International Journal of Fatigue 102 (2017) 112–120

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

# The effect of trepanning speed of laser drilled acute angled cooling holes on the high temperature low cycle corrosion fatigue performance of CMSX-4 at 850 °C

N. Morar [a], R. Roy [a], J. Mehnen [a], J.R. Nicholls [b], S. Gray [b],*

[a] The EPSRC in Through-life Engineering Services, Cranfield University, MK43 0AL, UK
[b] Surface Engineering and Nanotechnology Institute, Cranfield University, MK43 0AL, UK

ARTICLE INFO

*Article history:*
Received 8 December 2016
Received in revised form 28 April 2017
Accepted 28 April 2017
Available online 4 May 2017

*Keywords:*
Hot corrosion
Low cycle fatigue
Corrosion fatigue
Laser drilling
Recast layer
CMSX-4

ABSTRACT

The effect of laser trepanning speed and, as a result, recast layer thickness on the high temperature corrosion fatigue behaviour of CMSX-4 superalloy acute angled holes was investigated. The experimental test results show that an increasing laser drilling speed caused a reduction in corrosion fatigue life by 35–50% at 850 °C, under low cycle fatigue regime. This reduction was found to correlate directly with the recast layer thickness and surface anomalies within the recast layer produced during the laser drilling process. Corrosion had a smaller effect on the overall life of the laser drilled specimens under the conditions tested. The results presented show that laser trepanning speed is influential in limiting the life performance of laser drilled components in service.

## 1. Introduction

One of the main applications of the laser drilling process in the aerospace industry includes the manufacture of cooling holes in hot section turbine blades, nozzle guide vanes and combustor liners. These components are usually made of nickel-base alloys that are resistant to high temperature and associated corrosion environment. However, the laser drilling process is known to produce localised stress concentrations, a recast layer and associated microstructural and mechanical properties changes due to these surface breaking holes [1]. Therefore, the potential for degrading the alloy corrosion resistance and increasing the susceptibility to hot cracking [2]. The severity of the surface damage due to laser drilling is dependent on the laser intensity, which, in turn, depends on the laser trepanning/percussion parameters used. Previous studies have shown that for the Nd:YAG laser drilling process, parameters such as pulse energy, pulse duration, pulse frequency, and drilling speed are the most influential; increasing the recast layer thickness and leading to micro crack formation both in percussion [3] and trepanning mode [4].

The effects of laser drilling processing on the fatigue strength of nickel-base alloys has recently been studied, showing the effects of roundness error on the cooling film holes through experimental and finite element (FE) modelling [5]. The results showed that irregularities on the contour profile of the laser drilled hole caused by the recast layers could significantly decrease the life of the drilled holes. Moreover, the larger the roundness error, the shorter the low cycle fatigue life. In a another study, Degeilh et al. [6] investigated laser drilling effects on three different hole diameters. A damage model was used to characterise the fatigue lifetime. The model consisted of a 3D averaging method that takes into account the material microstructure and hole shape. The results showed that small hole diameters, under 0.4 mm, had a better performance when compared to large hole diameters, under 0.8 mm, and electro-discharge machined (EDM) holes of diameters of between 1.0 and 2.0 mm. The difference between the laser and EDM drilling fatigue life was caused by the difference in the microstructure, thickness of the heat affected zone and surface roughness of the specimens.

Further studies have been conducted to assess the thermal-mechanical properties of thin-walled cylindrical specimens with laser drilled holes [7]. The results showed that the lives of laser drilled holes were four times shorter than that observed for smooth plain specimens under similar loading conditions. Pan et al. [8] used a local stress approach for assessing the fatigue life of laser drilled holes at high temperatures, between 700 °C and 900 °C. The metallographic analysis suggested that the microcracks

---

* Corresponding author.
*E-mail address:* S.Gray@Cranfield.ac.uk (S. Gray).

http://dx.doi.org/10.1016/j.ijfatigue.2017.04.017
0142-1123/

induced by laser drilling had no significant influence on the total life of the specimen under a low cycle fatigue regime ($10^5$ cycles). In an earlier study, Gemma and Phillips [9] used fracture mechanics to predict the life of different cooling hole configurations formed by laser drilling, EDM, and electrochemical machining (ECM) under thermal-mechanical fatigue conditions. They found that the defects introduced by the different drilling techniques generates a range of initial defect sizes and that this knowledge could be used to estimate the life of cooling holes for each drilling technique, Nevertheless, studies reported in current literature as above referenced have not fully detailed the laser drilling conditions and their influence on the corrosion fatigue behaviour.

This paper attempts to fill this gap in the literature, relating to the effects of recast layer thickness, varied by laser trepanning speed, on the high temperature low cycle corrosion fatigue (HT LCCF) life of CMSX-4[*] nickel-based superalloy acute angled holes.

## 2. Experimental details

### 2.1. Specimen manufacture

The CMSX-4 material used for this study was in the form of single crystal cylindrical bars of 9.0 mm diameter that had been solution treated and aged. The chemical composition is listed in Table 1. The laser drilling was performed at an angle of 30 degrees on the fatigue specimens by a computer numerical control (CNC) Nd:YAG laser drilling machine. Due to the size and scope of this study, a decision was made to investigate only the laser trepanning speed settings. The decision was based on the reported work [4] and preliminary trial results conducted in previous work [10]. The three different laser trepanning speed settings selected has been shown to influence the recast layer thickness (RLT) and overall surface integrity of angled drilled holes. The remaining process parameters, including pulse energy, pulse duration, pulse frequency, nozzle displacement, focal point, and assisted gas pressure were kept constant for simplicity.

The laser drilling parameters employed based on parametric study [10], has ensured that the recast layer thickness after laser trepanning drilling (LTD) conditions A, B, and C achieved a range of values of between 4 and 85 μm mean maximum values, see Table 2. It was not possible to measure the RLT of the pre-tested fatigue specimens and thus the data was obtained from CMSX-4 flat plate using the same drilling parameters as the fatigue specimens.

Post drilling processes including, ultrasonic cleaning, grit blasting, and heat-treatment were conducted according to the manufacturer standard procedures as this would reflect the current practices in the production of holes in hot section aircraft engine components. The details of the post-drilling processes are proprietary data. A total of 5 groups of specimens were investigated. Three were from laser drilled batches, one from EDM drilling, condition D (see Table 2), and lastly, an undrilled plain specimen group. Each fatigue specimen contained three angled holes at 30 degrees to the surface on a centre line, with a diameter of 0.75 mm, and a depth of 4.0 mm, as shown in Fig. 1. The spacing between drilled holes is similar to that found on the of hot section aircraft engine components.

### 2.2. Test procedures

A servo-hydraulic environmental fatigue testing machine was used to perform corrosion-fatigue testing at 850 °C, with a continuous flow of premixed air + 300 vppm $S0_2$, at a flow of 80 $cm^3$/min. Before testing, all specimens were coated around the gauge length with salt solution consisting of a fully saturated 98% $Na_2S0_4$ + 2% NaCl mixture. This salt coating procedure, along with the test gas used, enables a good simulation, to achieve microstructures similar to those seen in the service operating environment of hot section aircraft engine components. The tests were conducted in a low cycle fatigue regime under load control to a stress ratio of zero and trapezoidal waveform of 1-1-1-1 s (0.25 Hz). Load control was used since strain control was not possible due to the test environment, and its containment, not being conducive for suitable strain measurement. The tests were performed at several maximal stress levels from as low as 290 MPa–550 MPa. The cyclic loading was applied continuously to each specimen until rupture occurred or a history of 110,000–120,000 cycles had been applied, at which point the testing was stopped and considered to be a run-out.

### 2.3. Metallography

After testing, all failed specimens were inspected via scanning electron microscopy (SEM) in order to confirm the fracture morphology and extent of corrosion. Electron dispersive X-ray spectroscopy (EDX) was used to identify the corrosion compounds on the fracture surface. Further examination required the fractured specimens to be cross-sectioned for measurement of the actual recast layer thicknesses. The metallographic preparation procedure is similar to that described in [10], with particular attention made to sectioning, grinding and polishing with an oil-base lubricant in order to minimise the loss of any corrosion products. The recast layer thickness measurements for the majority of the specimens were taken and recorded. These measurements were conducted at eight equally spaced points both from the leading edge side and trailing edge side of the hole. Only the maximum averaged values were used for the comparison and explanation of the results.

## 3. Results

### 3.1. HT LCCF tests

Fig. 2 shows the results of the tests conducted on the laser drilled specimens. Five sets of experimental data include laser drilling conditions: LTD set A (blue circle); LTD set B (green square), LTD set C (red triangle), and EDM (yellow diamond). The trendline for non-drilled specimens is depicted as a black dotted line and has been tested under the same environmental conditions. As a comparison, unpublished air only data has been included that was supplied by the sponsor of this work using the same loading conditions. It can be seen, from a comparison of non-drilled corrosion data with the non-drilled air only data, that there is a debit of approximately 10% associated with the corrosion-fatigue interaction. However, when comparing the drilled holes with the air data, there is a performance debit of approximately 35%–50% (or 25%–40% assuming a cumulative effect) suggesting a much greater impact of the drilling process. The results also show that the HT LCCF behaviour of specimens with laser drilled holes at different conditions are dependent on the trepanned recast layer thickness. The poorest HT LCCF performance was obtained in laser drilling conditions A and C specimens which had the thickest estimated recast layer. The results confirm that the HT LCCF strength was strongly influenced by high trepanning speed. Moreover, it highlights that the recast layer thickness induced by the laser drilling process, when less than 50 μm has the better fatigue life characteristics.

Further, unbroken specimens (previously stopped as a run-out) were later re-tested at an increased load in order to verify the endurance limit. The specimens with LTD set B conditions did

---

[*] CMSX-4 is a registered trademark of Cannon-Muskegon Corporation.