Wear 321 (2014) 79–86

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Areal parametric characterisation of ex-service compressor blade leading edges

Karl Walton [a,*], Liam Blunt [a], Leigh Fleming [a], Martin Goodhand [b], Hang Lung [c]

[a] *EPSRC Centre for Innovative Manufacturing in Advanced Metrology, University of Huddersfield, Canalside East Building 3/04, Huddersfield, West Yorkshire,HD1 3DH,United Kingdom*
[b] *Whittle Laboratory, University of Cambridge, 1 JJ Thomson Avenue, Cambridge, CB3 0DY, United Kingdom*
[c] *Rolls Royce plc, PO Box 31, Derby, DE24 8BJ, United Kingdom*

ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form
17 October 2014
Accepted 22 October 2014
Available online 31 October 2014

Keywords:
Surface topography
Solid particle erosion
Profilometry
Surface analysis

ABSTRACT

In-service the degradation of compressor blade leading edges can have a disproportional effect on compressor efficiency. The high surface curvature in this region makes quantifying the surface finish of this sensitive and prominent region difficult. An automated technique that characterises the roughness of the leading edge in terms of areal parameters is presented. A set of ex-service blades of differing sizes are used to demonstrate the procedure. Improved characterisation of this blade region will allow engine companies to better understand where in-service deterioration has the greatest effect and inform them as to how they might minimise the effect. The present work shows that the leading edges of compressor blades exhibit a significantly higher characteristic surface roughness than other blade regions, and the spatial distribution of peaks in this characteristic roughness is detailed. In addition it is shown that peak wear and roughness are not uniformly correlated.

1. Introduction

1.1. Leading edge significance

The prominence of the leading edge makes it particularly susceptible to both deposition and erosion. It is also a region where small changes to the roughness and geometry can have a disproportionate effect on compressor efficiency. Due to this susceptibility and by visual inspection it has been generally accepted that the leading edge typically exhibits greater surface roughness due to degradation than other similarly sensitive areas of compressor blades. The sensitivity to roughness was demonstrated by Wilshee [1] he tested compressor blades with roughness imposed onto discrete regions. He found that applying roughness over the leading edge and the first 4% of the chord (for blade nomenclature see Fig. 1) the aerodynamic losses increased by almost half of that seen when the whole blade was roughened. This can be attributed to the fact that the boundary layer around the leading edge is much smaller and the roughness will therefore have a larger effect. The sensitivity to geometry was demonstrated by Goodhand and Miller [2] they tested a compressor blade with different leading edges. They found that premature flow turbulence and associated losses caused by circular leading edges could be offset with a 3:1 elliptical leading edge. This change can be attributed to the more gentle change of the profile geometry of the elliptical edge, and the associated reduction in flow disturbance. In service, similar, or even greater changes to leading geometry may be expected due to either erosion or deposition. This raises the question what are the changes and what effect will they have on the flow?

1.2. Leading edge profile and areal metrology

To date the large majority of investigations into compressor degradation have focussed on military or power generation applications. In civil aero engines the levels of degradation are more modest, and unlikely to be safety critical, but can have a significant effect on fuel burn. The fact that they are not safety critical means that there is little published data of leading edge metrology. The compressor blades investigated have circular leading edges; typically with nominal leading edge radii less than 1 mm and high flank angles (see Fig. 2 (G)). A flank angle of 90° means the surface is parallel to the optical axis and not measurable; measurements become optimal as this angle approaches 0°. In practice imperfections arising during manufacture as well as the deterioration in-service, means that the leading edges are rarely circular in practice and as such, their dimension is typically described as 'half thickness'. This study focuses on the leading edges of the rotor blades from a single engine see Fig. 3; one blade

* Corresponding author. Tel. +441484 422288
E-mail addresses: k.walton@hud.ac.uk (K. Walton), l.a.blunt@hud.ac.uk (L. Blunt), l.t.fleming@hud.ac.uk (L. Fleming), mng24@cam.ac.uk (M. Goodhand), hang.lung@rolls-royce.com (H. Lung).

http://dx.doi.org/10.1016/j.wear.2014.10.007
0043-1648/

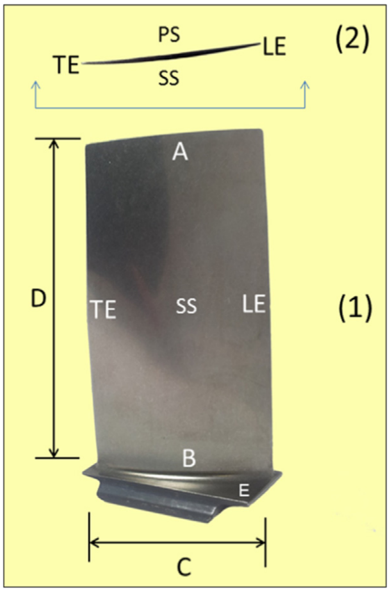

Fig. 1. Generic compressor blade nomenclature; (1)-side view and (2)-tip view(x section) showing; LE-leading edge, A-tip, B-root, C-chord (chordwise direction), TE-trailing edge, D-Span (spanwise direction), SS-suction side (convex), PS-pressure side (concave), E-end wall.

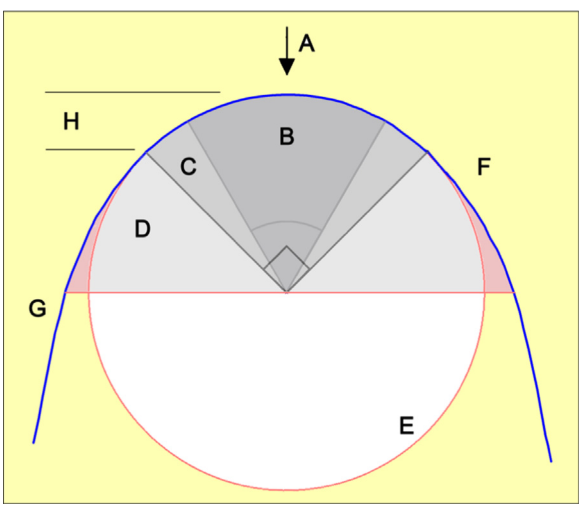

Fig. 2. Leading edge region cross-section schematic; (A) instrument optical axis (zero angle of attack) (B) central 60° frontal field of leading edge, (C) central 90° frontal field of leading edge, (D) nominal frontal field of whole leading edge, (E) circle fitted to nominal leading edge circular profile, (F) approximate blend point of leading edge into blade suction or pressure side (see Fig. 1), (G) leading edge flank, (H) approximate depth of measurement field.

from each row of the Intermediate Pressure Compressor (IPC) and one from each row of the High Pressure Compressors (HPC). Considering blades from all stages provides the opportunity to investigate different leading edge sizes as well as those with different levels of degradation.

Surface metrology in the form of a single line or 'profile' of surface point heights (and associated parameters) often acquired by a contact stylus instrument is widely understood and employed [3]. Areal surface metrology is an increasingly dominant development of this metrology field where a sample surface 'area' is assessed in preference to a simple profile. Areal analysis offers much improved statistical significance, giving better repeatability of results along with greater functional significance. New areal parameters sets have been developed expanding the surface characterisation tool kit to include surface volume and feature based analysis [4–6]. Non-contact optical metrology instruments are commonly employed for areal surface characterisation. Areal surface parameters are computed from the distribution of captured surface point heights with respect to the mean plane of this point height data set; hence to exclude the height influence of any residual form (geometry) of the sample surface this form must first be removed. The characterisation of degraded leading edges involves significant technical challenges in both instrumentation and data processing, amongst these are; significant residual form see Fig. 2 (H), a wide range of surface; roughness amplitude, texture, colour and reflectivity both specular and diffuse. Fig. 4 depicts a form removed false colour height map of a data set acquired from a ex-service compressor blade leading edge in an initial investigation employing a coherence scanning instrument (CCI)[7,8]. Areal surface parameters were computed from this data set, thus giving proof of concept, though this instrument was far from optimal for the task. 'Focus variation' surface metrology instruments [9] such as the Alicona G4 Infinite Focus Microscope [8,10] are one of the few instrument groups capable in practice of the metrology task detailed here. Specifically the Alicona is able to measure both high flank angles and roughness amplitudes.

1.3. Degradation

Particulates both domestic and foreign (from inside and outside an engine) can have a detrimental effect on compressor efficiency by way of deposition or erosion of gas flow path surfaces. Salt spray [11], oil, organic material and sand [12], and rotor path material *(anecdotal)* [13] are some of the many particulate sources an aero engine may encounter during service.

1.4. Fouling and erosion

Compressor rotor degradation by adherence of particulates (fouling) has been extensively investigated, and recently reviewed [14].

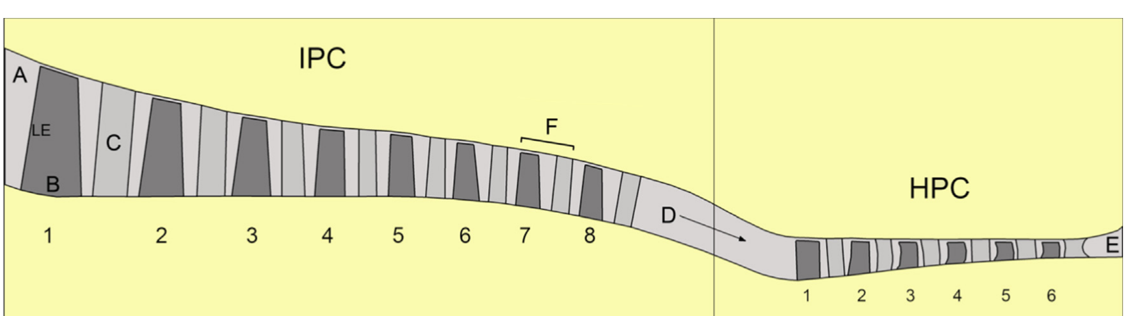

Fig. 3. Compressor jet core schematic; High pressure compressor HPC and intermediate compressor IPC (A) Inlet, (B) rotor blade root, (C) stator blade (vane), (D) compressor core flow, (E) combustion chamber, (F) single compressor stage, (LE) leading edge. Inset numbers indicate blade number.

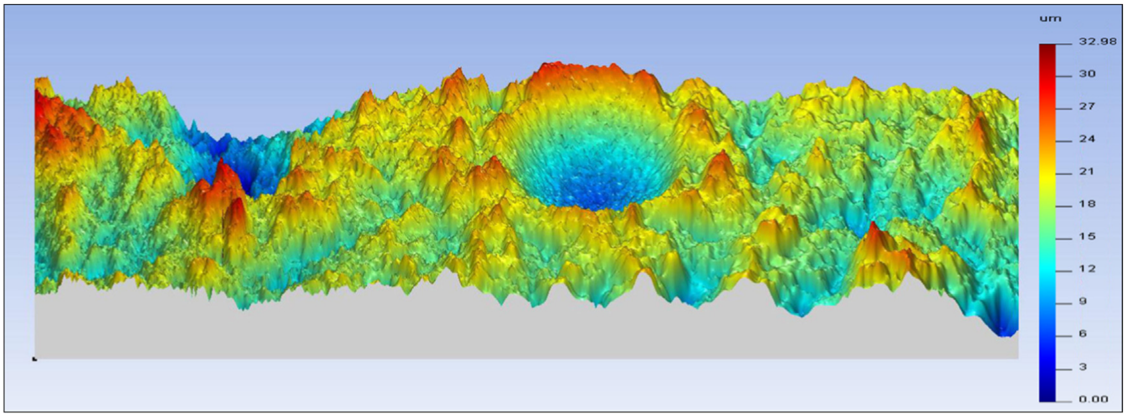

Fig. 4. 250 × 1000 μm leading edge false colour height map, acquired form a recovered HPC 1 blade employing a Taylor Hobson 'Coherence Correlation Interferometer' (CCI) and SurfStand™ software.

They note fouling is largely the result of particles from 10 μm to sub-micron size deposited by a diffusion mechanism, and that the smaller particles in that range predominate in the process. Wetness of particles or surfaces will increase the probability and possible size of particle adhesion. Additionally elevated temperature as seen in the HPC is considered to increase the stickiness and thus the adhesion probability of particulates. Fouling degradation offers the opportunity for partial or total recovery of surface integrity by detergent washing, documented by [11,15] In general, larger harder particles, somewhat above 10 μm tend to be responsible for erosion of compressor surfaces, predominantly by way of inertial impact [14]. Significant erosion degradation can only be mitigated by blade re-profiling and or polishing which necessitates engine time 'off the wing'. It is noted that leading edges unlike other blade regions are subject to all degradations mechanisms detailed in the available literature.

1.5. Objectives

In the present article the primary objectives are; to develop a substantially automated protocol to characterise the surface topography of gas turbine compressor rotor blade leading edges in terms of areal surface parameters, to employ this protocol to characterise the leading edges of a recovered set of IPC and HPC compressor blades, to characterise the trends of surface roughness and profile degradation and the correlation between them through the compressor stages. This work will improve the understanding of leading edge degradation in general and specifically in civil aero compressors and provide a useful technique for further investigation and simulation in this field.

2. Material and method development

2.1. Surface metrology

Fig. 2 details the approximate frontal (zero angle of attack) projected region of a typical leading edge that it is possible to capture both practically and with robust surface roughness data. Additionally the flanks of the edge can be captured, but this must be done with a minimum of two extra measurement fields perhaps 60° either side of zero. Due to the complex geometry of leading edges see Fig. 5 it is not practical to combine or spatially register the resulting fields, thus limiting their usefulness. Additionally, section 3.1 indicates these flank regions exhibit a transitional (non-uniform) surface roughness character and thus are not homogeneous; homogeneity being a prerequisite for areal parametric characterisation [16] Hence with a single instrument field employed at close to zero angle of attack the central 60° to 90° arc of the edge (corresponding to central 1/2 to 2/3 of the projected frontal leading edge area) was captured, see Fig. 2. Surface regions at flanks angles extending beyond this range offer increasingly poor data quality, and increased residual form to remove. Suitably fixed and aligned by goniometer for; pitch, yaw and angle of attack, a minimum vertical scan height and maximum traverse length were achieved for a given measurement traverse (see Fig. 5).

Dependent on specific curvature and geometry, one or more automated (spanwise) traverses were required to acquire data for the length of the leading edge in individual 500 μm fields, leading edges being ~180–30 mm long (IPC1-HPC6). Using this approach the desired leading edge region occupied varying areas and positions within a measurement field, consequently extraction of the required central data region proved subjective. Automation of this task was therefore necessary to allow for the scale of measurement envisaged and ensure repeatability. Alicona captured data has associated with each data point an uncertainty value (data quality) expressed in terms of the vertical distance over which the measurement is estimated to be repeatable within a two standard deviation confidence interval. It can be seen in Fig. 7 that as the leading edge flank angle increases, holes in the image begin to appear, representing data falling below the instrument default minimum quality value. It was seen that using data quality as a metric and assigning a suitable value the data field could be thresholded at any desired level, leaving only the high quality data from the central region of interest. It was then possible, employing script written for this purpose and implemented with respect to [17] [4],[18], to systematically; threshold for data quality, fit to and remove nominal cylindrical form, capture fitted cylinder radius, filter and compute areal parameters from the captured data sets. The 300 μm Gaussian L filtration in the script (see Fig. 7) was applied to attenuate the effects of longer surface wavelengths not removed by cylindrical form removal. Given the wide variation in surface character of individual leading edges or sections thereof it proved necessary to tailor the quality threshold values to suit, consequently extracted field sizes varied somewhat from those intended, in the approximate range 100–700 μm. Fig. 6 shows a measurement process flow chart.

3. Results and discussion

The leading edge roughness was found to vary through the compressor with variations in blade mean Sa of 75%. The roughness levels were found to be higher than elsewhere on the blades,

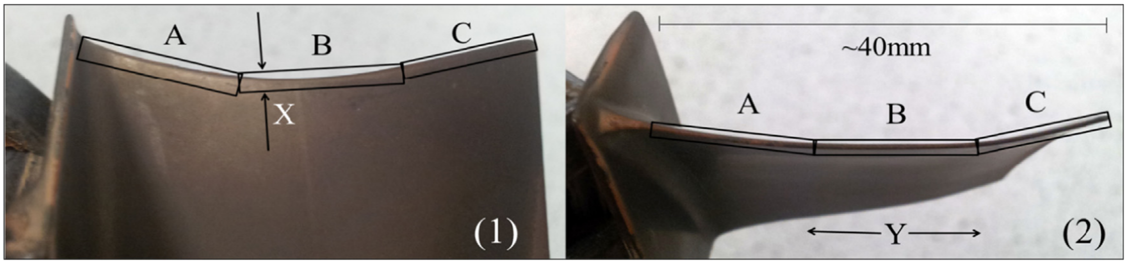

Fig. 5. Typical leading edge measurement traverses (spanwise), (1) leading edge profile from pressure side (2) leading edge viewed edge on from pressure side, showing 3 typical measurement fields A, B and C, field B having traverse length Y and scan height X. (see Fig. 1 for blade nomenclature).

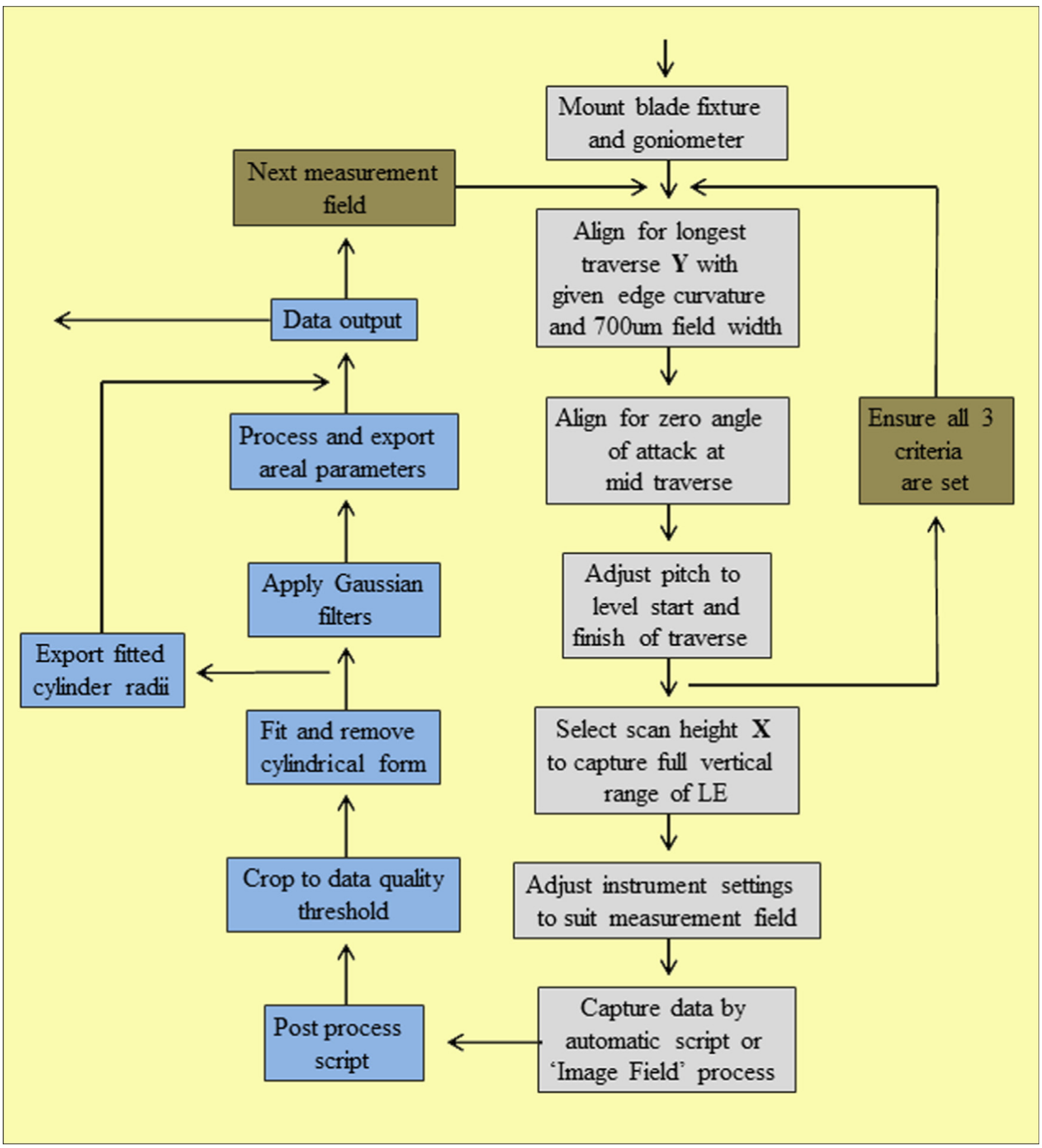

Fig. 6. Measurement and post processing flow chart (detailed with respect to Fig. 5).

typically 30% higher than the levels measured on the adjacent pressure surface. The roughness levels on two example blades are detailed in this section. The instrument's 3D colour imaging system made it possible to clearly distinguish between blade material and deposits. Thus it is clear where the topographical analysis is based on purely eroded edges or those influenced by

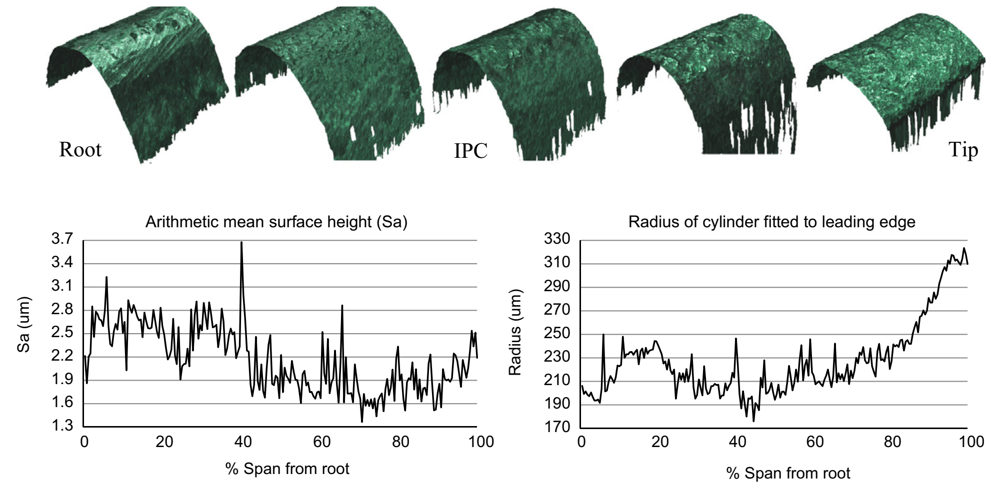

Fig. 7. Excerpted microscopic photographic images of a typical IPC blade, with charts detailing Sa (arithmetic mean surface height)[22] and fitted cylinder leading edge radius for each measurement field. Acquired with Alicona G4 IFM; X20 objective, lateral resolution 2.9 μm (sample spacing 1 μm), vertical resolution (quantisation) 100 nm, Gaussian L filter nesting index 300 um (high pass surface filter) [23].

varying degrees of deposition. The exact distribution of leading edge roughness through the engine has been omitted for proprietary reasons.

3.1. Example intermediate pressure compressor blade

Fig. 7 shows microscopic images of individual measurement fields for an example IPC blade spaced equally along the leading edge, and plots of Sa and fitted radius with % span from route. For proprietary reasons no comparative as manufactured edge half thickness values are quoted, though as a general trend these values decrease from root to tip. The data is plotted for individual captured fields ~450 μm of leading edge; this has the effect of showing the local variations due to the scale of impact features and deposits. This may or may not be desirable, and the data could be filtered or averaged to give a more general trend to suit another application. Fig. 7 illustrates the usefulness of fitted radius as a basic metric of leading edge profile change and hence the extent of wear; the tip region of this typical IPC blade is seen to have a significantly flattened profile and correspondingly elevated values of fitted radius in this region. Visual assessment confirms a positive correlation between deviation from the expected plot of a progressive reduction in fitted radius from root to tip and gross leading edge geometry change due to erosion. It was anticipated that a positive correlation would exist between peak leading edge wear and surface roughness, Fig. 7 clearly shows this not to be the case. Low wear (erosion) of the root half of the leading edge is seen to be associated with higher Sa values than the tip region which exhibits high wear. As a general rule abrasive particulates in the core flow tend to be centrifuged towards the blade tips [19] hence the characteristic tip biased wear pattern. It is noted that where erosion is the dominant in the IPC that a general positive correlation exists between peak regions 'Autocorrelation length' (Sal)[1] [20] [21] and Sa, meaning, as might be expected, that larger particulate impacts produce surface features of larger amplitude and lateral length scale (wavelength). This is to some extent borne out by visual inspection of Fig. 7. When deposition becomes apparent and erosion less dominant from the late IPC onwards this correlation is less notable. Thus it appears that the overall quantity and specific combination of particulate scales acting at a given leading edge location dictate the level of erosion and roughness character generated though the relationship between these effects is not straightforward.

3.2. Example high pressure compressor blade

Fig. 8 shows the same elements as Fig. 7 but shows an example HPC blade. The appearance of deposits at the leading edge tip is most notable and visible here. Fitted radius and surface roughness are strongly negatively correlated, and both are erratic, demonstrating large variations over short spanwise lengths of the leading edge. Deposits in this tip region are seen to be highly variable and often asymmetric, causing the resulting changes in fitted leading edge cylinder radius. It is suggested that surface impact features may, by way of flow disturbance at abrupt changes of profile (such as that seen in the lee of a road vehicle) result in this deposition, or conversely deposits may be partially spallated by surface impacts.

3.3. The intermediate pressure compressor

Fig. 9 shows colour coded details for the IPC of the spatial arrangement of leading edge peak roughness and regions of profile flattening (fitted radius increase) due to erosion of the leading edge. A single field image is included for each blade to illustrate typical features of the surface character and geometry. IPC1 shows essentially uniform roughness with the highest mean value in the IPC only exceeded in the compressor as a whole by that of HPC2. This pattern was attributed to the particulates entering the compressor not having yet been subjected to any significant fragmentary or centrifugal action, and hence being relatively large and uniformly distributed. Prior to the onset of deposition at IPC7 (see Fig. 9) it is only the effects of erosion that are characterised in the results.

All IPC blades exhibit some profile flattening erosion at the tip, IPC1–3 exhibit peak roughness at the tip, whereas IPC4–6 show peak roughness nearer the root. IPC7+8 begins to show deposition at the root where peak roughness is seen, it being highest on IPC7. Hence there is no clear correlation between peak erosion and peak roughness, and where deposition occurs it is associated with the highest roughness values.

[1] 'a quantitative measure of the distance along the surface by which a texture that is statistically different from that of the original location can be found' [23]. A measure of the lateral length scale of the dominant features on a surface, a large value indicates the dominance of large lateral surface scales and vice versa.

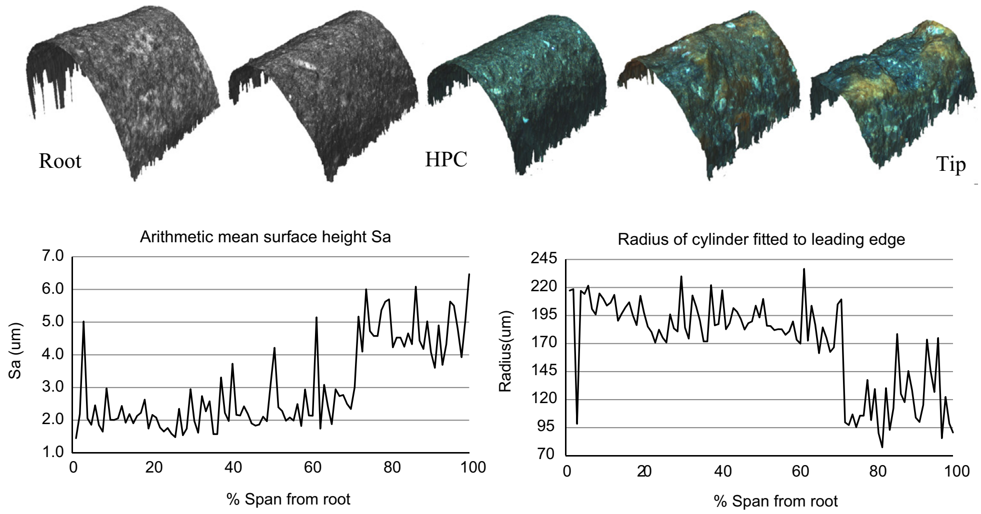

Fig. 8. Excerpted microscopic photographic images of a typical HPC blade, with charts detailing Sa (arithmetic mean surface height)[22] and fitted cylinder leading edge radius for each measurement field. Acquired with Alicona G4 IFM; X20 objective lateral resolution 2.9 μm (sample spacing 1 μm), vertical resolution (quantisation) 100 nm Gaussian L filter nesting index 300 um (high pass surface filter) [23].

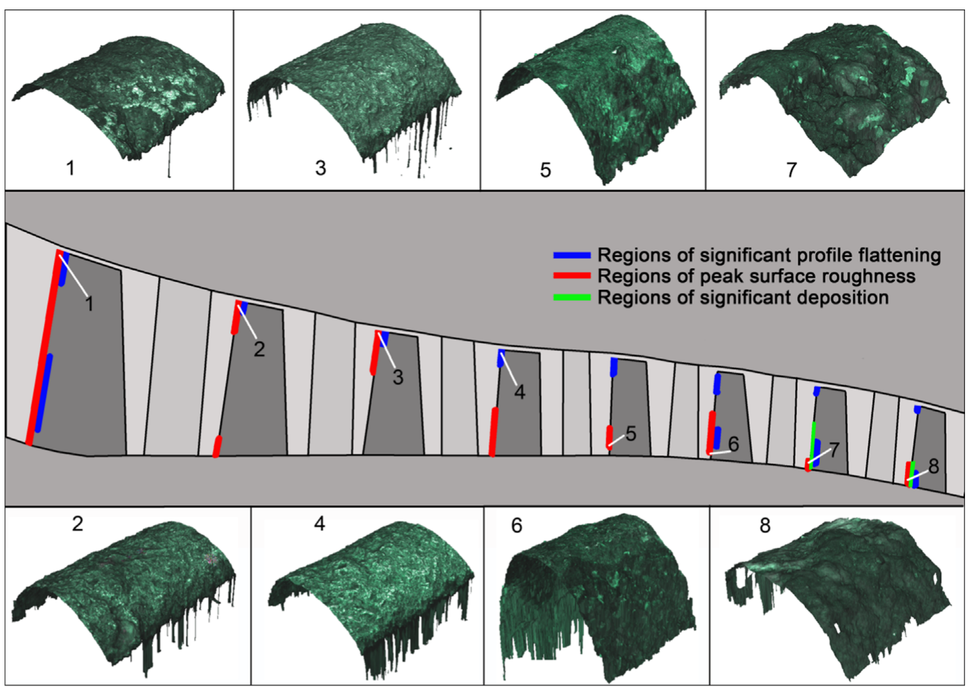

Fig. 9. Schematic annulus diagram of the IPC showing blade number. In red are regions of peak surface roughness. In blue are regions of (relative) pronounced increase of fitted radius due to erosion of profile. Above and below are leading edge fields from the numbered blades in the LE positions indicated by the white lines.

3.4. The high pressure compressor

All IPC blades exhibit some profile flattening erosion at the tip, IPC1-3 exhibit peak roughness at the tip, whereas IPC4-6 show peak roughness nearer the root. IPC7+8 begin to show deposition at the root where peak roughness is seen, it being highest on IPC7. Hence there is no clear correlation between peak erosion and peak roughness, and where deposition occurs it is associated with the highest roughness values.

3.5. The high pressure compressor

Figure 11 details the same information as Fig. 9 but for the HPC, peak roughness always occurs towards the blade tips, and is seen to be associated with erosion and deposition. Little profile flattening erosion is evident, HPC1 having the most notable region and to some extent at the tip of HPC6. The much reduced erosion levels in the HPC are attributed to the aggregated fragmentation effects on the flow particulates of the blades from the proceeding compressor rows. This explains the erosion seen on HPC1 but it is not clear why erosion is noted at HPC6. Deposits are also seen extensively at the blade roots of HPC (4)+(5), see Fig. 10 (4)+(5), with the mid spans in general showing little evidence of significant erosion or deposits, typified by HPC3 (Fig. 10 (3)).

It is noted that in general, where deposition occurs in conjunction with erosion, roughness values are greater than those seen from erosion alone. The scale of the largest degradation features raises the question of their appropriate characterisation; it could be argued their effects on flow can be seen as individual geometric feature events, or statistically as a function of surface roughness

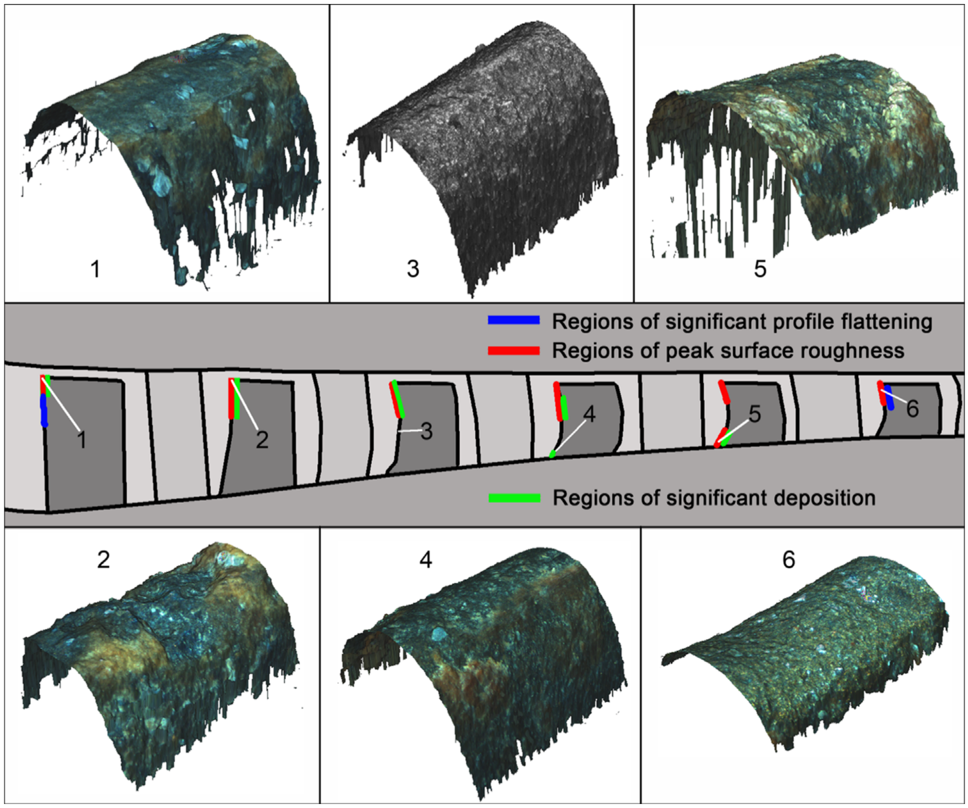

Fig. 10. Schematic annulus diagram of the HPC showing blade number. In red are regions of peak surface roughness. In blue are regions of *(*relative*)* pronounced increase of fitted radius due to erosion of profile. Above and below are leading edge fields from the numbered blades in the LE positions indicated by the white lines.

parameters. Some localised clipping of well-defined optical spike artifacts was carried out, to prevent a bias in the peak amplitude parameters, though this had little effect on the mean amplitude parameters (Sa and Sq).

4. Conclusions

The previously unpublished methodology detailed here allows for the systematic areal parametric characterisation of gas turbine compressor rotor blade leading edges. It has been demonstrated that the leading edges of compressor blades have a unique surface character, that differs from the rest of the blade and as such should be consideration as a distinct blade region in future analysis. In the compressor examined, leading edge erosion is only significant at the tips of the IPC blades, though peak roughness does not necessarily accompany it. The highest roughness values are seen at the tip of the HPC blades where both erosion and deposition are present. Such spatial characterisations, indicates the leading edge regions most susceptible to in service damage, and it may prove possible to target future coating applications were they will be most beneficial. Uncertainty remains as to the length scale at which degradation features should be segregated for characterisation as changes in geometry or surface roughness. Future work should consider how the different effects of leading edge surface roughness and changes in geometry impact on the fluid dynamics.

Acknowledgement

With thanks to Rolls-Royce PLC for providing sponsorship for the work undertaken here

The authors gratefully acknowledge the UK‘s Engineering and Physical Sciences Research Council (EPSRC) funding of the EPSRC Centre for Innovative Manufacturing in Advanced Metrology (Grant Ref: EP/I033424/1).

References

[1] M. Willshee, Compressor deterioration. Unpublished, 1999/2000.
[2] M.N. Goodhand, R.J. Miller, Compressor leading edge spikes: a new performance criterion, J. Turbomachinery 133 (2) (2011) 021006.
[3] BS EN ISO 4287, in Geometrical product specification (GPS). Surface texture: profile method. Terms, definitions and surface texture parameters2000, British Standards Institute.
[4] L. Blunt, X. Jiang, Assessment surface topography, Kogan Page, London, 2003 (First).
[5] X. Jiang, P.J. Scott, D.J. Whitehouse, L. Blunt, Paradigm shifts in surface metrology. Part II. The current shift, P. Roy. Soc. A Mat 463 (2085) (2007) 2071–2099.
[6] X. Jiang, P.J. Scott, D.J. Whitehouse, L. Blunt, Paradigm shifts in surface metrology. Part I. Historical philosophy, P. Roy. Soc. A. Mat 463 (2085) (2007) 2049–2070.
[7] BS EN ISO 25178-604 in Geometrical product specifications (GPS) Surface texture: Areal. Nominal characteristics of non-contact (coherence scanning interferometry) instruments 2013, British Standards Institute.
[8] R. Leach, Optical Measurement of Surface Topography, Springer, New York, 2011.
[9] BS ISO 25178-606 Draft, in Geometrical product specification (GPS) – Surface texture: Areal Part 606: Nominal characteristics of non-contact (focus variation) instruments2013, British Standards Institute.
[10] R. Danzl, F. Helmli, S. Scherer, Focus variation–a robust technology for high resolution optical 3D surface metrology, Strojniski Vestnik/J. Mech. Eng 57 (2011) 3.
[11] E, Syverud, Axial Compressor Performance Deterioration and Recovery Through Online Washing. 2007.
[12] A. Hamed, W. Tabakoff, R. Wenglarz, Turbine blade surface deterioration by erosion, J. Turbomachinery 127 (3) (2005) 445–452.
[13] Sulzer-Ltd. Thermal Spray Abradable Materials for Clearance Control Coatings, 〈http://www.sulzer.com/en/Products-and-Services/Coating-Materials/Thermal-Spray/Abradables-and-Polymer-Fillers〉, 2014 (accessed 06/04/14).
[14] R. Kurz, K. Brun, Fouling mechanisms in axial compressors, J. Eng. Gas Turbines Power 134 (3) (2012) 032401.

[15] J.P. Stalder, Gas turbine compressor washing state of the art: field experiences, J. Eng. Gas Turbines Power 123 (2) (2000) 363–370.

[16] BS EN ISO 25178-6, in Geometrical Product Specifications (GPS). Surface Texture. Areal. Classification of Methods for Measuring Surface Texture2010, British Standards Institute.

[17] BS EN ISO 11562, in Geometrical Product Specifications (GPS). Surface Texture: Profile Method. Metrological Characteristics of Phase Correct Filters1997, British Standards Institute.

[18] K. Stout, L. Blunt, W.P. Dong, E. Mainsah, N. Luo, T. Mathia, P.J. Sullivan, H. Zahouani, Development of Methods for the Characterisation of Roughness in Three Dimensions, Penton press, London, 2000.

[19] A. Ghenaiet, S. Tan, R. Elder, Prediction of an axial turbomachine performance degradation due to sand ingestion, P. Instit. Mech. Eng. A: J. Power Energ. 219 (4) (2005) 273–287.

[20] BS EN ISO_25178-71, in Geometrical Product Specifications (GPS). Surface Texture: Areal. Software Measurement Standards 2012, BSI.

[21] R. Leach (Ed.), Characterisation of Areal Surface Texture, Springer Verlag, Berlin, 2013 (Springer Berlin Heidelberg, Springer).

[22] BS EN ISO 25178-2, in Geometrical Product Specifications (GPS). Surface Texture. Areal. Terms, Definitions and Surface Texture 2012, British Standards Institute.

[23] BS EN ISO 25178-3, in Geometrical Product Specifications (GPS). Surface Texture: Areal. Specification Operators 2012, British Standards Institute.