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Procedia Manufacturing 16 (2018) 67–74

Procedia MANUFACTURING

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7th International Conference on Through-life Engineering Services

Modelling the influence of laser drilled recast layer thickness on the fatigue performance of CMSX-4

Nicolau Iralal Morar[a]* Rajkumar Roy[a], Simon Gray[a], John Nicholls[a] and Jörn Mehnen

[a]*Cranfield University, Department of Manufacturing, Bedfordshire, England, MK43 0AL, UK*
[b]*University of Strathclyde, Department of Design, Manufacture and Engineering Management, Glasgow, G1 1XQ, UK*

Abstract

This paper introduces a novel approach to fatigue life prediction modelling considering the laser drilling effect on film cooling holes of turbine vanes. The methodology proposed is based on a stress-life model such as the Basquin law and the introduction of manufacturing damage effect. The proposed empirical model gives a unique versatility compared to other stress-life models by considering surface damage such as the recast layer produced by the laser drilling process. The proposed empirical model has been thoroughly tested and validated using existing fatigue data. The statistical analysis shows that the proposed model is adequate for estimating the fatigue life of laser drilled specimens considering the recast layer thicknesses effect. The proposed model also can estimate the life of untested specimens even when only a small sample of fatigue data is available, thereby reducing the required testing data.

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Peer-review under responsibility of the scientific committee of the 7th International Conference on Through-life Engineering Services.

Keywords: Fatigue life, surface defects, laser drilling, recast layer

1. Introduction

Laser trepan drilling is one of the preferable methods of drilling shaped and complex effusion cooling film hole features in gas turbine engine blades, vanes and combustor liners [1]. However, the fatigue life of such features is

* Corresponding author. Tel.: +44 (0) 1234 75 4150
E-mail address: n.i.morar@cranfield.ac.uk

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Peer-review under responsibility of the scientific committee of the 7th International Conference on Through-life Engineering Services.
10.1016/j.promfg.2018.10.173

highly dependent on the geometrical and metallurgical quality. The quality characteristics of drilled holes are dependent on the laser processing parameters used during the drilling operation. One critical aspect of laser drilling is the formation of a recast layer thickness.

Nomenclature

ANOVA	Analysis of variance
CNC	Computer numerical control
I_P	Power intensity
LTD	Laser trepanning drilling
O_2	Oxygen
N_f	Cycles to failure
Nd:YAG	Neodymium-doped yttrium aluminum garnet
RLT	Recast layer thickness
SD	Surface damage
SEM	Scanning electron microscopy
SC	Single crystal
SN	Stress-life
R	Stress ratio
T_S	Trepan speed

The recast layer is the remaining molten material not vaporised or ejected away during the laser drilling process, which re-solidifies and remains attached to the sidewall of the holes [2]. This layer has poor surface roughness, micro-segregated microstructure and high tensile residual stresses, often leading to surface cracks, thus, having a detrimental effect on the fatigue performance.

Process parameters such as power density, pulse duration, trepan speed and associated interaction time are known to influence the recast layer thickness formation in cooling holes produced by laser trepan drilling process [3,4]. Past studies linked desirable geometrical and metallurgical quality characteristics to laser processing parameters according to specific hole shape and dimension, using experiments, statistical modelling or a combination of both [5,6]. However, no studies have modelled fatigue life considering the influence of laser drilling induced recast layer thickness. As such, this paper focuses on developing a methodology and validation of fatigue life prediction model considering the RLT effect on film cooling holes of turbine vane.

2. Experimental

2.1. Material and preparation of specimens

A second-generation SC nickel-based CMSX-4® superalloy is investigated in this work with a chemical composition presented in Table 1. CMSX-4 is widely used in gas turbines due to its inherent high resistance to creep and fatigue. The material was provided in the form of cast plates of 65mm x 8mm x 2mm in size for laser drilling trials. Fatigue specimens in the form of cast cylindrical bars of 9 mm diameter with the (001) orientation along the axis were produced. The cast plates and bars were supplied from a solution treated, precipitation hardened and hot isostatically pressed material batch in accordance with the collaborating company practices.

® CMSX-4 is trademark of Cannon-Muskegon.

Prior to laser drilling , plates were cut, machined, ground, polished and coated with anti-spatter solution as detailed in Ref [7]. The processing parameters of the LTD are shown in Table 2. The preparation of samples for metallography analysis, for example, or the recast layer thickness measurements were conducted according to the standard metallography procedures.

For the fatigue test specimens, cylindrical bars were machined according to dimensions shown in Figure 1. The laser drilling was conducted on a PowerDrill 80 CNC Nd:YAG laser drilling machine at the facilities of the Manufacturing Technology Centre, Ansty. The drilling was performed at an angle of 30 degrees to the fatigue specimen surface and the holes produced were representative of an elliptical and angled shaped effusion cooling film holes. Three levels of laser trepan speed as presented in Table 3 were used to drill the fatigue specimens and model the influence of different RLT on the fatigue performance.

Table 1. Chemical composition of CMSX-4 superalloy (wt%).

Element	Chromium	Cobalt	Tungsten	Rhenium	Molybdenum	Aluminium	Titanium	Tantalum	Hafnium	Nickel
Acronym	Cr	Co	W	Re	Mo	Al	Ti	Ta	Hf	Ni
wt%	6.5	9.6	6.4	3.0	0.6	5.6	1.0	6.5	0.1	Bal.

Table 2. LTD input parameters and their levels for OA L9 matrix.

Symbol	Control parameters	Level 1	Level 2	Level 3
A	Power density (W/mm^2)	2.89E+05	3.53E+05	4.41E+05
B	Pulse frequency (Hz)	20	22.5	25
C	Trepanning speed (mm/min)	75	100	125

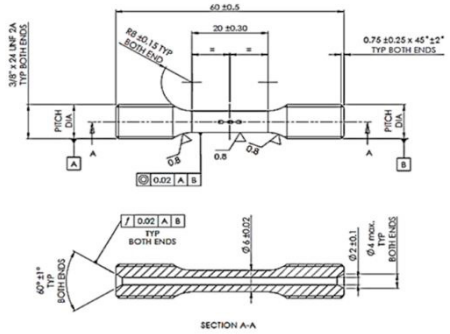


Fig.1. Fatigue specimen geometry with angled effusion cooling holes array [8].

Table 3. LTD process parameters used in fatigue specimens.

Symbol	Parameters	Values
I_P	Power density (W/mm^2)	3.53E+05
P_F	Pulse frequency (Hz)	25
T_S	Trepanning speed (mm/min)	75, 125, 150
λ	Wavelength (nm)	1064
-	No. Trepan orbits	2
-	Nozzle displacement (mm)	10
-	Focal position (mm)	0
-	Assist gas	O_2 at 100 psi

2.2. Surface damage measurements

The extent of surface damage produced by laser trepan drilling process was evaluated by measuring the recast layer thickness via SEM. Each trial sample consisted of four holes, in which the RLT was obtained by mean of maximum of 16x4 reading points each equally spaced along the leading and trailing edge side of the holes. Detailed procedure can be found in Ref [7].

2.3. Fatigue test

A uniaxial load control type rig with environmental chamber was used to for fatigue tests. Specimens were sprayed with standard salt solution prior to testing and then tested at temperature of 850ºC in an air+SO_2 environment to mimic extreme environmental conditions experienced in the internal walls of the cooling holes during service. A load ratio of R = 0 with trapezoidal 1-1-1-1 second waveform resulting in a frequency of 0.25Hz was used for all tests. A total of 24 specimens were tested under LCF regime with a 'run-out' declared at 120,000 cycles.

3. Fatigue life prediction

Fatigue life prediction methodology using the Basquin's function has been developed, and it is mostly used for fitting the observed stress-life data within the finite region of S-N curve [11]. Basquin's function has been validated for several materials, both notch specimens and smooth specimens [12]. The stress-life curve can be expressed as

$$S_a = AN_f^B \tag{1}$$

Where A and B are fitting parameters on the log-log scale S-N curve. The S_a is cyclic applied stress, and N_f is the number of cycles to failure. Several models have been proposed based on the Basquin's function to include the stress ratio and mean stress effects, stress concentration and notch sensitivity, such as Walker equation and the Smith, Watson and Topper's (SWT) model [12]. However, stress ratio effects and notch sensitivity study are beyond the scope of this study. A modified function is used to include the machining surface damage effects into proposed model as

$$N_f = (S_a SD^{\lambda} A^{-1})^{\frac{1}{B}} \tag{2}$$

In equation (2), SD is the surface damage due to machining process. The exponent λ on the SD is the fitting parameter and can be obtained using the test data under different cyclic stresses. Further, to determine each parameter in equation (2), a logarithm form can be expressed as

$$\log N_f = \frac{1}{B}\log S_a + \frac{\lambda}{B}\log SD - \frac{1}{B}\log A \tag{3}$$

Where A, B and λ are material constants obtained by the experimental SN data (see Table 4). A simple function has been proposed to determine the material constants by Ref [12] as

$$y = m_1 x_1 + m_2 x_2 + c \tag{4}$$

In equation (4), y is equal to log of N_f, x_1 is equal to log S_a, and x_2 is equal to SD_{RLT}. While, remaining parameters as in Table 5. The obtained material constants for this study are presented in the Table 6.

Table 4. Fatigue data used for modelling.

				Log transformed data		
Data No.	S_a (MPa)	Mean, SD_{RLT} (m)	N_f (Cycles)	x_1	x_2	Y
1	550	6.32E-05	6,353	2.74	-4.20	3.80
2	450	6.32E-05	54,490	2.65	-4.20	4.74
3	350	6.32E-05	108,624	2.54	-4.20	5.04
4	550	4.78E-05	18,660	2.74	-4.32	4.27
5	450	4.78E-05	80,768	2.65	-4.32	4.91
6	350	4.78E-05	240,000	2.54	-4.32	5.38
7	550	7.79E-05	4,333	2.74	-4.11	3.64
8	450	7.79E-05	38,336	2.65	-4.11	4.58
9	350	7.79E-05	89,076	2.54	-4.11	4.95

Table 5. Equation (4) parameters.

Parameters	Value
1	$m_1 = 1/B$
2	$m_2 = \lambda/B$
3	$c = (-1/B)\ log\ A$

Table 6. Estimated parameters for fatigue life prediction.

Parameters	Value
$B = 1/m_1$	-0.16
$\lambda = m_2/m_1$	0.365
$A = 10^{-c/m1}$	76.6

3.1. Modelling the influence of the recast layer

Laser drilling process is known to introduce surface damage such as recast layer and the heat-affected zone around sidewalls of the drilled hole. Latter surface damage is beyond the scope of this study. The thickness of the recast layer is highly influenced by the processing parameters used during the laser drilling operations, such as power density, pulse duration, pulse frequency and trepan speed based on the past studies [4,9]. The recast layers on the laser drilled holes not only introduce tensile stresses but also act as a stress raiser, which is detrimental for the fatigue performance of laser drilled specimens. To include the recast layer thicknesses effects, a polynomial function has been proposed to quantitate the surface damage induced by laser drilling process as

$$SD_{RLT} = \beta_0 I_P^{\beta_1} T_S^{\beta_2} \tag{5}$$

In equation (5), β_0, β_1 and β_2 are coefficients of the function. SD_{RLT} is the surface damage recast layer thickness, I_P is the power density, and T_S is the trepanning speed. The coefficient values (β_0 = 3.14E-4, β_1 = 0.22 and β_2 = 0.53) are calculated from the experimental data published by authors in Ref [7]. Equations (2) and (5) are combined to predict fatigue life considering the recast layer thickness effects on laser drilled specimens and can be written as

$$N_f = \left[\frac{S_a \left(\beta_0 I_P^{\beta_1} T_S^{\beta_2} \right)^{\lambda}}{A} \right]^{-B} \tag{6}$$

The empirical model proposed in equation (6) considers the initial surface damage caused by the key laser drilling process parameters and subsequent fatigue damage caused by the cyclic loading. The temperature, sea salt concentration and sulphur flux inputs were not variable. Therefore, environmental effect was not considered in the proposed model. The laser drilling parameters such as I_P and T_S values investigated were within a range of values typically used to generate film cooling holes in turbine blades and vanes.

4. Results and validation

Figure 2 (a-b) display plots of residuals and predicted responses versus observed data. These plots indicate that the predicted fatigue life values are in good agreement with observed data for all specimens tested. The relationship between the residuals and the normal scores is almost linear. Data points are close to the straight reference line and are randomly distributed on both sides of 0. Therefore, suggesting that the data points appears to be normally distributed. This type of plot indicates that the vertical deviations from the straight reference line are the actual residuals of the fit. A residual is positive if the corresponding data point is above the straight line and negative if the data point is below the straight line. Moreover, results of the ANOVA presented in Table 7 indicate that the proposed model (Equation 6) can acceptably predict fatigue life of laser drilled specimens within 95% confidence limits.

Table 7. Results of analysis of variance.

	Degree of freedom	Sum of Squares	Mean of Squares	F-Ratio	P-value
Regression	2	2.487334	1.243667	34.34054	0.000519
Residual	6	0.217294	0.036216	-	-
Total	8	2.704629	-	-	-
S = 0.19		$R^2 = 0.92$		Adjusted $R^2 = 0.89$	

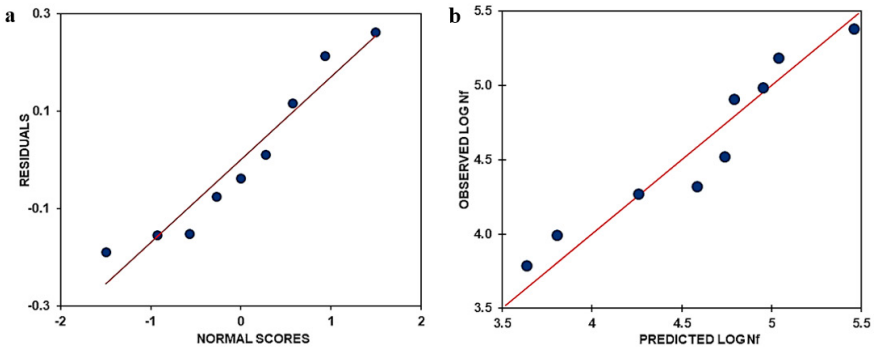


Fig. 2. (a) Normal probability plot of residuals; (b) Comparison plot of predicted versus observed data.

Figure 3 (a-b) displays the observed and predicted fatigue life performance as a function of RLT for tests with applied stress levels of 550 MPa and 450 MPa. In spite of the model predictions provide a good response against the observed data, there is relatively small difference with that of observed data. This stems from the actual fatigue data, where specimens from the same laser drilling conditions yield relatively different RLT's, hence, some scatter on the observed data.

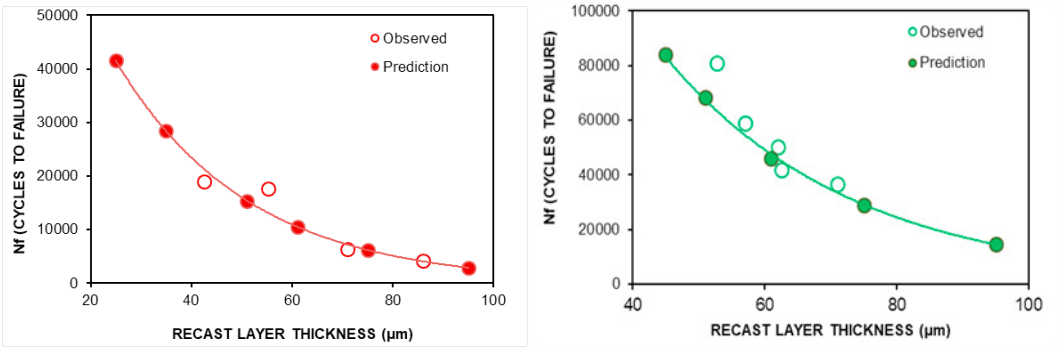


Fig. 3. Predicted and observed fatigue life versus various recast layer thicknesses for different specimens tested at: (a) 550 MPa and (b) 450 MPa.

5. Conclusions

In this study, a methodology for modelling fatigue life prediction of laser drilling specimens using stress-life approach considering the recast layer thickness is proposed. The RLT can be predicted using a polynomial function to experimental data. The proposed model can give reliable predictions under the conditions tested. The main conclusions are as follows:

1. The effect of key laser drilling parameters such as power density and trepanning speed can be modelled by the proposed methodology considering the recast layer thickness effect.
2. The thicker recast layer can significantly lead to high stress concentration and greatly reduce the fatigue strength of cooling holes. This is because thicker recast layer formed after laser drilling operation are brittle, micro segregated, and in some cases with micro cracks. The RLT can act as the main driver for crack nucleation in film cooling holes. Therefore, reducing the fatigue life of laser drilled specimens.
3. The proposed model is suitable for laser trepan drilling of CMSX-4 acute angled cooling holes. Other effusion shaped cooling holes, such as fan shaped, need further investigation because the laser parameters and hole geometry influence on the recast layer thickness might be different.

Overall, the proposed model provides satisfactory prediction responses based on laboratory testing and type of cooling hole shape investigated. It can be applied for understanding of the correlation between the laser drilling parameters, recast layer thickness, and fatigue performance. Also, the proposed model could be applied for parameters optimisation where an increase in productivity demands an increase in the drilling time.

Acknowledgements

The authors are thankful to the Engineering and Physical Science Research Council for financial support of the research work (Grant number EP/I033246/1) and Rolls-Royce Plc for the technical support and useful discussions.

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Morar, Nicolau I.; Roy, Rajkumar; Gray, Simon; Nicholls, John R.; Mehnen, Jorn

2018-11-02
Elsevier
https://doi.org/10.1016/j.promfg.2018.10.173
Nicolau Iralal Morar, Rajkumar Roy, Simon Gray, et al., Modelling the influence of laser drilled recast layer thickness on the fatigue performance of CMSX-4. Procedia Manufacturing, Volume 16, 2018, Pages 67-74

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