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Surface Roughness Effects on the Fatigue Behavior of As-Machined Inconel718

Hamid Javadi^{1,a}, Walid Jomaa^{1,2,b}, Damien Texier^{1,c}, Myriam Brochu^{3,d} and Philippe Bocher^{1,e}

¹ Mechanical Engineering Department, École de Technologie Supérieure, 1100 Rue Notre-Dame Ouest, Montréal, H3C 1K3, Québec, Canada

² Mechanical Engineering Department, Laval University, 2325 Rue de l'université, Québec, G1V 0A6, Québec, Canada

³ Mechanical Engineering Department, École Polytechnique de Montréal, 2900 Boulevard Édouard-MontPetit, Montréal, H3T 1J4, Québec, Canada

*^ahamid.javadi.1@ens.etsmtl.ca, ^bwalid.jomaa.1@ulaval.ca, ^cdamien.texier.1@ens.etsmtl.ca,
^dm.brochu@polymtl.ca, ^ephilippe.bocher@etsmtl.ca

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Abstract. Surface finish of machined components plays a key role in their life performance. The aim of this research is to investigate the effect of different roughness parameters on high cycle fatigue behavior of Inconel718. Rotating bending fatigue tests have been performed on Inconel718 specimens with various surface roughnesses produced by turning. Height and amplitude distribution roughness parameters were investigated. Statistical analyses show that a valley material component (Mr_2), as one of the amplitude distribution parameters, is the most relevant parameter for the high cycle fatigue life of machined specimens. Observations conducted at the surface of broken specimens gage length, have shown the impact of surface roughness and residual stresses on the crack propagation mode. When the roughness increases, valleys were shown to be deeper and larger, leading to a higher Mr_2 value and an increase of stress concentration.

Introduction

Wrought Inconel718 (In718) is a commonly used nickel-base superalloy for the fabrication of massive rotating components due to its excellent mechanical properties and corrosion resistance, especially at high temperatures [1]. In order to manufacture these components with complex geometries, various types of machining are used. In718 was reported to be a very difficult-to-cut material due to its high strain-rate sensitivity, leading to considerable work-hardening during machining operations [2]. Surface integrity induced by machining is particularly important for critical structural components subjected to alternative stresses in service and is well known to strongly affect fatigue life, especially in the low stress amplitude, high cycle fatigue regime [3]. In the present study, different turning conditions aiming at producing various roughness levels, for very comparable surface residual stresses, were selected in order to examine the pure effect of surface roughness on the fatigue behavior of machined In718 specimens as explained in the materials and methods section. Different surface roughness parameters were measured and correlated with the HCF lives. Moreover optical microscopy of crack propagation pattern within peaks and valleys was carried out comparing the turning conditions with a polished specimen to document the effect of crystallography, topography, and residual stresses on the crack behavior.

Materials and Methods

Half-inch-diameter In718 bars were solution-treated and aged to reach a hardness of 41 ± 1 HRC. After heat treatment, the material showed an average grain size of about $25\ \mu\text{m}$. Cylindrical straight-shank fatigue specimens were turned (Fig. 1). Using a broad design of experiments, specimens with different surface roughness values while keeping surface residual stress at similar levels were produced. Three finishing turning conditions were selected (see Table 1) to give an average roughness (R_a) ranging from 1.24 to $4.25\ \mu\text{m}$, but very comparable residual stress values in both axial and hoop directions.

Table 1: Selected Turning conditions.

Run	Cutting parameters		
	Cutting speed S [m/min]	Feed rate f [mm/rev]	Depth of cut d [mm]
1	58	0.142	0.179
2	83	0.186	0.300
3	67	0.264	0.230

Table 2: Surface roughness parameters.

Height Parameters	
R_a [μm]	Arithmetical mean deviation
R_t [μm]	Total height of profile
R_p [μm]	Maximum profile peak height
R_v [μm]	Maximum profile valley depth
R_z [μm]	Maximum height of profile
R_c [μm]	Mean height of profile elements
R_q [μm]	Root mean square deviation
Amplitude distribution parameters	
R_{sk} [-]	Skewness
R_{ku} [-]	Kurtosis of profile
R_{pk} [μm]	Reduced peak height
R_{vk} [μm]	Reduced valley depth
R_k [μm]	Core roughness depth
Mr_1 [%]	Peak material component
Mr_2 [%]	Valley material component

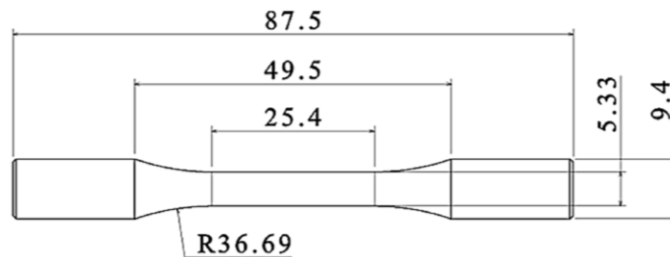


Fig. 1: Geometry of the straight-shank rotating bending fatigue (RBF) specimens (all in mm).

A 3D confocal laser microscope LEXT OLS4100 from OLYMPUS was used to measure roughness topography and its related parameters. In order to quantify the effect of surface roughness on HCF life, fourteen surface roughness parameters (shown in Table 2) were measured. Residual stresses were measured, using X-ray diffraction technique (PULSTEC μ -X360n) according to Cos α method [4], and the diffraction of *Cr K β* radiation from the (311) plane. RBF tests ($R = -1$) were triplicated for each turning condition on an INSTRON R.R. Moore machine, at room temperature, under a stress amplitude of 448 MPa and 30 Hz. After failure, an opto-digital microscope DSX500 from OLYMPUS was used to document the crack number and size observed in the gage length.

Results and Discussion

For the three selected turning conditions of Table 1, residual stresses measured in both axial and hoop directions were tensile in the range of 1000 to 1200 MPa. Nevertheless, the HCF lives varied from 4.4×10^5 to 5.5×10^5 cycles. The representative mean values of the measured roughness parameters are reported in Table 3. Most of the roughness parameters display high variations for one turning condition to the next except skewness (R_{sk}), kurtosis (R_{ku}), and peak material component (Mr_1) which remained practically constant. The equivalent 3D topographies are shown in Fig. 2 and as expected, the machined surfaces become rougher as the cutting feed increases from Run1 to Run 3.

A multiple linear regression model was used to calculate the adjusted coefficient of determination ($Adj.R_2$) for all the roughness parameters. The higher the $Adj.R_2$, the stronger is the correlation between roughness parameters and HCF life. In general, height roughness parameters exhibit a better correlation with HCF life, in agreement with [5], suggesting that fatigue stress concentration factors are well described by these parameters. The valley material component Mr_2 showed the highest $Adj.R_2$ (0.93) followed by R_p (0.91) (Fig. 3) and lower values (around 0.75) for most of the remained height parameters. The limited number of the HCF tests (three) performed for each condition and the corresponding dispersions are likely to affect the $Adj.R_2$ negatively. In addition, the high surface roughness (Table 3) and residual stress values (1000-1200 MPa) in a relatively narrow range of HCF lives may amplify the regression error. Despite these drawbacks, the calculated $Adj.R_2$ for these roughness parameters (Mr_2 , R_p , R_c , and R_v) are considered statistically acceptable. From a physical point of view, the R_v correlation illustrates the fact that a surface with deep valleys (high value of R_v) induces high stress concentration at the root of the surface profile which can reduce the HCF life. On the other hand, the Mr_2 parameter suggests that a smaller volume of critically stressed material within the base of the valley improves the resistance to crack initiation and therefore results in a longer life.

Table 3 : Measured surface roughness parameters for the turning conditions given in Table1.

Run	Height parameters							Amplitude distribution parameters						
	R_a [μm]	R_t [μm]	R_p [μm]	R_v [μm]	R_z [μm]	R_c [μm]	R_q [μm]	R_{sk}	R_{ku}	R_{kp} [μm]	R_{vk} [μm]	R_k [μm]	Mr_1 [%]	Mr_2 [%]
1	1.24	6.52	3.20	2.29	5.49	4.44	1.44	0.42	1.98	2.97	11.48	3.88	21.47	92.59
2	2.11	9.37	7.19	3.6	10.78	7.92	2.46	0.58	2.14	4.14	12.53	5.99	24.40	94.03
3	4.25	17.68	10.57	6.34	16.91	15.97	4.97	0.58	2.08	7.48	16.61	11.29	24.72	96.21

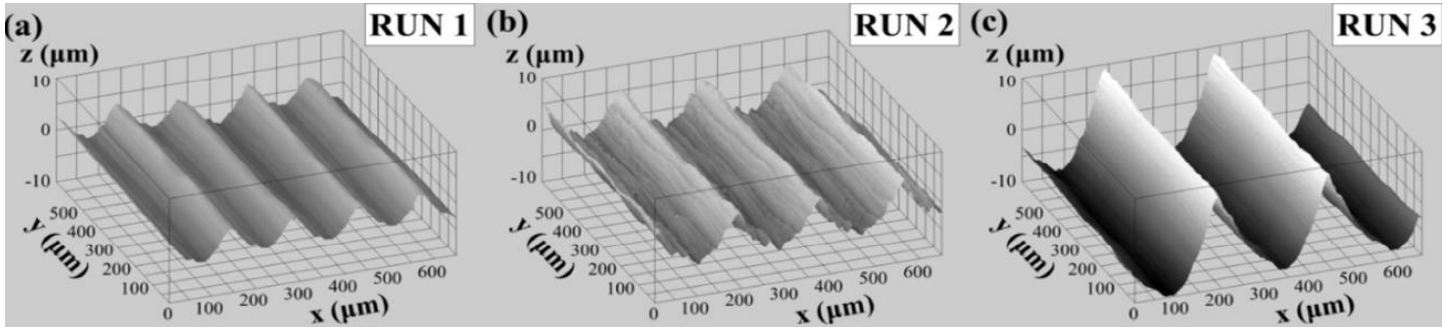


Fig. 2 : 3D topographies of turned surfaces for (a) Run 1, (b) Run 2, and (c) Run 3.

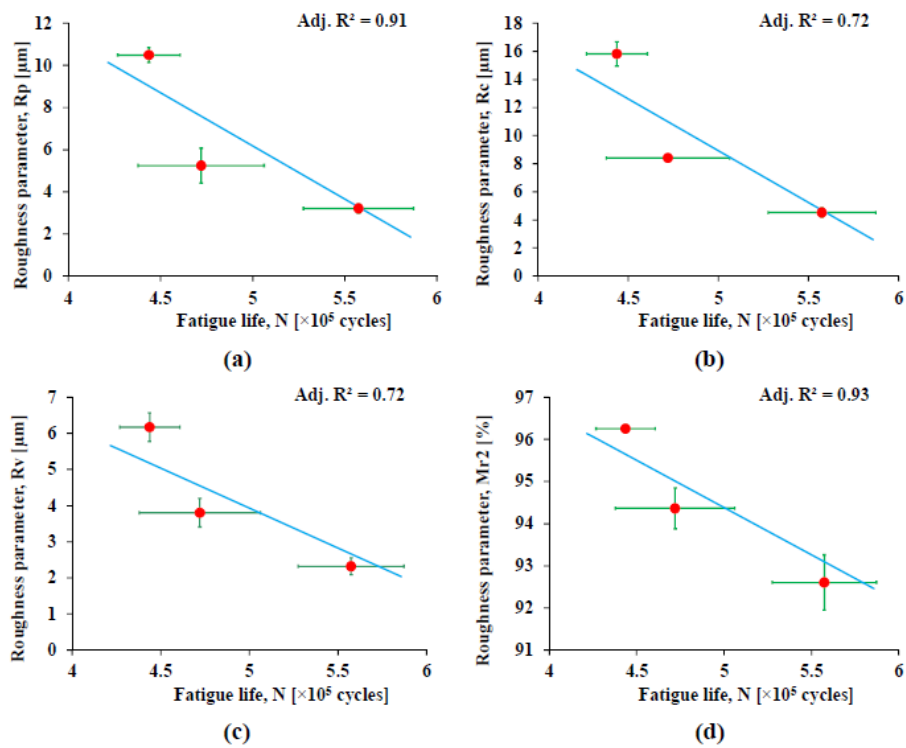


Fig. 3: Degree of direct correlation between surface roughness parameters and HCF life.

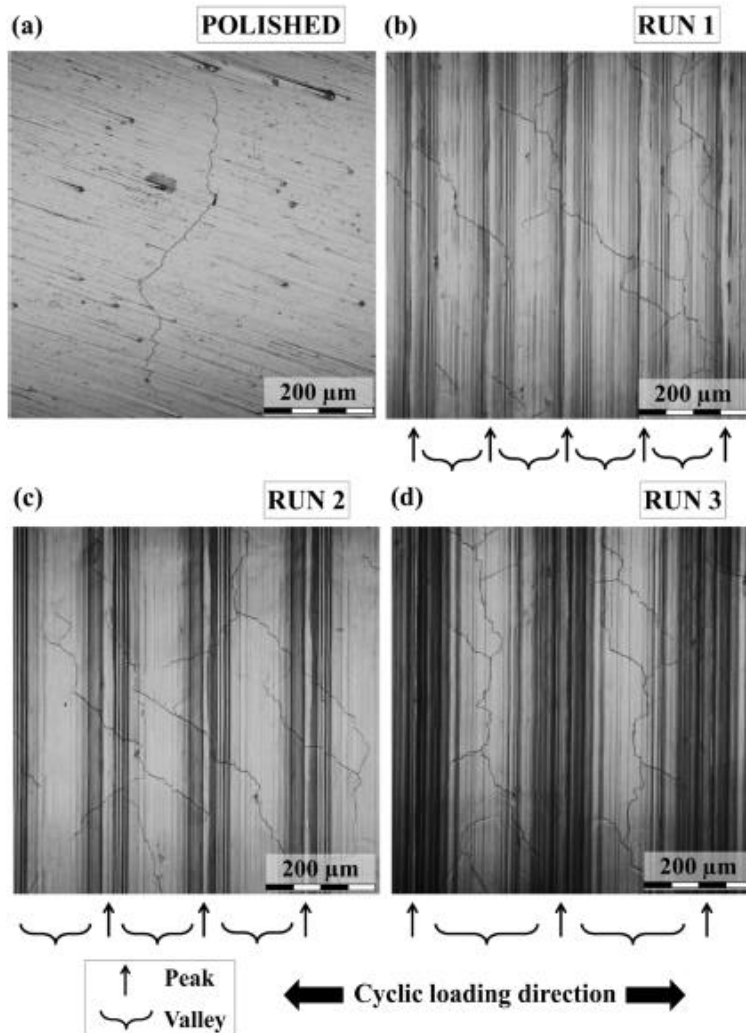


Fig. 4: Crack propagation pattern for different turning conditions: (a) Polished, (b) Run 1, (c) Run 2, and (d) Run 3.

Short crack propagation behavior seems to depend on crystal orientation, surface/subsurface residual stresses, and local topography. Fig. 4 compares the crack propagation pattern of a polished specimen with the ones observed on machined surfaces. The cracks observed on polished and relatively residual stress free specimens were found to be systematically 45-50° inclined with the loading direction. These short cracks appear in few favorably orientated grains, and when their length reaches about 200 microns, which corresponds to approximately 8 grains, they propagate in the normal direction from the loading direction, i.e. as they become long cracks (Fig. 4.a). In the conditions of low surface roughness, many crack segments, mainly oriented at 45° from the loading axis, are covering both peaks and valleys (Figs. 4.b and c). As the roughness increases, longer crack segments perpendicular to the loading direction are found on the sample surface. The turning condition characterized by the highest Rt generates millimetric cracks

confined in the valleys, crack branching between the valleys being prevented by peak regions (Fig. 4.d).

In machined samples, the presence of high residual stresses in the hoop direction and the significant roughness in the axial one generate a bi-axial stress state in the shallow region of the machining marks and causes fatigue crack growth in 45° orientation. On the other hand, as the Mr2 values are increased, machining valleys are deeper and wider, resulting in higher stress concentration in the highly stressed region of the machined surfaces. This seems to increase the number of fatigue crack initiation sites and cracks confined in between high peak regions. They end up joining together, resulting in a systematic propagation perpendicular to the loading direction in each machining valley. The machining-induced work hardening is another important parameter can be considered. The full width at half maximum (FWHM) is a good indicator of the degree of work hardening that the material undergoes [6]. The FWHM obtained for runs 1, 2, and 3 are 5.6, 5.9, and 6, respectively, against 4 for the polished condition. Obviously, the degree of work hardening is significantly higher for machined specimens, suggesting that the micro-plasticity state at the surface may have a significant role in multiple fatigue crack initiation.

Summary

The high cycle fatigue life of a wrought In718 was documented at room temperature for various turning conditions. Three different roughness ranges for a similar level of residual stress results were gathered to isolate the effect of roughness on HCF life. Fourteen surface roughness parameters from height and amplitude distribution classes were analyzed. Most of height roughness parameters demonstrated a strong correlation with HCF life. However, the amplitude distribution parameter Mr2, which represents the valley material component, showed the highest direct correlation. It was found that classical surface roughness parameters such as Ra and Rt are not the most efficient parameters to be used to quantify fatigue surface quality. It is thus suggested to use other relevant roughness parameters, such as Mr2 and Rp to better capture the fatigue performance of the machined parts. This research has also shown that roughness peaks in high roughness specimens confine crack paths in valleys. The authors suggest that the robustness of the proposed statistical analysis can be further improved by using large data of surface roughness values and HCF tests.

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