## OPTIMAL APPLICATION OF RIBLETS ON COMPRESSOR BLADES AND THEIR CONTAMINATION BEHAVIOR

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### ABSTRACT

During the last decades, riblets have shown a potential for viscous drag reduction in turbulent boundary layers. Several investigations and measurements of skin-friction in the boundary layer over flat plates and on turbomachinery type blades with ideal riblet geometry have been reported in the literature. The question where riblets must be applied on the surface of a compressor blade is still not sufficiently answered. In a first step, the profile loss reduction by ideal triangular riblets with a trapezoidal groove and a constant geometry along the surface on the suction and pressure side of a compressor blade is investigated. The results show a higher potential on the profile loss reduction by riblets on the suction side. In a second step, the effect of laser-structured ribs on the laminar separation bubble and the influence of these structures on the laminar boundary layer near the leading edge are investigated.

After clarifying the best choices where riblets should be applied on the blade surface, a strategy for locally adapted riblets is presented. The suction side of a compressor blade is laser-structured with a segmented riblet-like structure with a constant geometry in each segment. The measured profile loss reduction shows the increasing effect on the profile loss reduction of this locally adapted structure compared to a constant riblet-geometry along the surface. Furthermore, the particle deposition on a riblet-structured compressor blade is investigated and compared to the particle deposition on a smooth surface. Results show a primary particle deposition on the riblet tips followed by an agglomeration. The particle deposition on the smooth surface is stochastic.

## NOMENCLATURE

c	[m]	chord length
c <sub>f</sub>	[-]	skin friction coefficient
С	[m <sup>-3</sup> ]	particle concentration
C <sub>p</sub>	[-]	pressure coefficient
d	[m]	focus diameter
h	[m]	riblet height
h <sub>pl</sub>	[m]	longitudinal protrusion height
h <sub>pc</sub>	[m]	crossflow protrusion height
i	[°]	angle of incidence
1	[m]	length of flat plate
m	[g]	mass
М	[-]	Mach number
n	[-]	number of measurements / particles
p <sub>stat</sub>	[Pa]	static pressure
p <sub>tot</sub>	[Pa]	total pressure
Re	[-]	Reynolds number

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8	[m]	blade pitch
S	[m]	riblet spacing
s <sub>i</sub>	[m]	riblet spacing
$s^+ = \frac{su_{\tau}}{v}$	[-]	dimensionless riblet spacing
Т	[s]	measurement period
u <sub>τ</sub>	[m/s]	(skin) friction velocity
$\overline{U}, \overline{V}, \overline{W}$	[m/s]	average velocities
u´,v´,w´	[m/s]	turbulent velocity components
$y^+ = \frac{yu_{\tau}}{v}$	[-]	dimensionless distance
Greek symbols		
α	[°]	flow angle
β	[°]	blade angle
η	[Pa s]	dynamic viscosity
λ	[°]	setting angle
ν	$[m^2/s]$	kinematic viscosity
ρ	[kg/m³]	density
τ	[N/m <sup>2</sup> ]	wall shear stress
$\tau_0$	[N/m <sup>2</sup> ]	wall shear stress of a smooth surface
φ	$[m^2]$	calibration factor
ω	[-]	pressure loss coefficient
Subscripts		
+		non-dimensional, in wall coordinates

00	environmental conditions
0	reference
1,2	cascade upstream/downstream
	conditions
in	inlet/upstream flow conditions
ex	exit/downstream flow conditions
particle	particle
ref	reference side
riblet	riblet surface
smooth	smooth surface
stat	static
tot	total

## INTRODUCTION

The goal to save fossil fuel and to reduce the emissions of  $CO_2$  can be realized on two different ways: 1. by replacing fossil energy by renewable energy and 2. by increasing the efficiency of established power conversion techniques. This paper shows one opportunity of increasing the efficiency of modern turbomachinery, e.g. the efficiency of the compressor. A major part of the flow losses in a compressor is generated by skin friction on the blades mainly created in turbulent boundary layers.

Riblets have proven to reduce skin friction and wall shear stress in turbulent flow up to 10% compared with smooth surfaces. Riblets are tiny ribs on the surface aligned with the mean flow direction. The first publication on the exploration of riblets manufactured by industrial machining processes (Oehlert and Seume [1]) shows a brief overview of riblet research which is summarized here for readers convenience:

First investigations were motivated by the oil crises in the 1970s. NASA investigated the fuel saving potential of riblets applied to aircraft bodies and wings. During these investigations periodical structures were found near the wall characterizing areas of increased and reduced velocity. They are produced by vortices creating interference and turbulent shear stress. Walsh [2] showed the drag reducing effect of such riblets on flat plates.

Reif et al. [3] detected tiny ribs in streamwise direction on the scales of fast swimming sharks which reduce skin friction. Since then, most investigations concerning the benefit of riblets as a passive means of reducing skin friction and friction losses have been performed on flows with simple geometries, mostly on flat plates. For complex flows, such as in cascades, few investigations have been carried out.

Fang et al. [4] investigated a NACA-65-0010 compressor cascade at  $Re = 1.8 \cdot 10^5$ . They applied riblets only on the pressure side of the blades and obtained more than 10% loss reduction. According to Fang, the application of riblets on the suction side might suppress turbulence activity and thus weaken the capability of avoiding separation which means loss increase.

Bechert et al. [5] extensively investigated the skin-friction reduction of various 2-D riblet geometries in the oil channel of the German Aerospace Center (DLR) in Berlin. The experiments were confined to flows with zero pressure gradients. It was found that the best skin friction reduction is achieved by blade-type riblets. In addition, trapezoidal grooved riblets were optimized as a good compromise between loss reduction and manufacturability for practical applications. These results are an essential basis for the investigations described in this paper, as the geometrical design of the chosen riblets is based on the results achieved in the oil channel.

Nagao and Breugelmans [6] investigated foils carrying riblets on three different types of compressor blades. In addition to а variation of the Reynolds number (Re = 150,000...400,000) they also varied the angle of attack  $(\alpha_{in} = 30^{\circ}...50^{\circ})$ . The spacing of the riblets was s = 120 µm. It was found that riblets performed best in the midspan section of the blade. Riblets were tested on suction and pressure side. However, Nagao and Breugelmans indicated that riblets on the suction side may increase skin friction as the Görtler instability may be enhanced which in turn promotes the laminar-turbulent transition.

Boese and Fottner [7] examined the effect on overall loss behavior of a highly loaded compressor cascade. The riblets used for the experiments were v-groove (s = 76  $\mu$ m, s = 120  $\mu$ m, s = 150  $\mu$ m). It turned out that these riblets were able to reduce the pressure loss coefficient  $\omega$  in the best case by up to 8%. The main positive influence was achieved by arranging riblets only on the suction side, which contradicts the results presented by Fang. In addition, the boundary layer thickness of the smooth blade and the blade carrying the riblet foil were identical. Experiments with trapezoidal grooves produced no influence on loss behavior.

Most of the mentioned investigations were carried out by applying a foil carrying small ribs of constant geometry. These ribs are often not adjusted to the dominating wall shear stress. So, the full potential of riblets to reduce the profile losses is still not utilized by its full extend. This paper shows the additional profile loss reduction potential of riblets which are adjusted to the dominating wall shear stress.

In addition, the question where riblets have to be applied on the surface of a compressor blade, is still not satisfactory answered. The effect of riblets on a laminar separation bubble is shown as well as the influence of riblets on a laminar flow appearing near the leading edge.

As shown in Oehlert and Seume [1] and in Oehlert et al. [8], first investigations of riblets produced with industrial manufacturing processes were very promising. The present paper is a continuation of applying these riblet-like structures to 2-D surfaces (NACA compressor foils). Results and further steps are presented.

### **EFFECTIVENESS OF RIBLETS**

The effectiveness of machined riblets on flat plates was illustrated in Oehlert and Seume [1]. A brief summary of the mechanism of riblet drag reduction is given here for the readers' convenience:

"The mechanism of drag reduction caused by riblets occurs only in turbulent flow conditions. The boundary layer can be divided into three parts with the viscous sublayer nearest to the wall, the log-linear region, and the wake region which adjoins the surrounding potential flow.

In the viscous sublayer turbulent oscillating velocities and low speed-streaks can be detected as shown in Figure 1. These low speed streaks carry slow fluid from the wall to the main flow ('ejections') and, in order to fulfill continuity, fast high energy fluid is transported to the wall ('sweeps'). Low speed and high speed streaks are characterized by vortices. Figure 2 shows these vortices in lateral view.

Fluid momentum transport as described above generates turbulent shear stress. Sweeps and ejections always need and always create a cross flow. Turbulent shear stresses which are created by vertical fluid motion are always accompanied by cross flow. When the cross flow is suppressed, the vertical motion is also suppressed, which reduces shear stresses and skin friction. Riblets are able to hamper the cross flow (Bechert et al. [5]).

The parameter which matters for the reduction effect on the cross traverse is the height difference  $\Delta h$  between the virtual origins of longitudinal and cross flow according to Figure 4. For a given geometry,  $\Delta h$  according to Bechert et al. [10] is a constant fraction of the lateral rib spacing s:  $\Delta h_{p,max}$ =0.132 s."

The investigated riblet surfaces have been specially designed for application on NACA 6510 blades (Oehlert and Seume [1]). Since the first design step several improvements in

riblet-machining and in riblet design calculation have been fulfilled in order to increase the effectiveness of the riblets.



Figure 1. LOW SPEED-STREAKS IN VISCOUS SUBLAYER (Cantwell, Coles, Dimotakis in van Dyke [9])



Figure 2. VORTICES IN THE VISCOUS SUBLAYER (Cantwell, Coles, Dimotakis in van Dyke [9])



Figure 3. VISCOUS LONGITUDINAL AND CROSS FLOW ON A RIBBED SURFACE WITH  $\Delta h = h_{pl} - h_{pc}$  (Bechert et al. [10])

## **DESIGN OF RIBLETS**

Based on the experimental results of several scientific investigations concerning the design of riblets – especially on the results of Bechert et al. [5] - the trapezoidal groove geometry has been chosen as a compromise of structural strength and aerodynamic effectiveness (Figure 4).



Figure 4. THE EFFECT OF DIFFERENT RIBLET GEOMETRIES ON WALL SHEAR STRESS (Bechert et al. [5])

In addition, Bechert et al. also showed, that a dimensionless riblet width  $s^+$  according to

$$\mathbf{s}^{+} = \mathbf{s} \left( \frac{\mathbf{u}_{\tau_{\mathbf{W}}}}{\mathbf{v}} \right) \tag{1}$$

of  $s^+=17$  will reduce wall shear stress best (Figure 4). Having selected the shape of the riblets, the design calculations were started. As a carrier profile a NACA 6510 compressor stator vane is chosen. The numerical investigation of the flow conditions on the suction side of the NACA profile were performed with MISES, a code for the analysis of blade aerodynamics (Oehlert and Seume [1]). The test conditions are listed in Table 1. The blade is equipped with pressure taps on the suction side (7 holes) and on the pressure side (4 holes).

Table 1. COMPRESSOR BLADE SPECIFICATIONS

blade pitch s [mm]	65
chord length c [mm]	90
setting angle λ [°]	48
flow angle $\alpha_{in}$ [°]	60
flow angle $\alpha_{ex}$ [°]	129.7
M <sub>in</sub>	0.5
Re <sub>in</sub>	10 <sup>6</sup>

The chosen profile is characterized by a transition which begins at a dimensionless chord length of x/c = 4% on the suction side and at x/c = 8...10% on the pressure side. In the first iteration step a constant riblet geometry for the whole profile length is designed. The chosen riblet width of s=40 µm in comparison to the ideal riblet width for s<sup>+</sup>=17 as one result of the calculation is shown in Figure 6.



Figure 5. DEFINITION OF ANGLES [Wilson, Korakianitis [11]]



Figure 6. MISES CALCULATION OF IDEAL RIBLET WIDTH FOR s<sup>+</sup>=17 AND COMPARISON TO THE CHOSEN CONSTANT RIBLET WIDTH OF s=40  $\mu m$ 

Near the leading edge the designed riblets are obviously too high. An increasing effect caused by the riblets working as hydraulic rough elements can occur. In Figure 7 the expected reduction of wall shear stress is illustrated for different riblet widths. The negative effect of riblets near the leading edge can not yet be considered in numerical simulations. Therefore, the best effect for riblets which are applied over the whole profile length is shown in Figure 7. Experimental results presented later will show that it is more effective to start structuring after transition has ended in a fully turbulent flow.

The designed ideal riblet geometry of the first iteration step is shown in Figure 8.



Figure 7. CALCULATED REDUCTION OF WALL SHEAR STRESS ACCORDING TO THE CHOSEN RIBLET WIDTH s



Figure 8. DESIGNED RIBLET GEOMETRY

Riblets were not applied on the side walls for following reasons:

- 1. Riblets well adapted to the side wall flows outside separation zones may actually reduce the flow losses further. They were not considered here for design and manufacturing reasons.
- 2. Streamlines on the sidewalls are strictly depending on the operating point and therefore it is difficult to choose the right riblet-orientation.
- 3. If riblets were applied to reduce the flow losses in the separation zone, the effect might actually be contra productive because the secondary flows induced by the separation may be augmented.

## EXPERIMENTAL SETUP FOR AERDODYNAMIC MEASUREMENTS

## Linear Cascade Wind Tunnel

The aerodynamic measurements on NACA 6510 compressor blades with riblets are performed in the linear cascade wind tunnel of the Institute of Turbomachinery and

Fluid Dynamics. This wind tunnel has already been approved for the measurements of the profile losses of flat plates (Oehlert and Seume [1]) and for the exploratory experiments on NACA 6510 compressor blades with laser-structured and ground riblets (Oehlert et al. [8]).

The linear cascade wind tunnel (Figure 9) is supplied with air by three parallel screw-type air compressors with a mass flow of up to 11 kg/s. The compressed air first passes an air cooler and later a tube flow straightener to homogenize the flow before it enters the vertical section. There the flow is first decelerated in a settling chamber equipped with a flow conditioner in order to achieve homogeneous flow conditions. Subsequently, the flow is ducted from the circular into a rectangular tube section. The flow enters the linear cascade wind tunnel through a turbulence grid to induce a turbulence intensity of approximately 4% in the cascade inlet plane. The angle of the swivelling head can be adjusted to the desired angle of attack of the investigated blade cascade. The position of the side walls is variable to adjust the cross section of the vertical section to the individual setup of the wind tunnel, given by the investigated blade cascade and the angular position of the swivelling head.



Homogenous flow conditions at the inlet of the cascade are disturbed by developing boundary layers on the walls in the vertical section of the wind tunnel and by corner stalls at the blades transition to the side walls. To counteract the effects, the boundary layer thickness and their disturbing effects on the measuring section are reduced by a boundary layer suction system (Figure 10).

## Instrumentation

The inlet flow conditions are measured with a temperature sensor and a Prandtl probe which is installed approximately 0.35 m in front of the cascade inlet plane. The pneumatic wake measurements along the central blade row, which is divided into a reference and probe section, are carried out with two three-hole wedge-type probes for the determination of profile losses (Figure 10). These probes measure the static and total pressure and the flow angle in 60 positions along a pitch distance in a parallel plane 50 mm downstream to the outlet plane of the cascade. The distance between the wedge-type probes is 40 mm.



Figure 10. BLADE CASCADE WITH BOUNDARY LAYER SUCTION AND WAKE TRAVERSE SYSTEM WITH DOUBLE WEDGE-TYPE PROBES

For comparability of all overall pressure loss coefficients  $\omega$  of the tested surface structures, the cascade exit flow conditions are reduced to one-dimensional data by applying the averaging procedure of Amecke [13]. These values are used to calculate the pressure loss coefficients  $\omega$  from inlet and outlet velocity and pressure distribution. The profile loss coefficient is given as follows:

$$\omega = \frac{p_{tot,2} - p_{tot,1}}{p_{tot,1} - p_{stat,1}}$$
(2)

To determine the effect of riblets and their influence on the profile loss coefficient the difference in the loss coefficient is calculated:

$$\frac{\Delta\omega}{\omega} = \frac{\omega - \omega_{ref}}{\omega_{ref}}$$
(3)

In Eq. (3)  $\omega$  is the loss coefficient of the riblet-structured blade and  $\omega_{ref}$  the loss coefficient of the smooth reference blade.

To adjust the correct inlet flow angle the static pressure is measured in seven positions on the suction side and in four positions on the pressure side.

## **Flow conditions**

The influence of riblets on the profile loss was investigated for a Mach number of M = 0.5 and a Reynolds number of  $Re = 10^6$ . The correct adjustment of the inlet flow angle was validated by a comparison of experimental and calculated data of the pressure coefficient  $C_p$  which is exemplarily shown in Figure 11. The pressure coefficient  $C_p$  is calculated from the measured local pressure  $p_{local}$  on the blade surface and the inlet flow conditions:

$$C_{p} = \frac{p_{local} - p_{stat,1}}{p_{tot,1} - p_{stat,1}}$$
(4)



Figure 11. PRESSURE COEFFICIENT  $C_p$  FOR  $\alpha_{in}$ =60°

## EXPERIMENTAL SETUP FOR DUST CONTAMINATION MEASUREMENTS

### **Dust Channel**

Preliminary investigations to the dust contamination behavior of riblet structured compressor blades are performed in a separate wind tunnel (dust channel, see Figure 12). The flow is homogenized in a flow conditioner within a settling chamber. Downstream of the settling chamber the cross section is reduced to 403 mm x 403 mm and the flow is entering the test section with the blade cascade consisting of three blade rows carrying NACA 6510 compressor vanes. The blade specifications are equal to the blades investigated in the linear cascade wind tunnel (Table 1). In comparison to the cascade wind tunnel the flow velocity in the test section of the dust channel is lower, with a maximum Mach number of M $\approx$ 0.12.

The aerosol of air and solid particles is generated with a particle disperser which allows a fine adjustment of the particle concentration upstream of the blade cascade. To adjust the particle concentration to the desired value the particle concentration is measured with a laser 2-focus velocimeter (L2F) in front of the cascade.



Figure 12. EXPERIMENTAL SETUP FOR DUST CONTAMINATION MEASUREMENTS

The contamination is homogenously focussed onto the central blade row in which two small profiles are inserted (reference and test blade). As shown in Figure 13 the height of these profile sections is lower compared to the profiles investigated in the cascade wind tunnel so that the

contamination can be quantified by weighing in an analytical balance with a high resolution.



Figure 13. BLADE SECTIONS FOR DUST CONTAMINATION MEASUREMENTS

## **EXPERIMENTAL RESULTS**

#### Influence of ideal riblets on the profile loss

First the influence on the profile losses by ideal riblets on the suction and pressure side of the NACA 6510 compressor vane was investigated. The ideal riblet structure (Figure 14) was produced on a foil and is characterized by triangular ribs with a sharp tip and a trapezoidal groove. The riblet geometry with a constant spacing of s=40  $\mu$ m and height of h=20  $\mu$ m parallel to the flow direction along the blade surface is a good compromise concerning the achievable drag reduction. This structure represents the target geometry for the laser-structuring and grinding processes in this project. Therefore, the reduction of the profile losses measured for compressor blades with ideal riblet structures deliver the reference to evaluate the experimental results of the laser-structured blades presented later.



Figure 14. IDEAL RIBLET STRUCTURE ON A FOIL

For tests with the riblet foil, a thinner NACA 6510 compressor vane with a constant offset was manufactured. The magnitude of the offset was the cumulative thickness of the riblet foil and of an adhesive film. The leading and trailing edge was thickened with filler and milled using the same CNC program as for the blades without offset. Thus a pocket was generated on the suction and pressure side with a smooth leading and trailing edge. So a triggering of the boundary-layer transition or the repression of a laminar separation bubble and

their additional effect on the profile loss can be excluded. For the investigations with a smooth suction or pressure side a smooth foil was used with the same thickness as the riblet foil.

To avoid influences on the profile losses due to geometrical differences by the manufacturing process, the same blade was used for all measurements and only the type of foil (riblet or smooth) was changed. The geometrical quality of all configurations was checked with a coordinate measuring machine. An exemplary comparison of the measured blade thickness  $\Delta t$  of the blade with the riblet foil on the pressure side and the same blade carrying a smooth foil on the pressure side is shown in Figure 15. The blade contour comparison shows a very good agreement of both geometries with a maximum difference of  $\Delta t = 20 \,\mu m$ . Therefore, aerodynamic effects by geometric differences in the airfoil shape are negligible.



Figure 15. COMPARISON OF BLADE THICKNESS: RIBLET VS. SMOOTH

Experimental results of the profile loss measurements and the change of the exit flow angle  $\Delta(\alpha_{ex} - \alpha_{ex,0})$  are presented in Table 2. The change of the exit flow angle  $\Delta(\alpha_{ex} - \alpha_{ex,0})$  is calculated with the exit flow angle  $\alpha_0$  of the reference blade as follows:

$$\Delta(\alpha_{ex} - \alpha_{ex,0}) = (\alpha_{ex} - \alpha_{ex,0})_{riblet} - (\alpha_{ex} - \alpha_{ex,0})_{smooth}$$
(4)

According to Figure 5 a negative  $\Delta(\alpha_{ex} - \alpha_{ex,0})$  characterizes a higher turning and a positive value a lower turning of the flow through the cascade.

For each configuration a minimum of ten wake traverse measurements were performed on at least two different measurement days and the average value of the profile loss coefficient was calculated. With riblets on the suction side a profile loss reduction of  $\Delta\omega/\omega = -4\% \pm 0.57\%$  and a higher turning with a change of the exit flow angle  $\Delta(\alpha_{ex}-\alpha_{ex,0}) = -0.047^{\circ} \pm 0.01^{\circ}$  compared to the smooth surface can be achieved. The measurement inaccuracy is indicated by the 95% confidence interval of the student-t distribution.

The profile losses by riblets on the pressure side are slightly lower compared to the smooth surface with  $\Delta\omega/\omega = -1.01\% \pm 0.54\%$ . The change in the exit flow angle is  $\Delta(\alpha_{ex}-\alpha_{ex,0}) = -0.039^{\circ} \pm 0.01^{\circ}$ . The smaller reduction of the profile losses by riblets on the pressure side can be related to

differences in the wall shear stress level between suction and pressure side which is lower on the pressure side due to lower flow velocities. Thus the wall shear stress on the suction side is dominating the overall profile losses and the riblet spacing and height on the foil is for the pressure side too small. These differences in the profile loss reduction by riblets on the suction side, compared to the pressure side, are in good agreement with the results presented by Boese and Fottner [7], but are in contrast to the results presented by Fang et al. [4].

With ideal riblets on the suction and pressure side the highest reduction in the profile loss coefficient with  $\Delta\omega/\omega = -4.90\% \pm 0.47\%$  can be achieved. Hence the profile loss reduction by riblets on the pressure and suction side seems to be additive. The increase in the turning reaches a maximum with  $\Delta(\alpha_{ex} - \alpha_{ex,0}) = -0.097^{\circ} \pm 0.01^{\circ}$ .

 
 Table 2. PROFILE LOSS REDUCTION BY IDEAL RIBLETS AND INFLUENCE ON THE EXIT FLOW ANGLE

	$(\omega - \omega_0) / \omega_0 [\%]$	$\Delta(\alpha_{ex} - \alpha_{ex,0}) [^{\circ}]$
Suction side	$-4.00 \pm 0.57$	$-0.047 \pm 0.01$
Pressure side	$-1.01 \pm 0.54$	$-0.039 \pm 0.01$
Suction an pressure side	$-4.90 \pm 0.47$	$-0.097 \pm 0.01$

# Profile loss reduction of riblets at pressure side incidence

Before applying the functional microstructures to the suction side of a compressor blade, it is important to know where to start the application of the structure in flow direction. First test's aim is to show whether riblets have an influence on a separation bubble. Therefore a laminar separation bubble (oil picture in Figure 16) at the leading edge on the suction side was created by changing the incoming flow angle towards a strong pressure side incidence.



Figure 16. LAMINAR SEPERATION BUBBLE NEAR THE LE TAKEN IN THE LINEAR CASCADE WIND TUNNEL

A laser-structured test blade is installed in order to investigate the influence of riblets starting at the LE and ending at the TE. Experiments were conducted for the inlet flow design angle and for a strongly increased pressure side incidence. Riblets applied in the region of the separation bubble are able to reduce the integral pressure loss coefficient  $\omega$  by  $\Delta\omega/\omega = -7.2\% \pm 1.8\%$ . In contrast the same blade shows an increase of  $\Delta\omega/\omega = +1.9\% \pm 1.4\%$  for the inlet flow design angle.

It is assumed that riblets eliminate the separation bubble by operating as a rough surface. Near the LE the boundary layer is very thin. The calculated size of the displacement thickness near the LE is  $\delta_1 \approx 0...03 \cdot 10^{-3}$  mm. The machined riblet height is h=18 µm. So riblets probably generate and accelerate the transition process before laminar separation can happen. Boese and Fottner [7] observed a very similar phenomenon and also assumed an influence on a laminar separation.

#### Influence of riblets on the transition

The geometry of the Laser-shaped riblets on the test blade L1 (Oehlert and Seume [1]) does not correspond well to the designed geometry. However, it is amazing that the microstructured blade shows a higher pressure loss coefficient than the smooth reference blade. The obvious impact on the transition process could be one reason. So a new test is run with another laser-structured test blade carrying more effective riblets - L3 in Figure 17. In order to detect the influence of riblets in a laminar flow near the LE, two test runs are operated. The first investigates the test blade L3 as shown in Figure 17. In the second run, the riblets in the region of x/c=0...0.04 were abraded. The reduction of the pressure loss coefficient of the riblet-structured blade compared to a smooth reference blade is  $\Delta\omega/\omega = -1.7\% \pm 2.1\%$  for the blade with the structured LE and  $\Delta\omega/\omega = -5.1\% \pm 1.4\%$  for the smooth LE. The reduction of the pressure loss coefficient is very high for the case with the smooth LE. The profile geometry could be slightly changed due to the removal of the riblets near the LE. Although there is no significant deviation of the geometry measurable with the applied measuring technique, small variations can already create a significant influence on the pressure loss.



Figure 17. SURFACE STRUCTURE OF THE LASER-STRUCTURED BLADE L3

This result supports the assumption that riblets breaching the boundary layer create a transition process and diminish the size of the laminar region. The friction loss in a transitional and a turbulent flow is higher than in a laminar flow. The high riblets near the LE additionally increase the loss as there is a roughness effect.

Hence riblets applied in a laminar region have to be very small – smaller than the boundary layer.

## Locally adapted riblets

Riblets with a constant width of s=40 µm and a height of h=20 µm along the blade suction side are a good compromise. The change of the dimensionless riblet width s<sup>+</sup> along the suction side for a constant riblet width s=40 µm in the turbulent boundary layer is shown in Figure 18. The highest drag reduction is achieved for a dimensionless riblet width of s<sup>+</sup>=17 with  $\Delta \tau/\tau \approx -8\%$ . For 0.14 < x/c < 0.46 the riblet width and thus the height (h/s=0.5) are obviously too big. Nevertheless, an increased drag can not be expected because s<sup>+</sup><30 and therefore only the riblet effectiveness in drag reduction is reduced (Figure 4). Downstream of x/c=0.46 the riblets are too small and hence the drag reduction is reduced as well.



Figure 18. s<sup>+</sup>-DISTRIBUTION ALONG THE SUCTION SIDE FOR A CONSTANT RIBLET WIDTH OF s=40  $\mu m$ 

To optimize the drag reduction, the riblet geometry has to be locally adapted to the flow conditions along the blade surface. Due to limitations in the riblet production technology a continuously change of the geometry along the surface is not feasible. A compromise is a segmentation of the surface with a constant riblet geometry optimized to the local flow conditions in each segment. The boundaries of the segments are chosen by a minimum tolerable s<sup>+</sup> which is s<sup>+</sup>=15.5 for the first segment and continuously decreasing with a minimum in the last segment with s<sup>+</sup>=11 (Figure 19). Thus a compromise between drag reduction and production effort is achieved.

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The riblet-like structures on the suction side were applied by laser-structuring in individual segments. Due to temporary technical manufacturing problems the riblets in the first two segments could not be generated. The comparison between the target and the laser-structured riblet-like geometry is summarized in Table 3.



Figure 19. s<sup>+</sup>-DISTRIBUTION ALONG THE SUCTION SIDE FOR SEGMENTED RIBLETS

compont	Tai	get	laser-structured			
segment	s [µm]	h [µm]	s [µm]	h [µm]	r [µm]	
1	30	15	-	-	-	
2	33	16.5	-	-	-	
3	38	19	37	20	2	
4	43	21.5	44	22	2	
5	50	25	52	26	3	
6	62	31	60	42	3	

Table 3. SEGMENTED RIBLET-GEOMETRY

The measured profile loss reduction of the segmented laserstructured blade is  $\Delta\omega/\omega = -1.92\% \pm 0.52\%$  (Table 4). The suction side was structured downstream of x/c=0.4 and the measured drag reduction  $\Delta\tau/\tau_0$  of laser-structured grooves compared to ideal riblets is about 50% lower. Transferred from the profile loss reduction of  $\Delta\omega/\omega = -4\%$  by ideal riblets a blade with laser-structured grooves with a constant height and width downstream of x/c≈0.4 would achieve a profile loss reduction of  $\Delta\omega/\omega \approx -1.4\%$ . This aspect shows the potential of an increase of the profile loss reduction of up to an additional 0.5% by the locally optimized riblet-like geometry.

The measured change in the exit flow angle is  $\Delta(\alpha_{ex} - \alpha_{ex,0}) = +0.015^{\circ} \pm 0.01^{\circ}$ . This different behaviour compared to ideal riblets could not be explained eventually.

Table	4.	PROF	LE L	OSS	REDU	CTION	BY	SEGN	IENTED
		RIBLE	T-LIKE	E STF	RUCTU	RES (	Т ИС	HE SU	JCTION
		SIDE	COM	PARE	D TO	IDEA	L RI	BLETS	WITH
		CONS	TANT	GEON	<b>IETRY</b>				

	$(\omega - \omega_0) / \omega_0 [\%]$	$\Delta(\alpha_{ex} - \alpha_{ex,0})$ [°]
Segmented riblet- like structure	$-1.92 \pm 0.52$	$+0.015 \pm 0.01$
Ideal riblets	$-4.00 \pm 0.57$	$-0.047 \pm 0.01$

### **Dust contamination**

Preliminary measurements to investigate the contamination behavior of riblets on compressor blades were carried out in the dust channel. There the blades were exposed to a particle laden flow with a mean particle concentration of  $C\approx 1.96\cdot 10^9$  m<sup>-3</sup> for 3 hours. This concentration is significantly higher than annual average concentrations of particles of 10 µm and less (PM<sub>10</sub>) found worldwide (see [14]) but was chosen in order to get a significant particle deposition on the blades. The Mach number in the cascade inlet was constant with M=0.12.

The concentration was qualitatively measured with a laser 2-focus velocimeter in the cascade inlet plane at different positions by counting the particles crossing one of the two laser focal points. The concentration C is calculated with the measured number of counted particles n during the measurement period T and the flow velocity u as follows:

$$C = \frac{n}{T \cdot u \cdot d \cdot l} = \frac{n}{T \cdot u \cdot \varphi}$$
(5)

The coefficient  $\varphi$  with the unit [m<sup>2</sup>] replaces the unknown dimensions of the measurement volume with the focus diameter *d* and the length *l* and has to be determined by a calibration in a flow with a previously known concentration. For all measurements a mineral dust with an average particle size of d<sub>p</sub>=3.8 µm was applied.

In a first step the contamination of a laser-structured blade with a constant riblet width of s≈40 µm and height of h≈20 µm along the blade surface was investigated (Figure 20) and compared to a smooth reference blade. The dust contamination on both blades was quantified by weighing in a high precision analytical balance type ME235S from Sartorius. The contamination of the blades in the dust channel was repeated six times in order to get an average value and the 95% confidence interval of the student-t distribution.

In Table 5 the mass difference  $(m_c-m_0)$  for both blades is shown with  $m_c$  for the mass of the contaminated blade and  $m_0$ for the mass of the blade with a clean surface. The comparison of the results for the smooth and the laser-structured surface shows no significant difference in the integral deposition behavior on the different surfaces.

In a second step the local particle deposition was investigated for a blade carrying a foil with the ideal riblet structure as shown in Figure 14 and a blade with a smooth foil. The operating conditions in the dust channel and the contamination time were the same as for the experiments with the laser-structured blade. The local particle deposition was qualitatively investigated with a microscope at three positions on the smooth and on the riblet surface (x/c=0.28, 0.61, 0.83). The comparison of both contaminated blades at the three positions along the surface is shown in Table 6 for the smooth surface and Table 7 for the surface with riblets.



Figure 20. SURFACE STRUCTURE OF THE LASER-STRUCTURED BLADE

 Table 5. COMPARISON OF CONTAMINATION: SMOOTH VS.

 RIBLET

	$(m_c - m_0)/m_0 [10^{-3} g]$
Smooth	$1.55 \pm 0.22$
Laser-structured	$1.59 \pm 0.12$

A comparison of the particle deposition along both surfaces allows the following conclusions:

- The contamination of the smooth and the riblet surface is increasing from trailing to leading edge due to an increase of the turbulent diffusion and a decrease of the wall shear stress.
- The particle deposition on the smooth surface is stochastic.
- The particle deposition on the riblet surface starts on the riblet tips followed by a particle agglomeration on the tips and later a merging of the agglomerations across the riblet valleys.

The particle deposition behavior along the riblet surface seems unexpected at first glance. But considering the influence of the riblets on the low speed streaks in the turbulent boundary layer there is an explanation for this phenomenon: The riblets are damping the turbulent oscillations in the boundary layer and therefore the low speed streaks are moved away from the surface. Thus these flow structures are only in contact with the riblet tips which explains the primary deposition of particles in this area. The influence of this particle deposition behavior on the profile loss is subject of future studies. It is expected that the aerodynamic effectiveness of riblets is not strongly influenced by the contamination because the grooves are less contaminated than the riblet tips.

### CONCLUSIONS

Systematic investigations on the influence of ideal triangular riblets with a trapezoidal groove and a constant geometry along the surface on the suction and pressure side of a NACA 6510 compressor vane were carried out in a linear cascade wind tunnel. With ideal riblets on the suction side, a profile loss reduction of 4% is achieved. The profile losses with riblets on the pressure side are reduced by 1.01% which can be a result of the lower wall shear stress level compared to the suction side. A maximum profile loss reduction of 4.9% is achieved with riblets on the suction and pressure side. The increase in the turning of the flow also reaches a maximum value for riblets on both sides of the blade with 0.097°.

Investigations with a strong pressure side incidence and a laminar separation bubble on the suction side show a significantly higher profile loss reduction by riblets of up to 7.2%. It is plausible that riblets eliminate the separation bubble by operating as a rough surface in the laminar boundary layer triggering earlier transition. This behavior is also shown under design conditions by applying riblets right from the leading edge. Compared to a smooth leading edge, the profile losses are significantly higher. This result supports the assumption that riblets breaching the boundary layer induce a transition process and diminish the size of the laminar region. The friction loss in a transitional and a turbulent flow is higher than in a laminar flow. The high riblets near the LE additionally increase the loss as there is a roughness effect.

First experiments on locally optimized riblet-like structures show the potential to increase the profile loss reduction compared to a surface with a constant riblet structure of up to an additional 0.5%. In future experiments, this surface structuring strategy will also be investigated on locally optimized riblets on the pressure side.

The integral particle deposition is investigated for a laserstructured blade with a constant riblet-like geometry along the blade surface by weighing the contaminated vane sections in an analytical balance. Preliminary investigations for an average particle concentration of  $C=1.96\cdot10^9 \text{ m}^{-3}$  and a contamination time of three hours show no significant difference in the integral deposition behavior between the riblet-structured and the smooth surfaces.

The local particle deposition was qualitatively investigated for a blade carrying a foil with the ideal riblet structure. The particle deposition on the riblet surface starts on the riblet tips followed by a particle agglomeration on the tips and later a merging of the agglomerations across the riblet valleys. The particle deposition on the smooth blade is stochastic.

Future experiments to investigate the contamination behavior of riblets will be carried out in the linear cascade wind tunnel under turbomachinery-like flow conditions. This test bench gives the opportunity to quantify the decrease of the loss reduction by riblets due to contamination.

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### REFERENCES

- Oehlert, K. and Seume, J., 2006, "Exploratory experiments on machined riblets on compressor blades", *Proc. of FEDSM 2006*, Miami, FL, USA, FEDSM 2006 – 98093
- [2] Walsh, M. J., 1983, "Riblets as a viscous drag reduction Technique", AIAA Journal, 21(4)
- [3] Reif, W.-E., 1985, "Squamation and ecology of sharks", Courier Forschungsinstitut Senckenberg, Frankfurt/Main, 78, ISBN 0341-4116
- [4] Fang, C., Yan-Ping, T., Mao-Zhang, C., 1990, "An experimental investigation of loss reduction with riblets on cascade blade surfaces and isolated airfoils", *Gas Turbine* and Aeroengine Congress and Exposition, Brussels, Belgium, 90-GT-207
- [5] Bechert, D. W.; Bruse, M.; Hage, W., van der Hoeven, J. G. T. and Hoppe, G, 1997, "Experiments on dragreducingsurfaces and their optimization with an adjustable geometry", *Journal of Fluid Mechanics*, 338, pp. 59-87
- [6] Nagao, S. and Breugelmanns, F.A.E., 1999, "Investigation of riblets in a CDB, DCA and 65-S compressor cascade", *Proc. of IGTC*, IGTC99Kobe TS-25
- Boese, M. and Fottner, L., 2002, "Effects of riblets on the loss behaviour of a highly loaded compressor cascade", *Proc. of AMSE Turbo Expo*, Amsterdam, The Netherlands, GT-2002-30438
- [8] Oehlert, K., Seume J., Siegel F., Ostendorf, A., Wang, B.; Denkena, B., Vynnyk, T., Reithmeier, E., Hage, W., Knobloch, K. and Meyer, R., 2007, "Exploratory experiments on machined riblets for 2-D compressor blades", *Proc. of IMECE2007*, Seattle, Washington, USA, IMECE 2007 - 43457
- [9] Van Dyke, M., 1982, "An album of fluid motion", The Parabolic Press, Stanford, California, USA
- [10] Bechert, D. W., Bruse, M., Hage, W. and Meyer, R., 2000, "Fluid mechanics of biological surfaces and their technological application", Naturwissenschaften 87, pp. 157-171, Springer Verlag
- [11] Wilson, D.G., Korakianitis, T., 1998, "The design of highefficiency turbomachinery and gas turbines", 2nd Edition, Prentice Hall Upper Saddle River, NJ/USA, ISBN 0-13-312000-7

- [12] Harbecke, U., Riess, W. and Seume, J., 2002, "The Effect of Milling Process Induced Coarse Surface Texture on Aerodynamic Turbine Profile Losses", *Proc. of ASME TURBO EXPO*, Amsterdam, The Netherlands, GT-2002-3033
- [13] Amecke, J., 1967, "Auswertung von Nachlaufmessungen an ebenen Schaufelgittern", report 67 A 49, AVA, Göttingen, Germany
- [14] World Health Organization, 2006, "Air Quality Guidelines, Global Update 2005", WHO Regional Office for Europe, pp. 31-40

# Table 6. DUST CONTAMINATION ALONG THE SUCTION SIDE OF THE SMOOTH BLADE



## Table 7: DUST CONTAMINATION ALONG THE SUCTION SIDE OF THE BLADE WITH IDEAL RIBLETS