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Surface machining condition and fatigue life on Inconel 718

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Abstract

Life assessment of components working in aero-engines at elevated temperatures is critical. Machining has a serious effect on these nickel-based alloys, for example in turbine discs, affecting their life in service. Machining (turning, broaching…) modifies surface roughness, thickness of the affected substrate layer (including the effect of possible broken carbides) and residual stress distribution near the component surface. On top of that, it is possible to shot-peen or not the component, which again modifies its surface integrity. The aim of this work is to discern among the effect of the different parameter: roughness, damage and residual stresses on fatigue performance and optimum machining conditions.

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Keywords: Machining; Surface Condition; Fatigue; High Temperature; Inconel 718

1. Introduction

Life assessment of components that work at high temperatures is essential for their proper performance and simple maintenance, especially for critical components whose failure need to be avoided. For their assessment, fatigue tests are carried out on test-pieces of reference material. Surface condition, a consequence of machining procedures on component manufacture, plays a key role on their future in-service behavior, and –more relevant- in fatigue life.

Within the framework of a European project (ENOVAL), one part of the research is devoted to the study of fatigue behavior of representative specimens on Inconel 718, having turned surfaces generated of Inconel 718, under different machining conditions: cutting speeds, tool advance, tool edge wear… what introduce different depths for the

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affected/distorted substrate layer. As a consequence of these processes, different surface roughnesses and residual stresses are produced. Afterwards, the component might be shot-peened or not, what again modifies its surface roughness, residual stress patterns…

The aim of this work is to determine the effect of each one of these factors (summarized into the term of surface condition [1-13]) to its future fatigue performance at high temperature (at those temperatures pertinent for the operation of the new generation aero-engines).

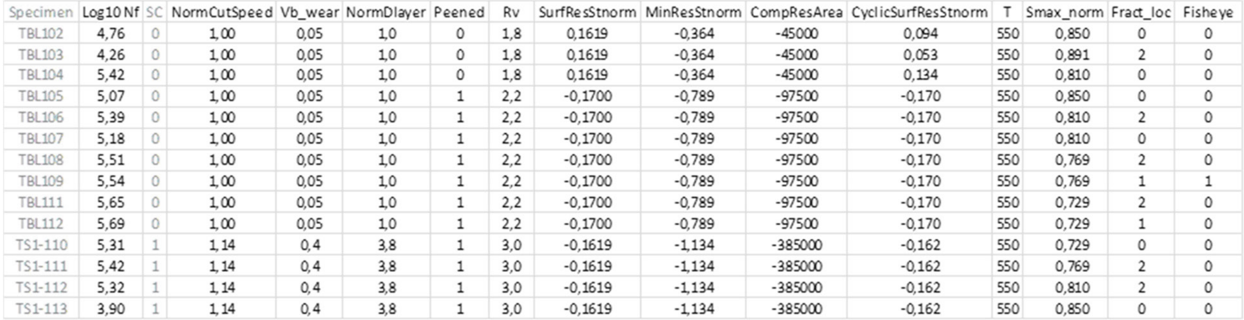
Nomenclature

BL	base line (surface condition)
Dlayer	thickness of subsurface distorted layer (µm)
MLR	mean linear regression
N_f	fatigue life (cycles)
R	load ratio (min. stress/max. stress)
R^2	discrimination coefficient
R^2_{adj}	adjusted discrimination coefficient
Rv	surface roughness (from valley, µm)
RS	normalized residual stress
SC	surface condition
Smax	maximum stress (MPa)
T	temperature (ºC)
V_{b_wear}	normalized tool wear

2. Experimental results

Table 1 shows a small section (the first 15 tests) of 105 fatigue tests carried out. All fatigue tests were under stress control, with a load ratio of R = 0.03, in a range of lives between 1E4 and 1E7 cycles. Test frequency is 2 Hz a sinusoidal stress wave was imposed for the first 500,000 cycles, afterwards test frequency was raised to 5 Hz (to speed up the test). Fatigue tests were conducted on a servo-hydraulic testing machine (Instron model 8802). Direct current heating (Joule's effect) is used to heat test-pieces. Testing temperature is controlled by means of a pyrometer, previously calibrated to compensate emissivity shifts due to surface oxidation. All test are carried out in air.

Table 1. Experimental fatigue data (only first 15 experiments).



Specimen	Log10 Nf	SC	NormCutSpeed	Vb_wear	NormDlayer	Peened	Rv	SurfResStnorm	MinResStnorm	CompResArea	CyclicSurfResStnorm	T	Smax_norm	Fract_loc	Fisheye
TBL102	4,76	0	1,00	0,05	1,0	0	1,8	0,1619	-0,364	-45000	0,094	550	0,850	0	0
TBL103	4,26	0	1,00	0,05	1,0	0	1,8	0,1619	-0,364	-45000	0,053	550	0,891	2	0
TBL104	5,42	0	1,00	0,05	1,0	0	1,8	0,1619	-0,364	-45000	0,134	550	0,810	0	0
TBL105	5,07	0	1,00	0,05	1,0	1	2,2	-0,1700	-0,789	-97500	-0,170	550	0,850	0	0
TBL106	5,39	0	1,00	0,05	1,0	1	2,2	-0,1700	-0,789	-97500	-0,170	550	0,810	2	0
TBL107	5,18	0	1,00	0,05	1,0	1	2,2	-0,1700	-0,789	-97500	-0,170	550	0,810	0	0
TBL108	5,51	0	1,00	0,05	1,0	1	2,2	-0,1700	-0,789	-97500	-0,170	550	0,769	2	0
TBL109	5,54	0	1,00	0,05	1,0	1	2,2	-0,1700	-0,789	-97500	-0,170	550	0,769	1	1
TBL111	5,65	0	1,00	0,05	1,0	1	2,2	-0,1700	-0,789	-97500	-0,170	550	0,729	2	0
TBL112	5,69	0	1,00	0,05	1,0	1	2,2	-0,1700	-0,789	-97500	-0,170	550	0,729	1	0
TS1-110	5,31	1	1,14	0,4	3,8	1	3,0	-0,1619	-1,134	-385000	-0,162	550	0,729	0	0
TS1-111	5,42	1	1,14	0,4	3,8	1	3,0	-0,1619	-1,134	-385000	-0,162	550	0,769	2	0
TS1-112	5,32	1	1,14	0,4	3,8	1	3,0	-0,1619	-1,134	-385000	-0,162	550	0,810	2	0
TS1-113	3,90	1	1,14	0,4	3,8	1	3,0	-0,1619	-1,134	-385000	-0,162	550	0,850	0	0

3. Statistical analysis

From a simple visualization, in Figure 1, the effect of shot peening on fatigue lives can be analyzed. It is concluded that it is doubtful an improvement of fatigue behavior (note that surface hardening avoid the introduction of large compressions by shot-peening). In the same way, the effect of testing temperature is shown in Figure 2. It is evident that a better fatigue live is obtained at 450ºC in comparison with 550ºC. It is much clearer the effect of turning conditions, see Figure 3. The different surface conditions are denoted as BL for Base Line, SC1 and SC2 for surface conditions 1 and 2, respectively. BL have longer lives than SC2, SC1 having the shortest lives of the three tested conditions.

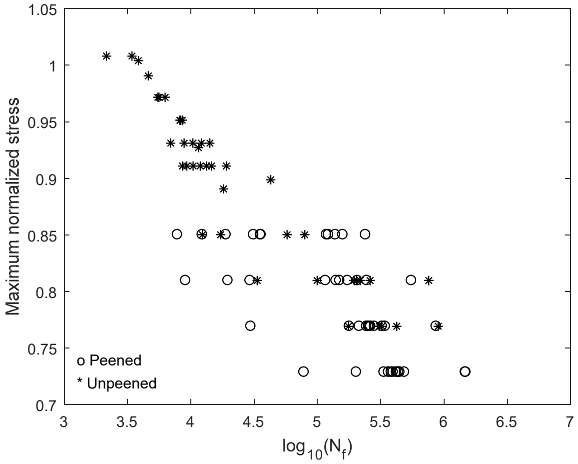


Fig. 1. *Fatigue lives versus maximum applied stress in loading cycle. Shot-peening effect.*

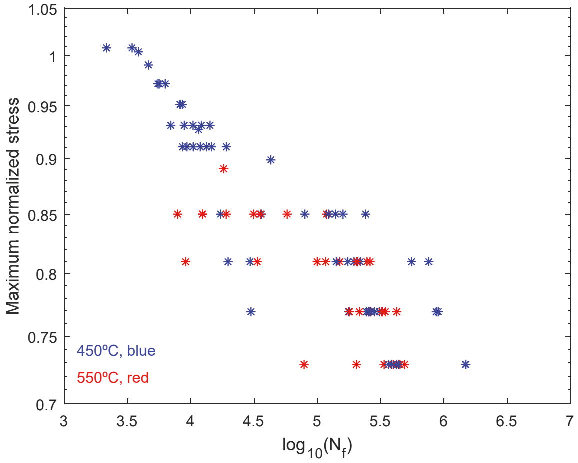


Fig. 2. *Fatigue lives versus maximum applied stress in loading cycle. Effect of temperature.*

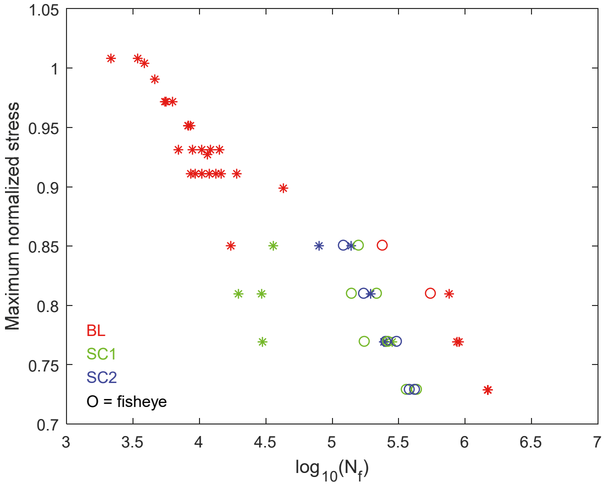


Fig. 3. *Fatigue lives versus maximum applied stress in loading cycle. Surface condition effect.*

The statistical analysis of test data is done by using Essential Regression® (free software [14]), assuming a linear relationship among the different parameters. The analysis will be split in two parts. First part is the study of the effect of machining parameters (turning: cutting speed, tool wear) and shot peening (yes/no) on the variables considered relevant for life assessment: surface roughness (*Rv*), maximum size of induced defects (Distorted layer, *Dlayer*), residual stress (RS) distribution (compressive residual area, maximum surface RS, cyclic surface RS). In a second step, we shall move from these selected variables to life estimation. A set of 105 fatigue tests is used for a Multiple Linear Regression (MLR) analysis [15,16].

3.1. From machining to physically significant parameters

Obtained surface roughness shows a very good correlation with machining parameters (R_v is considered most relevant for life assessment in comparison with other typical roughness parameters). The obtained equation for R_v, discrimination and adjusted discrimination coefficients are shown

$$R_v = 2.685 + 2.896\, V_{b_{wear}} + 0.384\, Peen - 1.052\, cutSpeed \qquad R^2 = 0.981,\ R^2_{adj} = 0.981 \quad (1)$$

In all equations, coefficients are ordered by their statistical significance. Other parameter have good correlation with machining parameters. From higher to lower correlations:

$$RS_{comprArea} = 250589 - 765599\, V_{b_{wear}} - 263177\, cutSpeed \qquad R^2 = 0.971,\ R^2_{adj} = 0.970 \quad (2)$$

$$RS_{\min(in\ depth)} = 0.305 - 0.306\, Peen - 1.099\, V_{b_{wear}} - 0.668\, cutSpeed \qquad R^2 = 0.927,\ R^2_{adj} = 0.925 \quad (3)$$

$$D_{\text{layer}} = 4.033 + 15.10\, V_{b\_wear} - 1.412\, Peen - 1.988\, cutSpeed \qquad R^2 = 0.831,\ R^2_{adj} = 0.826 \quad (4)$$

Other parameters have poorer correlations, as surface RS and cyclic surface RS

$$RS_{\text{surf}} = 0.315 - 0.170\, Peen - 0.476\, V_{b_{wear}} - 0.203\, cutSpeed \qquad R^2 = 0.577,\ R^2_{adj} = 0.565 \quad (5)$$

$$RS_{\text{cycl}} = 0.135 - 0.365\, V_{b_{wear}} - 0.0898\, Peen - 0.140\, cutSpeed \qquad R^2 = 0.429,\ R^2_{adj} = 0.412 \quad (6)$$

It is also noticeable when there is nearly no correlation. For example, fracture from an interior fisheye has no correlation with turning parameters

$$Fisheye = 0.426 - 0.209\, Peen + 0.461\, cutSpeed + 0.531\, V_{b_{wear}} \qquad R^2 = 0.185,\ R^2_{adj} = 0.161 \quad (7)$$

It should be concluded that the reasons for a fisheye are independent of machining parameters. In other words, reasons for a fracture from a fisheye should be looked far away from turning conditions.

3.2. From physical parameters to fatigue life

In a second analysis, we shall try to understand the effect of these physically significant parameters on fatigue life of test-pieces (and then on life of actual components). The variable to be predicted is fatigue life, or -more precisely- its decimal logarithm ($\log_{10}N_f$). The target is not to predict N_f, but its order of magnitude: an error of 100 cycles is not so relevant in 1 million of cycles but is a huge big error if it is compared with 2 cycles (500 cycles)…(2 cycles ≈ static failure). The parameters included for fitting are those related to the machined test-piece condition of each class (BL, SC1, SC2):

1. Surface roughness*, Rv*
2. Residual Stress field description: *RSsurf, RScomprArea, RScycl*
3. Defects and depth of distorted layer, *Dlayer*

In addition, those parameters describing testing conditions:

1. Maximum stress in the cycle, *Smax*
2. Testing temperature, *T*

In this approach, *Peen* is not included (its effects are included within *Rv, RS, Dlayer*). The best possible fitting (with significance for all parameters below 0.5) for test-piece fatigue life is given by

$$log_{10}N_f = 12.25 - 6.408\, \sigma_{max} - 4.568\, RS_{surf} + 4.087\, RS_{cycl} - 0.00223\, T + 1.084 \times 10^{-6} RS_{comprArea} - 0.256\, R_v,$$

$$R^2 = 0.783,\ R^2_{adj} = 0.770 \quad (8)$$

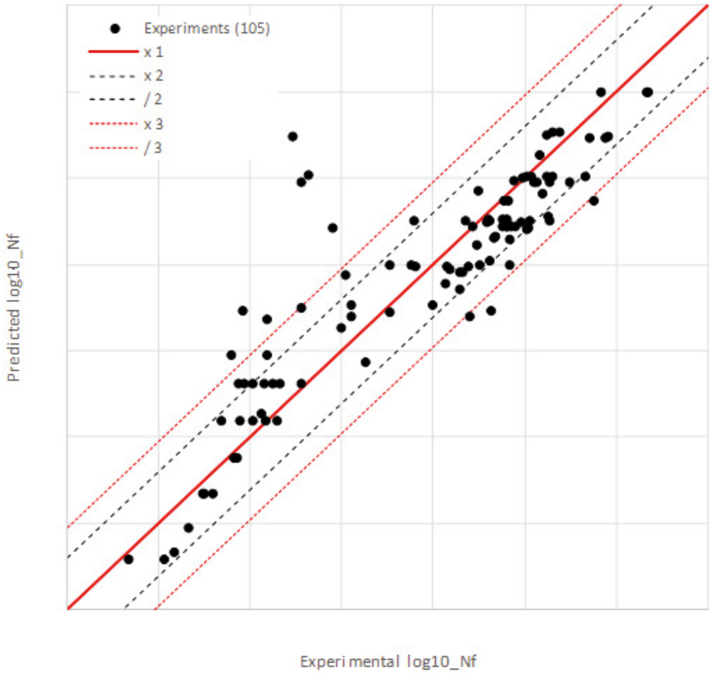


Fig. 4. *Experimental life vs. predicted by expression (8) (log-scales).*

Parameters are ordered by their statistical significance. The most important parameter for fatigue life is the maximum applied stress. (Negative values of coefficients result in life reductions.) The second parameters in importance are related to residual stresses; third parameter in importance is testing temperature (an increment in temperature results in a reduction of life. Obviously within the testing temperature range: 450°C - 550°C), and finally roughness has a negative influence in life. Figure 4 shows observed lives vs. lives predicted by expression (8). Those symbols with a common ordinate correspond to repetition tests (the experimental lives vary, but predicted life is the same for tests under identical conditions).

4. Conclusions

1. The most important factor in fatigue life is the maximum stress applied in loading cycle.
2. Surface condition plays a major role in test-piece fatigue life and by extension in later component in-service fatigue performance. The best life is obtained turning in Base Line conditions, then after SC2 machining and the shortest life is obtained after SC1 turning conditions.
3. A temperature increment from 400ºC to 550ºC is detrimental for fatigue life in this superalloy (Inconel 718).
4. Shot peening has no significant effect on fatigue life (probably because it has very little effect on surfaces hardened by turning).

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