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Microstructure and mechanical properties of surface and subsurface layers in broached and shot-peened Inconel-718 gas turbine disc fir-trees

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ABSTRACT

Metallurgical and mechanical characterization of surface and subsurface regions in broached and shot-peened fir-trees in an industrial gas turbine disc made of Inconel-718 were carried out. High resolution scanning electron microscopy (SEM) equipped with energy-dispersive X-ray spectrometry (EDS), electron backscatter diffraction (EBSD), X-ray diffraction, optical microscopy, and microhardness instruments were employed for qualitative and quantitative assessment of alterations at surface and subsurface levels. Five specific locations along the broached and shot-peened path were selected and thoroughly examined. Original metallography methods were developed to clearly and reliably reveal microstructure constituents. Special emphasis was placed on the generated defects in view of the manufacturer's quality indices, formation mechanisms of defects, and their potential impact on the service capability of the disc. Also, advanced analysis of the EBSD data allowed assessment of the deformed layer thickness as well as the misorientation angle and grain size variations from the broached and shot-peened surface towards the bulk parent material (PM). Furthermore, through successive material removal by electro-polishing, measurement of residual stresses as a function of depth from the surface was performed by the $\sin^2\Psi$ method. The obtained results are analyzed in terms of impact of the processing conditions on the evolution of microstructure, microhardness, and residual stresses. The findings are also related to the geometrical location in the disc.

1. Introduction

Inconel-718 is a wrought Ni-Fe-Cr superalloy which is widely used in the hot sections of power generation and aerospace gas turbine engines as disc material with service temperatures up to 650 °C because of its room and high temperature mechanical properties and oxidation/corrosion resistance [1,2]. The nominal chemical composition of this alloy in wt% is 52.50 Ni-18.50 Fe-19.00 Cr-5.10 Nb-3.00 Mo-0.50 Al-0.08 C-1.01 Ti [3,4]. The microstructure of Inconel-718 consists of a face-centered cubic (FCC) Ni γ matrix containing solid solution strengtheners, *i.e.*, Fe, Cr, Mo, Al and Ti [5]. The alloy is primarily strengthened at room and elevated temperatures by uniformly dispersed Ni_3Nb body-centered tetragonal (BCT) γ'' precipitates which are coherent with the γ matrix [5]. Also, $Ni_3(Al, Ti)$ FCC γ' precipitates, Ni_3Nb orthorhombic plate-like δ phase, and MC carbides (TiC and NbC) supply additional strength for the alloy [6]. Moreover, Al and Cr form the protective impermeable Al_2O_3 and Cr_2O_3 oxide films in most atmospheres and provide the corrosion resistance for the alloy [2].

Discs and blades are generally assembled mechanically using fir-tree arrangements and broaching is one of the widely-used processes for manufacturing of the complex fir-tree profiles. This is due to the high productivity of this process as a result of very high material removal rates as well as its high potential to achieve the required surface qualities and accuracies [7]. To produce the fir-tree arrangement, the broached tool is drawn in a single or multiple passes through the disc to remove material by axial cutting [8]. The broaching operation is usually carried out in three main steps: roughing, semi-finishing, and finishing [9]. In each step, one or multiple tools with various teeth with increasing pitches are engaged to remove the material at different depths [10]. The standard broaching tool for nickel-based superalloys is made of high-speed-steel (HSS) [11]. From material aspect, it is expected that during broaching, the surface and subsurface areas experience plastic deformation under severe strain and strain rates which could result in considerable temperature gradients at specific points. Plastic deformation during machining occurs due to: (i) shearing of the work piece material and (ii) friction at the tool-work piece interface

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[12]. Consequently, under such thermomechanical conditions significant changes in the microstructure of the surface and subsurface layers can occur which will significantly affect the service capability of the disc. In addition, broaching process may induce tensile residual stresses at surface and near-surface regions. For instance, Afazov et al. [13] reported that for a work piece with a u-notch generated by broaching, the tensile residual stresses are up to 1000 MPa at the broached surface. The presence of such tensile residual stresses reduces drastically the fatigue, creep, and corrosion resistance of the component [14]. Therefore, the fir-trees are shot-peened after the broaching operation to eliminate the surface and near-surface tensile residual stresses and replace them with compressive residual stresses [15].

However, a review of the literature indicated that the impact of the broaching operation on the surface and subsurface integrity of Inconel-718 has been rarely assessed in detail in particular for components with industrial sizes. In general, compared to other machining processes, little has been published on broaching in spite of its wide industrial application. Recently, Chen et al. have published data on defects produced mostly for one point in the fir-tree profile in the broached Inconel-718 $200 \times 200 \times 50\ \mathrm{mm}^3$ coupons [16], white layer characterization [17], and effect of broaching and heat treatment on the bending fatigue behavior of Inconel 718 [18]. In particular, they observed deformed layer, white layer with nano-sized grains (20–50 nm), and tensile residual stresses at surface and subsurface layers [16,17]. For other conventional machining methods such as turning, previous studies on Inconel-718 and RR1000® nickel-based superalloy have indicated surface cracking, formation of white layer consisted of nanostructured material with the grain size in the 50–150 nm range as well as development of surface/subsurface tensile residual stresses with values close to the yield strength of the alloy [5,19–21]. The mechanisms for the grain refinement in the white layers in turned Inconel-718 [21] and broached Inconel-718 coupons [17] is related to dynamic recrystallization (DRX) occurrence as a result of: (i) grain subdivision as a consequence of sever plastic deformation [21] and (ii) adiabatic shear localization where the governing metallurgical development is rotational DRX due to mechanically-driven subgrain rotations [17]. However, these mechanisms need further clarification.

The present research inscribes in this context and its main objective is to develop a better understanding of the impact of the broaching and shot-peening operations on surface and subsurface quality, microstructure evolution, and residual stress patterns in industrial Inconel-718 gas turbine disc fir-trees. This is very important in the assessment of the disc service capability. In particular this study is different from those of Chen et al. [16–18] in: (i) examining of an industrial-size disc instead of subsize coupons, (ii) using a sharp tool rather than a semi-worn tool, and (iii) through examination of at least five locations in the fir-tree profile in place of limited number of points. Therefore, this study is more representative for industrial circumstances in terms of work piece geometry, process parameters, and thermomechanical conditions. However, the results of this study were compared with those of Chen et al. [16–18] in this contribution. Also, occurrence of any grain refinement at surface/subsurface layers and related operative mechanisms need a through and precise investigation which is conducted in this study by using EBSD and advanced analysis of the obtained results. Also, any improvement in the surface and subsurface integrity requires a well understanding of the mechanisms of defect formation during these two processes. This aspect is also addressed in this work. To achieve the aforementioned objectives, the surface and subsurface regions of broached and shot-peened fir-trees were examined by advanced characterization tools and the obtained results were documented and related to the process parameters and geometrical locations in the disc. The generated data will be used for optimization of broaching and shot-peening operations. Also, they serve as key inputs for the development of material-based finite element models predicting the fatigue life of the disc.

Fig. 1. An as-received section of the Inconel-718 disc with broached and shot-peened fir-trees.

2. Experimental Material and Procedures

An as-received section of the broached and shot-peened stage 4 Inconel-718 low pressure gas turbine disc was used for this study (Fig. 1). The part was supplied by Siemens Canada Limited, the manufacturer of the gas turbines. The broaching tools were made of HSS and were dressed after broaching of every three discs. Therefore, it can be indicated that sharp broach tools were used in this study. During broaching the disc was submerged in an oil-based coolant (Microcool 153). The broaching and shot-peening process parameters are provided in Tables 1 and 2, respectively. The as-broached disc was not available to perform an independent study on the sole impact of the broaching process on the surface and subsurface alterations.

To assess any microstructural changes that may have occurred by the broaching and shot-peening processes, metallographic sections were prepared (Fig. 2). In particular, the part was sectioned into 12 samples and samples 7, 8, 9, 10, and 12 were considered for surface and subsurface examinations. Samples 7 and 10 were from the middle section of the second and third rows, respectively. Sample 9 was from the beginning of the third row whereas samples 8 and 12 were from the end of the second and third rows, respectively. The investigated surface for each sample is also marked by an arrow in Fig. 2.

It is noteworthy that special attention was paid to preserve the sharp edge finish during metallography sample preparation as the surface and near-surface areas were of particular interests. To this end, the samples were hot mounted using a special conductive graphite powder to have the maximum edge retention and avoid edge rounding at the broached and shot-peened surface. Also, due to sensitivity of the surface and subsurface regions, automated grinding and polishing procedures were used to prepare the samples for metallographic examinations. After conventional grinding with *SiC* papers, the samples were polished on a medium nap cloth for 2 min while using 1 μm diamond suspension polishing solution.

Table 1
The broaching process parameters.

	Cutting speed		Coolant
	Surface feet per minute (SFM)	Meters per minute (m/min)	
Pass 1	9	2.80	Microcool 153
Pass 2	9	2.80	Microcool 153
Pass 3	9	2.80	Microcool 153
Pass 4	5.5	1.72	Microcool 153