Application of Vibropeening on Aero-Engine Components

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Abstract:
Vibropeening is a ball pressure polishing method mainly used for treatment of car rims, various types of furniture and cutlery to improve their visual appearance. Vibropeening combines two important capabilities: the "burnishing" effect which decreases surface roughness without material removal and the "peening" effect which increases fatigue life through introduction of residual compressive stresses. This combination of effects in one technology enables a replacement of the two generally used technologies shot peening and vibrofinishing which allows reduction of cost especially on complex 3D shaped parts with large surfaces such as *blade integrated disk* (blisk) rotors. This paper describes the treatment of test components, the investigation of the key process variables and the method applied for process evaluation. Compared to shot peening and vibrofinishing (drum-blade-polishing), surface roughness, residual stress depth distribution and *high cycle fatigue* (HCF) strength are investigated. Assets and drawbacks are shown and discussed.

Keywords: mechanical surface treatment, vibropeening, shot peening, drum blade polishing, x-ray diffraction, residual stress, high cycle fatigue, Almenstrip

INTRODUCTION

The global competition between the aircraft engine manufacturers leads to increasing requirements regarding cost and performance efficient manufacturing. Today's increasing customer demands are focussed on low acquisition, running and maintenance cost as well as performance effective design (low fuel consumption combined with low emissions of pollutants), lightweight and failsafe construction. To fulfil these requirements the engine architecture changed from conventional bladed disks to blade integrated disks (blisks), from bolted single stages to welded multi-stage drums. Simultaneously optimized geometries generating higher compression ratios made out of new higher temperature withstanding materials became state of the art. All these modifications challenge the production departments and lead to tremendous changes of the requirement to manufacturing technologies. Especially the highly pressure and temperature loaded core engine (see box in Fig. 1) is affected by these changes [1]. Modern HPC rotors (see Fig. 2) have to resist heavy loads caused by a combination of cyclic mechanical and thermal loads as a result of high rotational speeds, instable aerodynamic forces, and high compression ratios [1]. These loads are effective against the blades. Blade thicknesses are progressively decreasing caused by aerodynamic design and lightweight construction. The demand for high compression ratios, small compressor sizes and weight saving causes the need of reducing component dimensions as well as raising the number of blades per stage. Decreasing accessibility between stages and blades combined with increasing demands for aerodynamic and product life cycle performance brings current mechanical surface treatment technologies to their limits. Today's standard requirements for HPC aerofoils are a low surface roughness of Ra ≤ 0,25 µm, elliptical leading edges for performance reasons as well as appropriate high cycle fatigue (HCF) life. To achieve these partly competitive requirements more than one surface modification process is needed today. One applied solution is shot peening of the aerofoils followed by vibrofinishing. Shot peening is used to introduce the desired compressive residual stresses but typically increases the surface roughness. Vibrofinishing improves the roughness, but might impact the shot peening effect and influence the leading edge geometry by material removal.

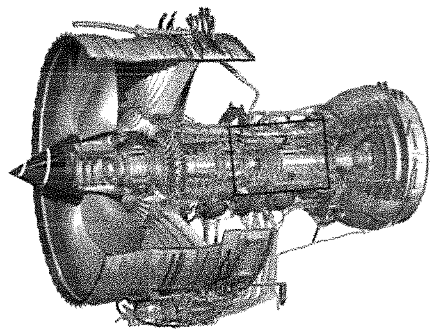

Figure 9: Rolls-Royce Trent 1000 cut-away [2]

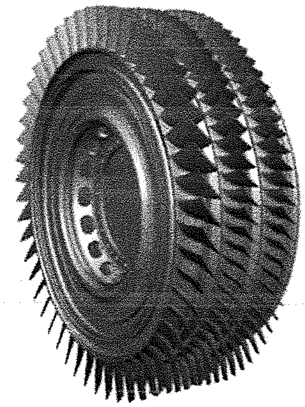

Figure 10: Rolls-Royce Trent XWB 3 stage high pressure compressor blisk rotor [2]

This paper describes the development of an alternative mechanical surface treatment of blisk rotors named vibropeening to enable a replacement of the current used processes shot peening and vibrofinishing (drum-blade-polishing). Vibropeening combines the two main effects: PEENING, the introduction of residual compressive stresses to increase high cycle fatigue strength and BURNISHING, the reduction of roughness to generate a high aerodynamic performance. Results discussed below cover surface roughness, residual stress profiles and high cycle fatigue life.

SURFACE MODIFICATION PROCESSES

Common technologies for increasing residual compressive stresses in compressor blades are shot peening, deep rolling, ultrasonic peening or laser shock peening. Each technology is experienced in single blade or single blisk treatment but only shot peening is currently used as a standard manufacturing method in multistage blisk rotors [3, 4]. The main challenge looking at alternative technologies in mechanical surface treatment of blisk rotors is the lack of space between the blisk stages and their blades. The requirement of generating even surface roughness and uniform residual stress states limits the number of capable technologies. [5] Economic aspects set additional demands to the technology with regard to acquisition, running and maintenance cost as well as complexity of the technology and training of operators.

Shot Peening

Conventional shot peening is commonly used to introduce compressive residual stresses in a wide variety of applications using steel, ceramic or glass peening media. Key process variables are the impact of the media particle on the surface influenced by the media itself (mass, hardness, size, shape and velocity) and the surface coverage, i.e. the number of hits on the surface [3]. For peening of blisks or blisk drum aerofoils it needs to be considered that accessibility is a concern and the typical impact angles around 90° are hardly achievable for all areas of the aerofoils especially for small high pressure compressor blisk assemblies. Furthermore distortion of thin aerofoils has to be minimized and elliptical leading edge geometry must be sustained. To achieve that a calliper nozzle for shot peening (Fig. 3) has been developed and patented to enable simultaneous peening of the suction and pressure side of an aerofoil. An increase in surface roughness which results in the need of further processing aiming for a decrease in roughness is the major disadvantage of shot peening.

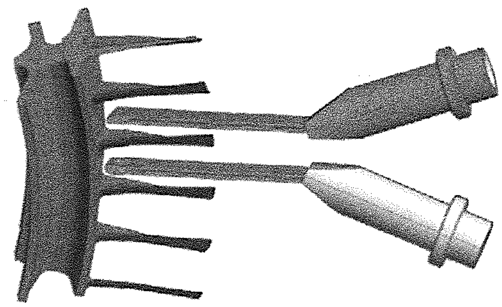

Figure 11: scheme of a calliper flat jet nozzle for shot peening of aerofoils on blisk rotors [2]

Vibrofinishing

Vibrofinishing or vibropolishing is a widely used media finishing technology, in which components are immersed in a bowl containing a polishing mixture made out of polishing chips (ceramic or plastic), abrasive paste, compound and water. The round or trough vibrators are common machine concepts used for the treatment (Fig.4). Due to vibration of the bowl the vibrations are transferred to a polishing media and cause the media flow round the work piece. Two types of media movement are realized in the bowl – circulate around in a vertical plane while moving forward around a vertical axis in a horizontal plane. The relative movement of media particles leads to interaction between chips and component surface resulting grinding, deburring, polishing and strain hardening effects. In comparison to other surface polishing technologies as burnishing or chemical polishing the vibrofinishing is simpler (fewer variables for controlling, simple design), cheaper (all features treated during one processing) and environmentally friendly. The treatment of components with complicated geometry demands investigations of geometry of each feature due to possible differences in media flow and influence of gravitational force. Vibrofinishing is used for mass finishing of aerospace engine components like aerofoil parts from fan blades to the high pressure compressor aerofoils as well as single blisk and multistage blisk assemblies [4, 5].

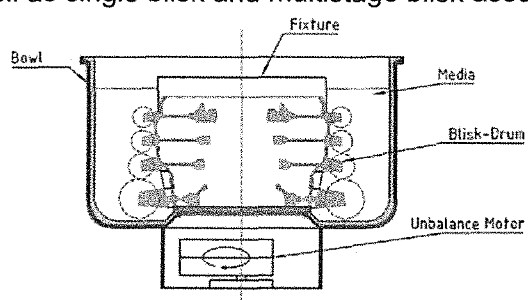

Figure 12: schematic view of a vibrofinishing (drum blade polishing) equipment [5]

Vibropeening

Vibropeening belongs to media finishing technologies and combines residual compressive stress introduction equivalent to shot peening and roughness improvement comparable to vibrofinishing.

The component to be processed is rigidly fixed to a trough or barrel, which is filled up with steel or ceramic media and moved by an unbalanced motor. The component-trough-connection starts to move through which all surfaces in contact with the media are transferring the kinetic energy to the media. This induces a movement and flow of the media which works against the surface. The parameters define the amount of simultaneous increase of residual stresses and decrease of surface roughness [5, 6, 7]. The first approach using vertical vibropeening equipment comparable to the vibrofinishing equipment (see Fig. 4) uncovered two effects. The PEENING effect generated by the movement of the media at the free surface and the BURNISHING effect inside the trough supported by the gravitational force with increasing dumping heights. Caused by the measured unevenness of induced residual compressive stresses and roughness reduction above the dumping heights a horizontal vibropeening solution became necessary (Fig. 5). The horizontal vibropeening with a driven rotational shaft enables a more uniform treatment of the areas diving through the vibropeening media.

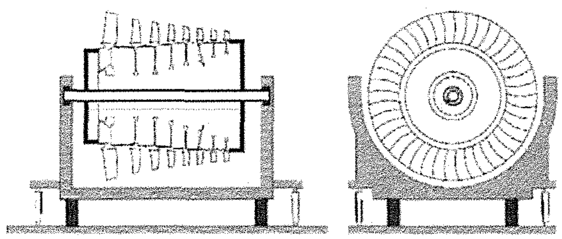

Figure 13: schematic view of a horizontal Vibropeening equipment [2]

The main advantage of vibropeening is the simultaneous treatment of all media contacted surfaces and the significant processing time reduction e.g. compared to shot peening and vibrofinishing of blisk-rotors. The results of both attempts vertical (1^{st} attempt) and horizontal (2^{nd} attempt) are shown and discussed below.

RESULTS

Experimental results reported are related to a multistage blisk assembly out of a nickel based alloy.

Roughness

Roughness was measured with a tactile measurement system from Mahr. The roughness requirement targeted in this application is Ra ≤ 0,25 µm. As shown in Fig 6 the input roughness after passing the process chain before mechanical surface treatment is an average of Ra = 0,32 µm. Shot peening increases the roughness to Ra ≈ 0,43 µm which leads to the need of an additional roughness reducing process step which decreases the roughness below requirement. Both vibropeening attempts decreases the roughness comparable to vibrofinishing below requirement. The horizontal vibropeening (2^{nd} attempt) shows the highest decrease and most even surface finish generated by slow movement through all diving depths.

Residual Stress Profiles

All of the above mentioned technologies are inducing residual compressive stresses (RCS), the standardized profiles are shown in Fig. 7. Shot peening shows high surface RCS, a RS maximum in 25 µm depth and an influence depth of about 80 µm [7]. The 1st vibropeening attempt on vertical equipment shows high surface RCS with a continuous decrease to an influence depth of about 150 µm. The 2nd vibropeening attempt on horizontal equipment shows surface RCS almost equal to shot peening with a bellied distribution in a depth of 25 µm equal to shot peening. The influence depth is higher than shot peening and lays about 150 µm.

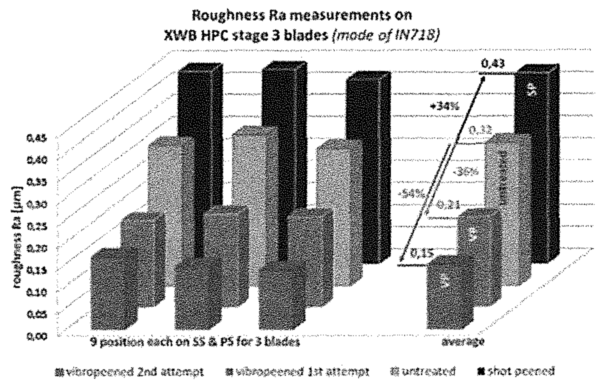

Fig. 6: roughness values for different treatments [2]

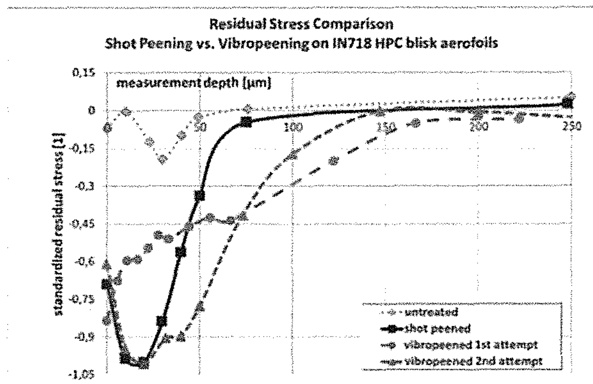

Fig. 7: comparison of standardized residual stress distributions [2]

High Cycle Fatigue

The results of the high cycle fatigue tests of the treated blisk blades are shown in Fig. 8. For each condition a set of 6 respectively 7 blades were tested for the 1st flap mode at room temperature. The bar on the right shows the average of each tested set. The untreated blades show an average value of 2,47 mHz (amplitude A in (m) times frequency F in (Hz)) with a standard deviation of 0,10 mHz. The vertical vibropeening treatment (1st attempt) increases the HCF strength of the blades of around 35 % to 3,33 mHz with a standard deviation of 0,16 mHz. The horizontal vibropeening treatment (2nd attempt) increases the HCF strength of the blades of around 51 % to 3,71 mHz with a standard deviation of 0,10 mHz.. The results of the shot peening blades show an increase of 61 % to an average value of 3,97 mHz with a standard deviation of 0,18 mHz.

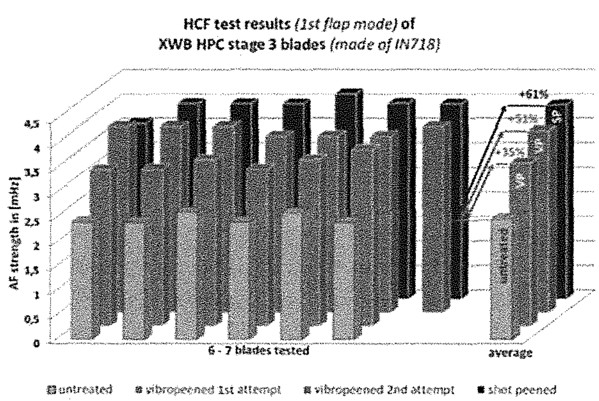

Fig 8: HCF results [2]

Component geometry
The material removal rate was defined after measurements using conventional coordination measurement systems (CMM) and optical measurements (GOM) before and after treatment.
All of the mentioned treatments affected the component geometry within the tolerances of the component.

DISCUSSIONS

Results reported show that vibropeening treatment reduce the roughness significantly below the requirement of Ra ≤ 0,25 µm whilest shot peening increases the roughness. Vibropeening treatment increases the residual compressive stresses of the untreated condition. A significant difference between the treatment with vertical vibropeening equipment (1st attempt) and with horizontal vibropeening equipment (2nd attempt) is visible. The horizontal vibropeening treatment shows beside a more even surface finish as well an almost equal residual stress state compared to shot peening. The linked high cycle fatigue results show an increase of the fatigue strength for the vertical vibropeening of about 35%, of the horizontal of 51 %. The shot peening treatment leads to an increase of 61%. The geometrical change as well as the material removal through the vibropeening process is negligible. Furthermore a dimensional change (wear) of the vibropeening media was not measurable. Assessing all results in total it can be stated that the 2nd attempt of vibropeening exceeds the capability of shot peening regarding surface roughness and residual compressive stress state, it reaches the evenness of surface finish and geometrical shape, but leads to slightly lower high cycle fatigue strength. Comparing cost assumptions for the vibropeening treatment of blisk rotors offers a significant cost reduction potential. This is due to the fact that during vibropeening all immerged aerofoils are treated simultaneously. In contrast to that during shot peening aerofoils are treated individually. In summary the vibropeening process offers potential to replace shot peening and vibrofinishing to process blisk assembly aerofoils. Cost wise vibropeening looks attractive to replace shot peening and vibrofinishing.

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Literature
[1] BRÄUNLING, W.J.: *Flugzeugtriebwerke*, Vol. 3, Springer, Berlin 2009
[2] ROLLS-ROYCE Deutschland Ltd & Co KG
[3] SCHULZE, V.: *Modern Mechanical Surface Treatment: States, Stability, Effects*; Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2006
[4] ADAM, P.: *Fertigungsverfahren von Turboflugtriebwerken*: Birkhäuser Verlag; 1998
[5] FELDMANN, G.G.: Dissertation: *Verbesserte mechanische Oberflächenverfestigung von Schaufeln an integral beschaufelten Hochdruckverdichterrotoren*, Shaker Verlag, Aachen 2012
[6] HAUBOLD,T. et al: *Optimized surface modification processes for aerofoils of blisk assemblies – shot peening, vibrofinishing and alternatives*, DLRK 2012, Berlin 2012
[7] FELDMANN, G.G.. et al: *Mechanical surface treatment technologies for improving HCF strength and surface roughness of blisk-rotors*, ICRS 9 Conference Proceeding 2012, Garmisch-Partenkirchen 2012