrial scale with regard to tool wear.

2. Grinding wheel geometry

Grinding of riblets on flat surfaces with a straight tool path is well investigated [6]. In this process the ground groove is influenced only by the shape of the grinding wheel profile. Due to the straight contact length, the process kinematic can affect the riblet-geometry in case of five-axis-grinding. To investigate the influence of the five-axis-kinematic on the riblet quality, grinding experiments were done. The workpieces were made of soft obomodulan material in order to neglect tool wear.



Grinding wheel:	**Workpiece:**	**Parameter:**	**Lubrication:**
R_{WZ} = var.	Obomodulan	a_e = 50 µm	synth. ester
SIC, vitrified bonding	R_{WS} = var.	v_f = 120 mm/min	
V-profile, 60°	R_{path} = var.	v_c = 30 m/s	

Fig. 2. Expected and real aspect ratio for five-axis grinding

Fig. 2 illustrates the effect of tool path and workpiece radius on the aspect ratio. Riblets with an aspect ratio of nearly 0.5 were only obtained for $R_{path} \geqslant 400$ mm and a curved workpiece. In all other cases, smaller aspect ratios were obtained. Smaller tool path radii and larger convex workpiece radii lead to a decreased aspect ratio. As a result, flat workpieces and a tool path radius of 50 mm generates the smallest aspect ratio of 0.2. This deviation from the ideal case is caused by undercuts resulting from the contact conditions of grinding wheel and workpiece. On the right of Fig. 2, it is illustrated how undercuts occur. To grind ideal riblets, the target groove has to be ground in cross section A-A. Due to the straight contact length, the grinding wheel removes in cross section A-A material outside of the target groove. When the grinding wheel moves forward on the curved tool path, the remaining material will be removed and an undercut results. As a consequence, the width of the ground groove will be enlarged and the face angle of the groove differs from the targeted one. Undercuts can be avoided when the contact length is small enough and the contact area fits into the target groove. Since the tool path radius is defined by the streamflow and therefore fixed, the grinding wheel geometry must be adapted to prevent the occurrence of undercuts.

This knowledge was used to calculate the maximum applicable diameter of the grinding wheel in dependence on the tool path radius. The mathematical description of the target geometry that is needed for the calculation of the maximum grinding wheel diameter bases on a 2D calculation (fig. 3). Here, the target geometry is represented by a circle segment within a coordinate system. The coordinate origin is located in the centre of the groove. The circle segment starts at (0, Z=s/2).

The maximum contact length is calculated in the next step. In order to grind ideal riblets, the whole contact length must fit into the target geometry. Otherwise, undercuts occur. The positon of maximum contact length depends on Z. In case of a triangular grinding wheel profiles, the maximum contact length is in the centre of the groove. For grinding wheels with