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THE INFLUENCE OF TECHNICAL SURFACE ROUGHNESS ON THE FLOW AROUND A HIGHLY LOADED COMPRESSOR CASCADE

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ABSTRACT

A highly loaded compressor cascade which features a chord length that is ten times larger than in real turbomachinary is used to perform an investigation of the influence of technical surface roughness. The surface structure of a precision forged blade was engraved in two 0.3mm thick sheets of copper with the above mentioned enlarging factor (Leipold and Fottner, 1998). To avoid additional effects due to thickening of the blade contour the sheets of copper are applied as inlay's to the pressure and suction side. At the high speed cascade wind tunnel the profile pressure distribution and the total pressure distribution at the exit measurement plane were measured for the rough and the smooth blade for a variation of inlet flow angle and inlet Reynolds number. For some interesting flow conditions the boundary layer development was investigated with the laser-two-focus anemometry and the one-dimensional hot-wire anemometry. At low Reynolds numbers and small inlet angles a separation bubble is only slightly reduced due to surface roughness. The positive effect of a reduced separation bubble is overcompensated by a negative influence of surface roughness on the turbulent boundary layer downstream of the separation bubble. At high Reynolds numbers the flow over the rough blade shows a turbulent separation leading to high total pressure loss coefficients. The laser-two-focus measurements indicate a velocity deficit close to the trailing edge even at flow conditions where positive effects due to a reduction of the suction side separation have been expected. The turbulence intensity is reduced close downstream of the separation bubble but increased further downstream due to surface roughness. Thus not the front part but the rear part of the blade reacts sensitively on surface roughness.

NOMENCLATURE

C_f	[-]	skin friction coefficient
h	[m]	airfoil height
H_{12}	[-]	shape factor $H_{12} = \delta_1/\delta_2$
l, L	[m]	airfoil chord
Ma	[-]	Mach number
p, p_t	[Pa]	static pressure, total (stagnation) pressure
Ra	[µm]	arithmetic average deviation from centre line
Re	[-]	Reynolds number
Rz	[µm]	ten point height parameter
Rsk	[-]	skewness
S	[mm]	average spacing between local peaks
Sm	[mm]	average spacing of peaks over centre line
t	[m]	pitch
T_t	[K]	total (stagnation) temperature
Tu	[%]	local turbulence intensity
Tu_1	[%]	turbulence intensity related to freestream velocity
w	[m/s]	flow velocity
x, u, z	[m]	axial, circumferential, spanwise coordinates
x,y	[mm]	lateral coordinates
z	[µm]	surface height
β	[°]	circumferential (pitchwise) flow angle
β_S	[°]	stagger angle
δ	[m]	boundary layer thickness
δ_1	[m]	displacement thickness
δ_2	[m]	momentum thickness
ω	[-]	loss coefficient; $\omega = (p_{t1}-p_t)/(p_{t1}-p_1)$

Subscripts, Superscripts

1, 2	cascade upstream and downstream conditions
ax	axial
is	isentropic
u	at local circumferential position

Abbreviations

PS, SS	pressure side, suction side

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INTRODUCTION

The demand for increased cycle efficiencies leads to increased turbine inlet temperatures and to high pressure ratios of modern turbomachines. This trend to high pressures in the high pressure compressor requires very smooth blade surfaces to keep the profile boundary layer in the hydraulically smooth region. Thus, not only in terms of turbomachine performance but also in terms of cost reduction for the manufacturing process, surface roughness is a very interesting field to investigate.

The influence of surface roughness has been of interest for researchers for almost 100 years. One of the first and well known investigations is that of Nikuradse (1933) who did intensive research on pipe flows with sand grain of different size applied to the pipe walls. His measurements led to the so called Nikuradse diagram where the flow can be divided into three regions. The first region concerns the whole laminar region and a part of the turbulent region. It is marked by the fact that surface roughness has no influence on the flow. The second region shows an increase of the pressure drop coefficient when raising the Reynolds number. In the third region the pressure drop coefficient is independent of the Reynolds number. Nikuradse interpreted these regions with the relation of surface roughness height to the thickness of the laminar sublayer. In the first region the surface roughness is completely covered by the laminar sublayer, thus no influence of surface roughness can be found. In the second region the decrease of the laminar sublayer thickness lets some roughness elements protrude through the sublayer leading to an increase of the pressure drop coefficient. For the third region the complete surface roughness protrudes through the sublayer leading to no further increase of the pressure drop coefficient.

The influence of lateral surface roughness parameters was found to be important by Schlichting (1936) who varied the density of roughness elements like hemispheres, cones and rectangular dice of a plate flow. When increasing the density of roughness elements up to a critical value the drag coefficient increased. A further increase of roughness density leads to a decrease in drag coefficient.

Even in turbomachines the influence of surface roughness is subject of various investigations. Several investigations concern the influence of surface roughness on the performance of turbine or compressor rigs. An extensive investigation about the change of performance of turbine rigs is found at Bammert and Sandstede (1973, 1972 and 1975). They observed a performance degradation and a shift of the characteristic to smaller mass flow coefficients for the investigated turbine rigs that have been covered with sand grains of different size. Even for compressor rigs (Bammert and Woelk 1976, Bammert and Woelk 1979) an increased performance degradation was observed for an increased size of sand grains covering the compressor blades. A shift to smaller specific volumes is observed when increasing the size of adhered sand grains too. However, for all of these investigations the blades undergo a thickening of the profile contour when the sand grain is adhered to the blades. This effect has not been considered for the above investigations. Suder et al. (1994) took this effect into account and measured the characteristics of a transonic rotor where the blades have been covered with a rough and a smooth paint. The characteristics indicate that in the subsonic region the thickening of the blades is not negligible due to a shock system in the blade passage. When covering only parts of the blade the front part of the suction and pressure side is found to react sensibly on applying surface roughness or thickness.

An investigation of boundary layer development along a rough turbine blade at a Reynolds number of $5.6*10^5$ and a Mach number of 0.14 is given by Bammert and Sandstede (1980). The measurements inside the boundary layer have been performed with a small pitot tube. The blade is covered with sand grains of different size causing the laminar to turbulent transition to move upstream when increasing the sand grain size. On the pressure surface the location of transition is almost not affected by surface roughness. But the laminar to turbulent transition is steeper for the rough blades than for the smooth ones. The boundary layer development along various compressor cascades (Bammert and Milsch 1972) indicates only a small influence of the adhered sand grains on the laminar to turbulent transition. But the impulse deficit thickness, even of the laminar boundary layer, is increased due to surface roughness. For large sand grains covering the profile surface a turbulent separation is detected on the suction side. A study of the performance of a compressor cascade which is covered with sand grains over varying lengths of surface is shown by Saxena et al. (1978). They found that a separation bubble on the suction side is likely to disappear due to surface roughness.

In spite of the fact that there are several investigations on the influence of surface roughness on flow fields, most of the investigations have been performed on complete rig-setups or on cascades covered with sand grain. Thus, there is a need to investigate the influence of surface roughness caused by modern manufacturing methods. This is met by the present investigation.

EXPERIMENTAL SET-UP

High Speed Cascade Wind Tunnel

The experiments were carried out in the High Speed Cascade Wind Tunnel (Fig. 1) of the "Universität der Bundeswehr München".

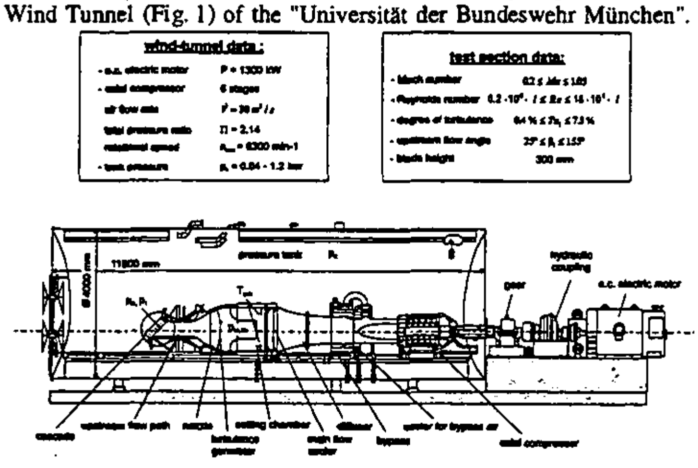
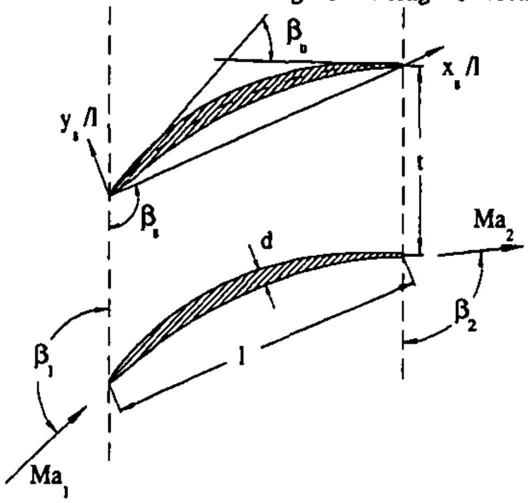


Fig. 1: The High Speed Cascade Wind Tunnel

This facility operates continuously in a large pressurized tank. Mach number and Reynolds number can be varied independently hy setting the compressor delivery pressure and the pressure level inside the tank while the total temperature is kept constant. The turbulence intensity in the test section can be varied by using different turbulence generators in front of the nozzle. The following data were used in order to monitor the flow conditions of the cascade main stream flow (Sturm and Fottner, 1985): the total temperature in the settling chamber, the static pressure in the tank (downstream conditions), the static pressure and the total pressure of the main stream flow upstream of the cascade.

Compressor Cascade

To investigate the influence of surface roughness on a flow around a compressor cascade the chord length should be as large as possible in order to maximise the spatial resolution of the flow phenomena. On the other hand the cascade should offer a large two dimensional flow region at midspan. As a compromise the cascade chosen consists of five blades featuring a chord length of 180mm. The



design conditions: NACA 65 K48, l=180mm			
t/l	= 0.55	Ma_1	= 0.67
d_{max}/l	= 0.055	Re_1	= 450000
β_u	= 48°	β_1	= 132°
β_s	= 112.5°	β_2	= 96°

Fig. 2: The Cascade NACA 65 K48

profile is a 48° circle bow with a superimposed NACA 65 thickness distribution. The main geometrical parameters and design flow conditions are shown in Fig. 2. The cascade is mounted in the test section as shown in Fig. 3. The measurements concentrate on the centre blade of the cascade. To ensure a homogenous inlet flow boundary layer suction is applied to the upper and lower walls. To

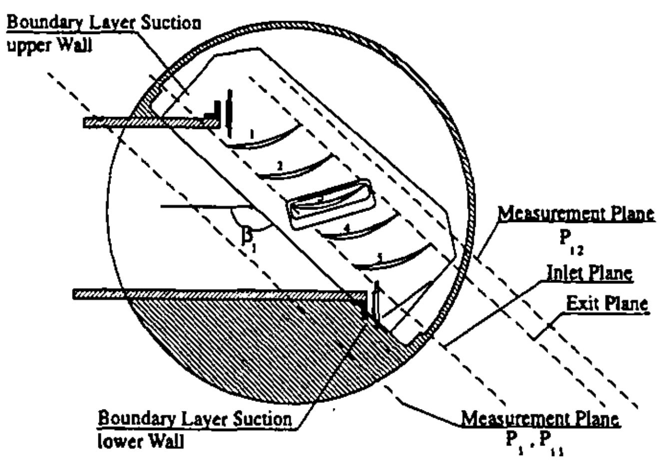


Fig. 3: Cascade NACA65 K48 mounted in the test section

monitor the main flow condition the static inlet pressure, the total inlet pressure and the total temperature in the settling chamber are measured. The local total pressure is measured at the exit measurement plane. A glass window is mounted to the sidewall of the cascade to deliver optical access to the centre blade for the laser-two-focus measurements.

Transfer of Surface Roughness to the Airfoil

In order to correctly simulate technical surface roughness for the enlarged compressor model blades a special technique has been developed (Leipold and Fottner 1998). The three dimensional surface structure of a real blade is measured with a scanning white light interferometer obtaining an ASCII data set that is used to create an bitmap used to control a laser micro machining process. With this process it is possible to engrave a with a factor of ten enlarged copy of the original blade surface roughness into a sheet of copper. For the present investigation the surface of a precision forged airfoil is used as input for the laser machining process. Due to problems at the

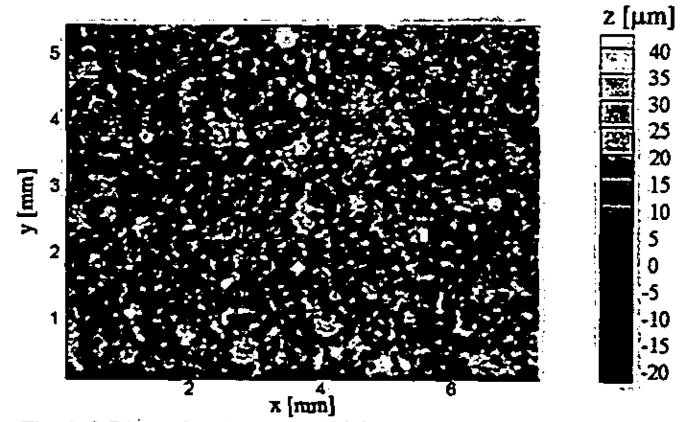


Fig. 4: 3-Dimensional topology of the applied sheet of copper

fabricator in creating an input bitmap out of the ASCII data file only a qualitative reproduction of the original surface has been achieved. A scanning white light measurement of the sheet of copper with the enlarged surface roughness is displayed in Fig. 4. Some important roughness parameters of the real blades surface and the enlarged and

	Ra	Rz	Rsk	S	Sm
real blade	0.70	7.27	-1.28	0.017	0.035
transferred surface	11.15	69.3	0.47	0.168	0.335

Tab1: Roughness parameters of real blade and the applied sheet of copper

transferred surface are given in Tab.1. In order to perform the measurements at the large scale compressor cascade two sheets of copper are necessary, one for the suction side and one for the pressure side. Both sheets of copper are adhered to the centre blade where the profile contour is changed to avoid a undesirable thickening of the blade contour.

Total Pressure Wake Traverse and Static Profile Pressure Measurement Technique

The total pressure loss of an airfoil can be estimated when traversing a total pressure probe through the wake caused by the airfoil. When investigating the influence of surface roughness it is important to isolate the roughness influence from other parameters. This has been achieved by the use of two total pressure probes which are traversed simultaneously over one pitch behind a blade which is divided into a rough and a smooth half. One probe is positioned behind the smooth blade, the other one behind the rough one. From these probes two pressures differences are recorded: the inlet total pressure versus the total pressure measured by the probe behind the smooth half of the airfoil and the total pressure difference between the two probes. This set up enables the use of accurate pressure transducers to measure the total pressure difference between the wake of the smooth and the rough blade. Each probe has a distance of 45mm from midspan. It has been ensured by previous measurements of the secondary flow field with a five hole probe (Hübner 1996) that both probes are not affected by secondary flow phenomena. In order to correct small total pressure inhomogenities each flow condition has been additionally measured with the centre airfoil equipped with smooth sheets of copper. The wake traverse results have been corrected with the results of the wake traverse behind the smooth blade.

In order to determine the isentropic Mach number distribution over the blade, the centre airfoil is equipped with 42 static pressure tappings. To enable a comparison of the isentropic Mach number distribution between the rough and the smooth half of the blade each half is equipped with 8 pressure tappings on the pressure side and 13 pressure tappings on the suction side. The tappings are located at a distance of 40mm from midspan. It has been ensured by Oil-and-dye surface flow patterns that the measurement of profile pressures is not affected by secondary flow phenomena.

Investigation of Profile Boundary Layer

With the-laser two-focus technique (Schodl, 1978) the 2-D flow vector can be measured. This non-intrusive technique is able to measure the velocity and the direction of the flow very close to a wall. Thus, the velocities inside the profile boundary layer can be measured. The laser-2-focus technique is based on the principle of a light barrier. The light of a water cooled Argon Ion laser with an output power of 1.5 Watt is used to produce two parallel laser beams which are focused to a size of 9μm at a distance of 168μm building the light barrier for particles which are made of an aerosol with an average diameter of 0.5μm. The back scattered light of particles passing the focal volumes is received by two photo detectors. After an amplification and signal processing the time between the pulses of a particle passing the two foci is used to calculate the velocity with the known distance between the two foci. A statistical evaluation is necessary because the two pulses detected by the photo detectors are sometimes not of one particle. The flow angle can be detected by rotating the two foci. The measurement planes along the suction surface used to investigate the boundary layer development with the laser-two-focus anemometry are displayed in Fig.5. Even though the statistical evaluation of velocity and angle are very accurate, the evaluation of turbulence is only qualitative. To minimise this lack of information the hot wire anemometry is used.

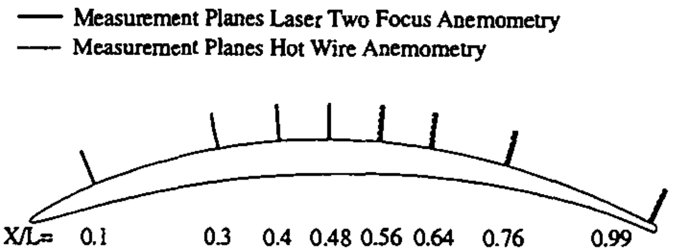


Fig. 5: Location of measurement planes

The hot wire anemometry engaged at the HGK is based on the principle of constant temperature. A Wheatstone Bridge is compensating the change of temperature of a wire which is applied to the flow. A change in flow velocities results in a changing thermal conduction at the wire. To keep the temperature of the wire constant the electrical power has to be controlled. The control of the measurement chain and the data acquisition and evaluation is done with the Dantec streamware system. Different flow conditions require different types of probes. The measurement inside the profile boundary layer has been performed with the boundary layer probe 55P15 with a wire diameter of 5μm.

RESULTS

Variation of Reynolds number

The influence of the inlet Reynolds number at the design inlet angle β_1=132° and the design inlet Mach number Ma_1=0.67 on the

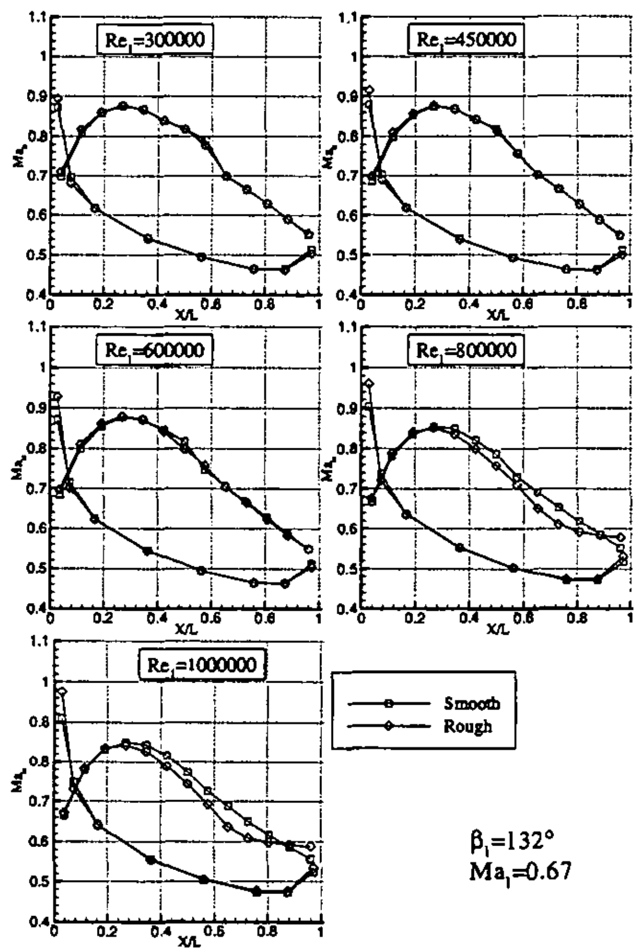


Fig. 6: Influence of Reynolds number on the isentropic Mach number

isentropic Mach number distribution of the rough and the smooth blade is displayed in Fig. 6. At the lowest Reynolds number a laminar separation bubble is detected between X/L=0.43 and X/L=0.66 for the smooth and the rough blade. There is no reduction of separation length due to surface roughness. Only the thickness of the laminar separation bubble seems to be reduced indicated by slightly reduced isentropic Mach numbers at X/L=0.6 for the rough blade. The rest of the distribution of isentropic Mach number is nearly identical for the rough and the smooth blade even on the pressure side. At a design inlet Reynolds number of Re_1=450000 the laminar separation bubble is reduced compared to the lower inlet Reynolds number. However there is no difference in the extent of the bubble between the smooth and the rough blade (X/L=0.43 and X/L=0.6). A reduction of bubble height is imaginable for the rough blade but not clearly shown by the isentropic Mach number. For a further increase of inlet Reynolds number (Re_1=600000) the separation bubble disappeares on the rough blade. The isentropic Mach number of the smooth blade again indicates a laminar separation occurring between X/L=0.43 and X/L=0.58. At an inlet Reynolds number of Re_1=800000 no laminar separation is detected for the smooth and the rough blade. But at X/L=0.72 a large turbulent separation can be observed for the rough

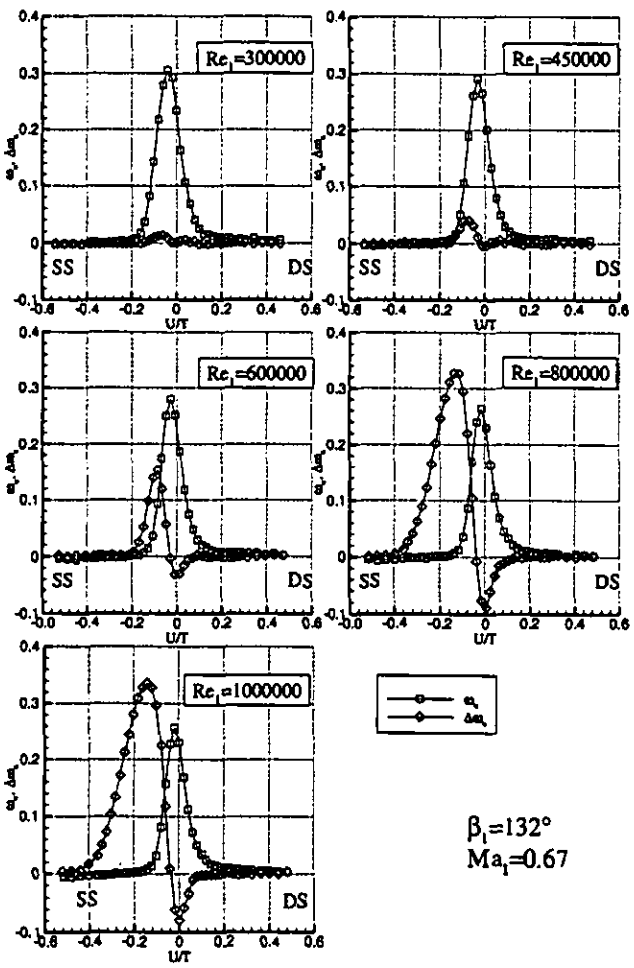


Fig. 7: Influence of Reynolds number on local total pressure loss

blade that does not reattach. Even at the highest inlet Reynolds number of Re_1=1000000 a turbulent separation is shown by the isentropic Mach number distribution of the rough blade that is slightly shifted upstream to X/L=0.65. For all inlet Reynolds numbers no roughness effect on the isentropic Mach number of the pressure side could be observed.

The results of wake traverse with two total pressure probes are displayed in Fig. 7 for a variation of Reynolds number. The local total pressure loss and the local total pressure loss difference between the rough and the smooth blade is shown. Positive values of local total pressure loss difference between the rough and the smooth blade mean that there is additional total pressure loss due to surface roughness. At the lowest Reynolds number Re_1=300000 a slight additional total pressure loss at the suction side can be observed although a reduction of laminar separation bubble height in the distribution of isentropic Mach number is shown in Fig.6. For higher inlet Reynolds numbers the local maximum of additional total pressure loss increased up to very high values, indicating high additional losses due to turbulent separation on the suction side caused by surface roughness.

The integral total pressure loss coefficient versus the inlet Reynolds number is displayed in Fig. 8. At an inlet Reynolds number of Re_1=300000 the total pressure loss coefficients of the smooth and the rough blade are nearly identical. When increasing the inlet Reynolds number, the total pressure loss coefficient of the rough blade

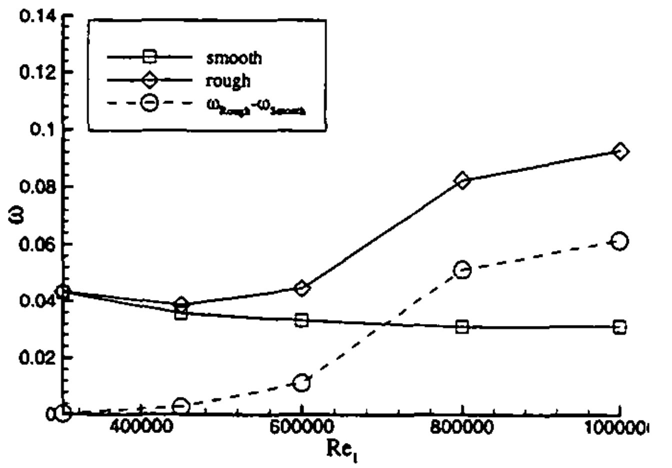


Fig. 8: Influence of Reynolds number on total pressure loss coefficient

is always higher than that of the smooth blade. At Re_1=600000 a sharp increase of total pressure loss coefficient for the rough blade indicates the beginning of turbulent separation on the suction side of the rough blade.

In order to obtain detailed information about the status of the boundary layer the laser-two-focus anemometry has been used. Due to the fact that this is a very time consuming technique, only two inlet Reynolds numbers have been investigated (Re_1=450000, 600000). A further reduction of measurement time has been achieved by reducing the number of chordwise measurements for Re_1=600000. The results of the laser-two-focus anemometry are the velocities inside the boundary layer. A spline approximation is used to evaluate the boundary layer parameters displayed versus the dimensionless chordwise position in Fig. 9. At Re_1=450000 the boundary layer

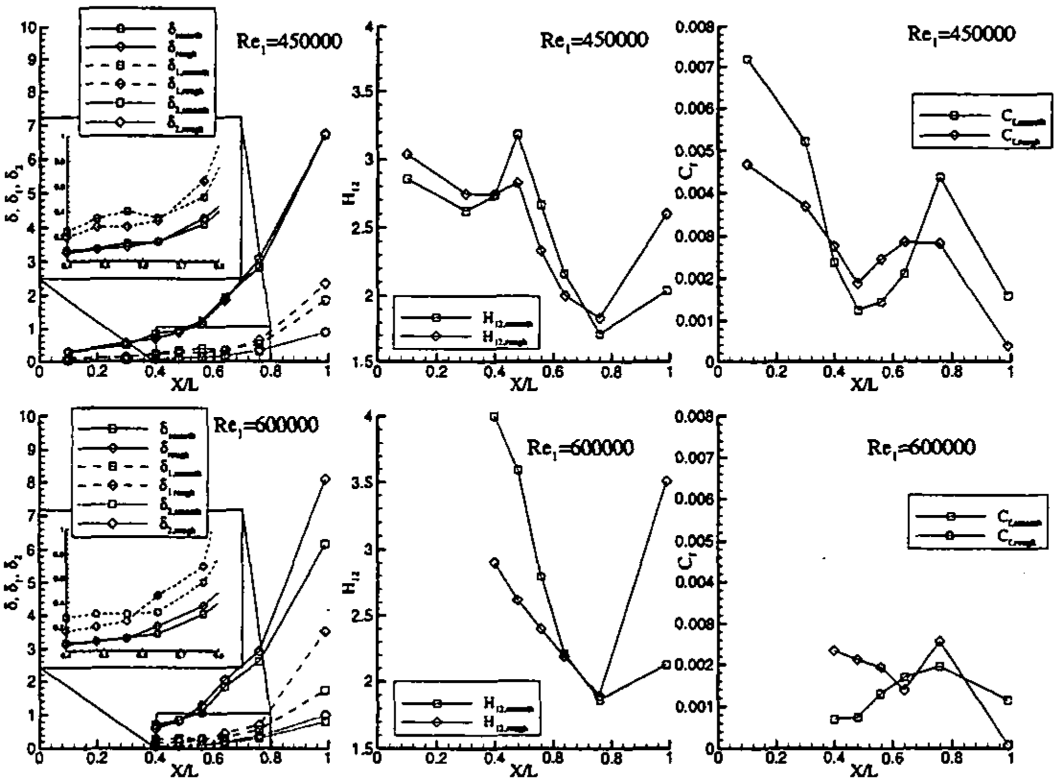


Fig.9: Influence of Reynolds number on boundary layer parameters

thicknesses of the smooth and the rough blade are identical whereas at Re_1=600000 the boundary layer of the rough blade is always slightly thicker than the boundary layer of the smooth blade especially at X/L=0.99. The displacement thickness at Re_1=450000 confirms that the laminar separation bubble is thicker for the smooth blade than for the rough blade (zoomed out). Even at Re_1=600000 the displacement thickness indicates the laminar separation bubble for the smooth blade. Over the rough blade no laminar separation can be detected. The impulse deficit thickness shows no difference between the rough and the smooth blade at Re_1=450000. At Re_1=600000 the impulse deficit thickness of the rough blade is always slightly higher than of the smooth blade even close to the trailing edge indicating that the higher impulse deficit in the rough boundary layer is responsible for the observed higher total pressure loss coefficient. The comparison of shape factor H_{12} indicates the laminar separation at Re_1=450000 due to very high values at X/L=0.48. The higher increase of shape factor close to the trailing edge for the rough blade is a hint that turbulent separation is likely to occur. At Re_1=600000 the decrease of shape factor from a value of H_{12}=4 down to H_{12}=1.8 for the smooth blade is another indicator for a laminar separation over the smooth blade. The decrease of shape factor for the rough blade makes a transition without separation bubble likelier. The steep increase at X/L=0.99 for the rough blade is again clearly indicating a beginning turbulent separation. The skin friction coefficient at Re_1=450000 relieves the above discussion by a sharp decrease at X/L=0.48 also indicating the laminar separation. Very small skin friction coefficients at X/L=0.99 for the rough blade at both inlet Reynolds numbers confirm that there is a beginning turbulent separation.

The development of dimensionless root mean square of time resolved velocity obtained by the hot wire anemometry is displayed in Fig.10 for three inlet Reynolds numbers at the design inlet flow angle β_1=132° and the design inlet Mach number

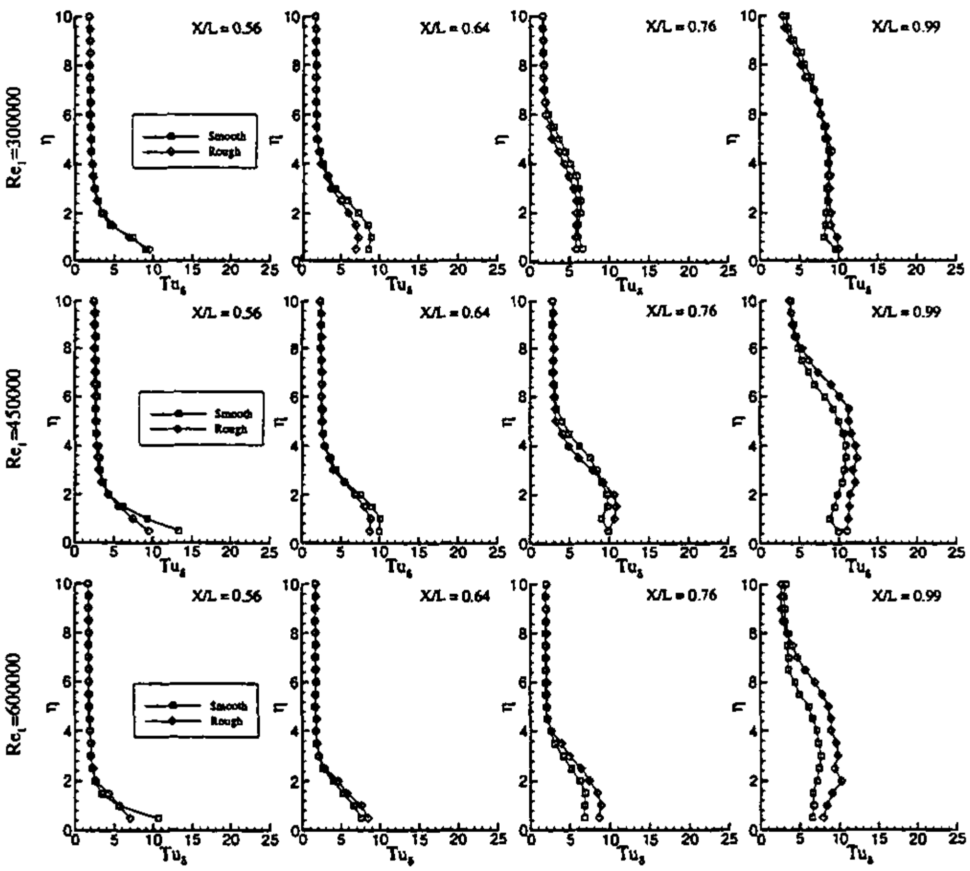


Fig. 10: Influence of Reynolds number on the distribution of turbulence in the boundary layer

Ma_1=0.67. For each Reynolds number the measurements have been performed at four chordwise positions (Fig.5). The distribution of turbulence at X/L=0.64 show higher levels of turbulence for the smooth blade at an inlet Reynolds number of Re_1=300000. Further downstream at X/L=0.76 the turbulence intensity of the rough blade is only slightly lower than for the smooth blade and at X/L=0.99 no difference is found between the rough and the smooth blade. This behavior indicates that the laminar separation is reduced for the rough blade leading to lower levels of turbulence. But downstream of the laminar separation surface roughness does increase the turbulence in the boundary layer of the rough blade. The decrease of turbulence short behind the laminar separation and the increase after the separation are of the same order resulting in an equal distribution of turbulence at the trailing edge. At the design inlet Reynolds number Re_1=450000 higher levels of turbulence can be observed at X/L=0.56 and X/L=0.64 in the boundary layer of the smooth blade. This indicates a stronger laminar separation for the smooth blade than for the rough blade. At X/L=0.76 the surface roughness causes higher levels of turbulence only in the vicinity of the wall. Above a wall distance of 3mm the degree of turbulence is higher for the smooth blade. The turbulence distribution close to the trailing edge shows higher turbulence up to the undisturbed flow for the rough blade. For the highest Reynolds number Re_1=600000 only at X/L=0.56 higher degrees of turbulence can be detected close to the wall for the smooth blade. At the three downstream positions the turbulence level in the boundary layer on the rough blade is always higher than on the smooth blade.

The variation of Reynolds number shows an increased influence of surface roughness for an increased Reynolds number. The strength of a laminar separation occurring for the smooth blade up to a Reynolds number of Re_1=600000 is decreased by surface roughness. The presence of a laminar separation leads to the assumption that the laminar boundary layer is not affected by surface roughness. The positive effect of decreasing strength of a laminar separation bubble due to surface roughness is compensated by negative effects of surface roughness on the turbulent boundary layer downstream of the laminar separation. For increasing Reynolds numbers even this negative effect is increasing leading to a turbulent separation.

Variation of Inlet Flow Angle

The influence of inlet flow angle on the isentropic Mach number distribution and the local total pressure loss at the design inlet Reynolds number Re_1=450000 and the design inlet Mach number Ma_1=0.67 is shown in Fig.11. At negative incidence (β_1=129°) and zero incidence (β_1=132°) the isentropic Mach number is not affected by surface roughness. A separation bubble is detected between X/L=0.4 and X/L=0.65. At positive incidence (β_1=140°) turbulent separation is detected. The turbulent separation is slightly shifted upstream for the rough blade. The local total pressure loss and the total pressure loss difference between the rough and the smooth blade show the same behavior for the inlet flow angles β_1=129° and β_1=132°. Only small additional total pressure losses due to surface roughness are observed. For the highest inlet flow angle β_1=140° surface roughness causes higher additional losses than for the two lower inlet flow angles. Here only a deceleration is observed on the suction side making a complete turbulent boundary layer possible.

The integral total pressure loss coefficient difference versus the inlet flow angle is shown in Fig.12 for three different Reynolds numbers. For the lowest Reynolds number (Re_1=300000) surface

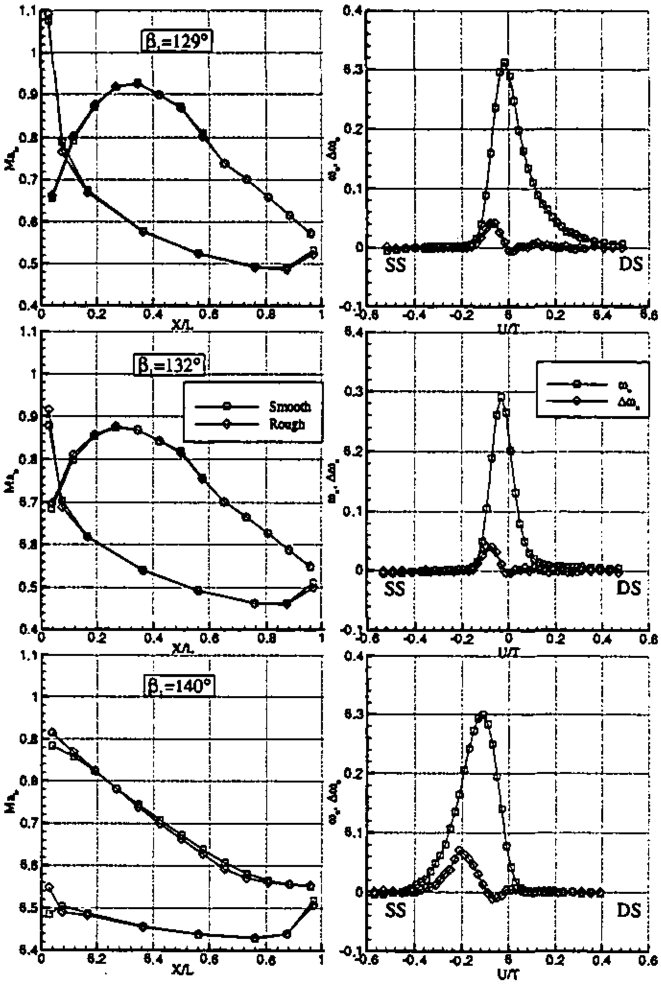


Fig. 11: Isentropic Mach number and wake traverse results for a variation of inlet angle

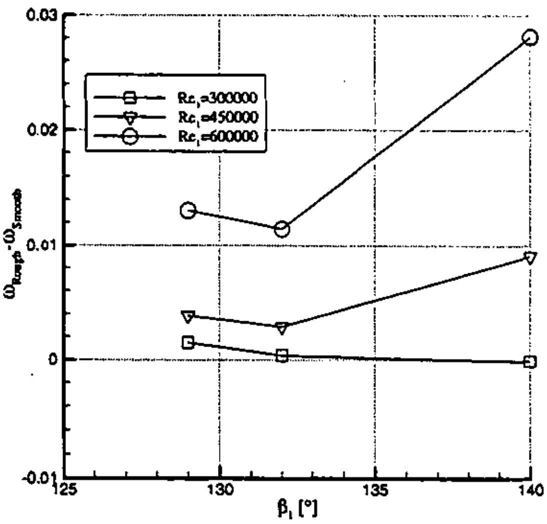


Fig.12: Total pressure loss coefficient difference versus inlet flow angle

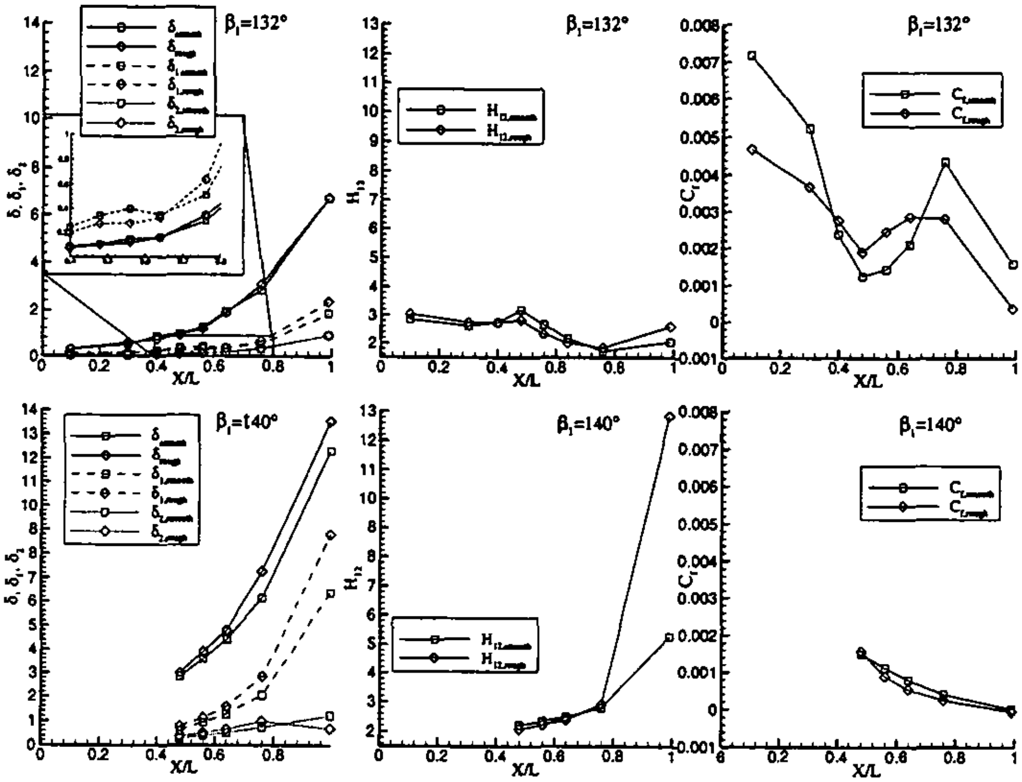


Fig.13: Influence of inlet flow angle on boundary layer parameters

roughness causes slightly higher losses for β_1=129°. A Reynolds number of Re_1=450000 gives higher loss coefficients for the rough blade. For β_1=129° and β_1=132° the difference between the loss coefficient of the smooth and the rough blade is nearly the same, whereas for β_1=140° the difference in loss coefficient is higher. This trend can clearly be identified for the Reynolds number Re_1=600000. This leads to the presumption that the flow is more sensitive to surface roughness at high inlet flow angles.

The boundary layer investigated by the laser-two-focus anemometry is illustrated in Fig.13. In order to reduce measurement time and due to the results of isentropic profile Mach number and wake traverse not showing any differences between β_1=129° and β_1=132° only at β_1=132° and β_1=140° and at Re_1=450000 the boundary layer development has been investigated by means of laser-two-focus anemometry. The boundary layer parameters for an inlet flow condition Re_1=450000 and β_1=132° have already been discussed above. The boundary layer thickness at β_1=140° is larger than for β_1=132° because of a complete turbulent boundary layer at the suction side. The turbulent separation at X/L=0.7 leads to a thick boundary layer. At an inlet flow angle β_1=132° surface roughness does not change the thickness of the boundary layer but at β_1=140° the boundary layer of the rough blade is thicker than of the smooth blade. The distribution of displacement thickness shows a steep increase at X/L=0.7 because of the turbulent separation. Higher values for the rough blade especially downstream of X/L=0.7 indicate a more distinct turbulent separation for the rough blade. The high gradient of the shape factor indicates a stronger turbulent separation. Even at β_1=132° the shape factor shows a steeper increase at the trailing edge for the rough blade indicating the tendency to turbulent separation for the rough blade. The progression of skin friction coefficient at β_1=140° indicates a stronger turbulent separation due to lower values for the rough blade.

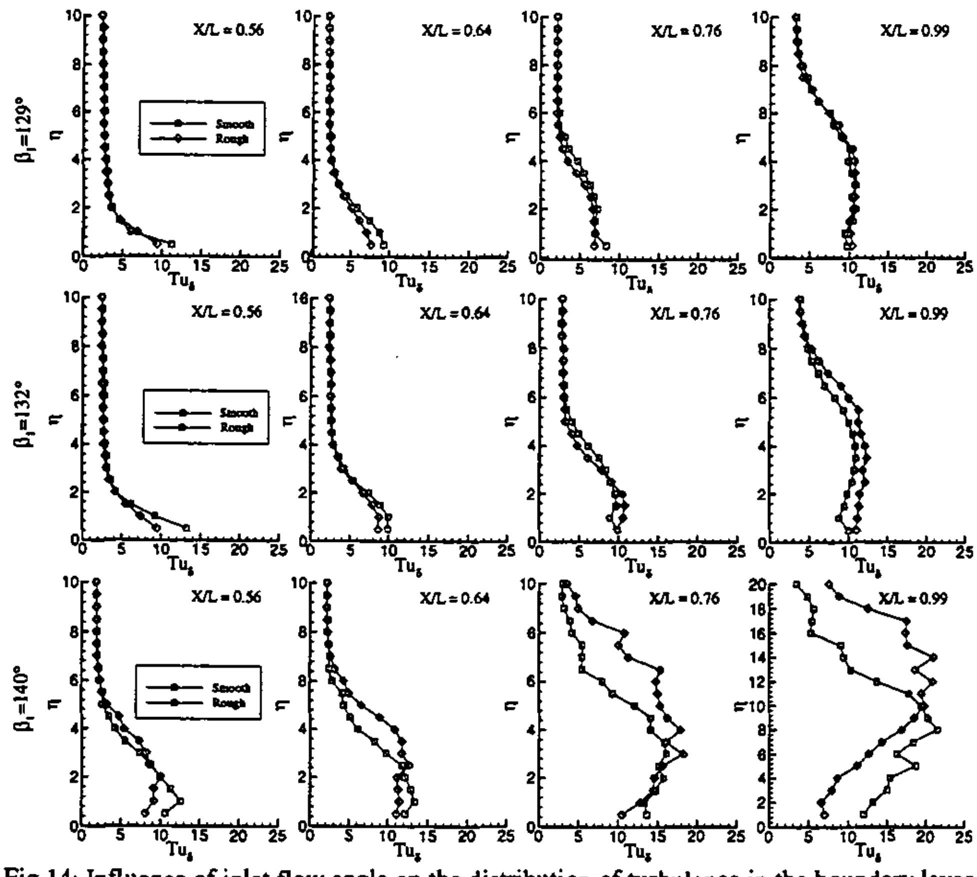


Fig.14: Influence of inlet flow angle on the distribution of turbulence in the boundary layer

Fig.14 shows the root mean square of the time resolved velocity measured by the one-dimensional hot wire anemometry for three inlet flow angles. A stronger laminar separation for the smooth blade is marked by higher levels of turbulence at the positions X/L=0.56 and X/L=0.64. Further downstream the surface roughness increases the turbulence intensity, leading to a compensation of turbulence reduction achieved in the laminar separation bubble. Even at an inlet flow angle β_1=132° the strength of laminar separation is reduced by surface roughness resulting in lower levels of turbulence. The production of turbulence after the laminar separation is now higher than the decrease of turbulence in the laminar separation bubble. Thus, the turbulence is higher for the rough blade close to the trailing edge. At β_1=140° the position of maximum turbulence is closer to the wall for the smooth blade for all positions marking the stronger turbulent separation of the boundary layer for the rough blade (at X/L=0.99 the traverse length has been extended to 20mm instead of 10mm). A significant decrease or increase of turbulence due to surface roughness could not be observed.

The variation of inlet flow angles shows a similar influence of surface roughness for β_1=129° and β_1=132°. The reduction of the strength of the laminar separation is compensated by an increase of turbulence in the turbulent boundary layer. For an inlet flow angle of β_1=140° an increased influence of surface roughness is observed. The reason is a complete turbulent boundary layer at the suction side for the highest inlet flow angle without any laminar separation.

CONCLUSIONS

In order to investigate the influence of surface roughness on the flow around a highly loaded compressor cascade measurements of the isentropic profile Mach number distributions and of the local total pressures at the exit measurement plane of a smooth and a rough blade have been performed. Furthermore, a detailed investigation of the suction side boundary layer has been done with the laser-two-focus anemometry and the one-dimensional hot wire anemometry. The important results can be summarized as follows:

- Due to the presence of a laminar separation even for the rough blade the laminar boundary layer seems not to be affected by surface roughness.
- The beginning and end of a laminar separation at low inlet Reynolds numbers is not affected by surface roughness. Only at Re_1=600000 the laminar separation is completely suppressed by roughness.
- The displacement thickness is larger in the region of a laminar separation bubble for the smooth blade. This leads to the assumption that the strength of a laminar separation is reduced by surface roughness.
- The positive effect on the laminar separation does not decrease the total pressure loss coefficient for the rough blade because the turbulent boundary layer is affected negatively by surface roughness.
- At high Reynolds numbers surface roughness causes the turbulent boundary layer to separate from the blade.
- At negative incidence and at design inlet flow angle the influence of surface roughness on the boundary layer and the total pressure losses is similar, but at positive incidence the boundary layer reacts more sensitively to surface roughness

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