Improving Part Qualifying Performance Using Compliance Crack Monitoring Under Rotating Bending Tests

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Abstract

Part qualifying testing is a critical part of product development especially for mission critical components. This is more pronounced in cases where new manufacturing techniques such as high speed machining, additive manufacturing and wire electrical discharge machining are applied. Such techniques invariably modify the surface integrity of the components by introducing amongst others residual stresses and altering surface roughness. If left unattended, this may affect the performance of the product in service. Therefore, there is a need to qualify products before full commercial production and to link the manufacturing strategy to anticipate in service part performance. Endurance qualifying tests for certain products and components may include full scale endurance testing and/or a machining strategy endurance evaluation by fatigue testing either axially or in bending. Crack growth monitoring can be used to indicate the durability and performance of the product. However, crack growth monitoring during axial or rotating bending conditions is challenging and expensive. The aim of this paper is, therefore, to report on the development of a compliance based crack monitoring technique that can reduce the cost and improve the effectiveness of product qualifying tests. Tests are conducted on grade 5 titanium alloy (Ti6Al4V) specimens produced using high speed turning. These are then subjected to a rotating four point bending configuration test. Defect (crack) formation and growth (size) may then be estimated by compliance (strain) monitoring. This technique was found to be a viable low cost option for monitoring components during rotating bending conditions and to link the manufacturing technique to part performance with specific reference to dynamic loading.

Keywords

Compliance monitoring, Part qualifying tests, Rotating bending fatigue tests, Surface integrity

1 INTRODUCTION

Mechanical products and other technical products in general, experience a wide range of mechanical stresses during production, transportation and service. In addition, they are subjected to a variety of environments during their life cycles which may extend or shorten product life. Some of these conditions cannot be predicted during product development and hence have to be verified by testing. Furthermore, manufacturing techniques are always evolving as new methods are developed mainly aimed at reducing product cost. A case in point is the introduction of high speed machining in the production of titanium components which may result in reduction of secondary processing costs. However, such techniques may have unintended consequences on product performance by introducing, among others, residual stresses and altering the surface roughness of the component [1], [2].

In the aerospace and automotive industries, more so for military applications, proving and certification tests are a necessity and stringent. For example military standards require certain levels of ruggedness which is qualified under a range of demanding conditions [3]. The same applies to civilian applications [4]. Therefore, Original Equipment Manufacturers (OEM's) have to conduct extensive product qualifying tests to comply [5]. This calls for low cost qualifying solutions to keep product development costs viable.

Most damage in critical mechanical components is due to alternating loads and hence stresses. This damage progresses through crack initiation and propagation leading to fracture. This commonly occurs at stress hotspot locations that typically exist on the surface of the component especially in components subjected to bending loads. Hence, this phenomenon determines the life of the component or product (fatigue). Fatigue tests are therefore a significant part of product development, product qualification and durability assessment.

Four and three point rotating bending tests including rotating cantilever tests are well established fatigue testing procedures for establishing the performance of rotating components such as rolling stock and automotive axles [6]. Crack growth monitoring, which is important to establish the extent of component damage and residual life, is difficult to implement under these conditions. Development of damage tolerance maintenance regimes relies on the ability to detect and monitor crack initiation and propagation. Therefore, this paper reports on a low cost methodology with potential to detect and monitor cracks during rotating bending fatigue testing which is suitable for application in qualifying product components subjected to rotating bending.

2 EXPERIMENTAL PROGRAMME

2.1 Aim

The aim of this experimental programme was to assess the fatigue performance of a selected machining strategy by measuring the variation of surface strain on a specimen during four point rotating bending fatigue testing.

2.2 Materials

Tests were conducted on specimen machined from grade 5 titanium alloy (Ti6Al4V), extra low interstitial (ELI) alloy supplied in bars of 31.55 mm diameter and length of 152.4 mm. According to the material certificate, the composition of the material was 0.008% nitrogen, 0.013% carbon, 0.0021% hydrogen, 0.18% iron, 0.12% oxygen, 6.03% aluminium, 3.94% vanadium and the balance being titanium. The material met the ASTM F136 specifications. Nominal mechanical properties according to the material certificate are given in Table 1.

Ultimate Strength (MPa)	0.2% Proof Stress (MPa)	Elastic Modulus (GPa)	Hardness (HRC)	Elongation (%)
1026.6	939.3	115	32	14

Table 1- Material properties of Grade 5 titanium alloy.

2.3 Specimen Preparation

2.3.1 Specimen Geometry

A range of different specimens are suggested for rotating bending fatigue testing. The configuration for the specimen used in this investigation is shown in Figure 1. This geometry is also recommended by ASTM E466-96(2002) and the DIN 50113 standards. It was selected based on the need to capture the effect of high speed turning over a representative size of the specimen surface. The gauge length of 50 mm provides an effective turning cut length of 12.57 m that allows this to be achieved. The specimen diameter of 16 mm was dictated by the need to attain 250 m/min for the available maximum machine spindle speed of 6000 rpm.

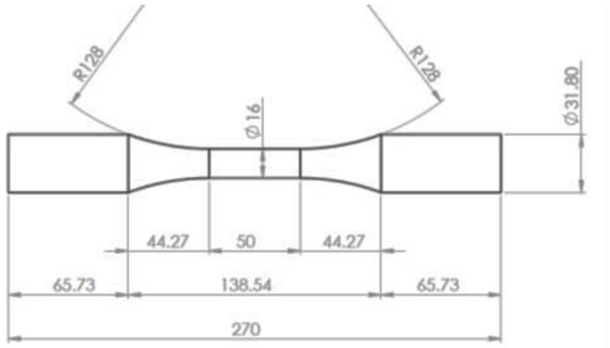


Figure 1 - Rotating bending fatigue specimen

2.3.2 Specimen Manufacture

Specimen were manufactured by turning using a range of cutting speeds. Machining speeds of 70 m/min, 150 m/min and 200 m/min were selected to investigate the effect of HSM on fatigue performance of Ti6Al4V. These cutting speeds corresponded to spindle speeds of 1392.3 rpm, 2984.2 rpm and 3978.9 rpm respectively. Accelerated tool wear and spontaneous ignition of chips limited the cutting speed to 200 m/min for both dry cutting and conventional flood cooling. The depth of cut was set at 0.25 mm with a feed rate of 0.2 mm/rev under flood cooling. This represents typical finishing cut machining conditions. This also captures the typical conditions under which machined components are placed into service. A total of 10 specimens were prepared at each of the selected cutting speeds.

The cutting tools used were supplied by Sandvik Coromat. The recommended tools for cutting titanium are H1P and H13A. These are both supplied with and without chip breaking technology. An uncoated cemented carbide tool insert (H13A) with a tool nose radius of 0.8 mm and chip breaking technology was used for this investigation. The exact designation of the tool used is:

DNMG 15 06 08 – 23 H13A

where D represents 55^o included angle tool shape, N is the 0^o insert angle, M is the tolerance, G is the chip breaker shape, 15 is the tool cutting edge length in mm, 06 is the insert thickness in mm, 08 represents the 0.8 mm tool nose radius and 23 is a manufacturer geometry code, in this case indicating finishing cutting.

2.4 Equipment

Specimen machining was conducted on a high speed Efamatic RT-20 S CNC lathe machine running a FANUC controller (Figure 2). This is a single spindle machine with a maximum spindle speed of 6000 rpm driven by a 15 kW hydraulic motor. The AC servo motor driven x- and z-axes travel at 24m/min with a maximum radius of 260 mm for the x-axis and 450 mm for the z-axis. The machine is equipped with a quick indexing 12 post tool turret with integrated high pressure coolant delivery system. All specimens were prepared using the same machine which ensures that variables of machine stiffness remain constant.

Figure 2 - Efamatic RT-20 S CNC machine

Specimen were subjected to rotating bending fatigue to initiate defect formation. A special rotating bending fatigue testing machine was developed for this purpose to achieve the required load levels. The machine developed is shown in Figure 3.

Figure 3 - Rotating bending fatigue testing machine

2.5 Experimental Procedure

Prior to testing, the fatigue machine was calibrated by loading the specimen while monitoring strains under static conditions. To monitor crack initiation and growth, strain gauges were mounted onto the specimen as shown in Figure 4. Strain logging was done using wireless strain loggers (SG Link) supplied by Microstrain. These allow real-time wireless transmission of the strains to a base station connected to a data logging computer. Two strain gauges were used connected in quarter bridge configuration. System control was achieved using Node Commander Software supplied by Microstrain.

Figure 4 - Strain logging configuration

Calibration data obtained for the machine is shown Figure 5. The difference in loading and unloading data points is due to frictonal effects in the system. Since there was not return spring mechanism, the specimen remained loaded by displaced machine components leading to higher unloading strains. Furthermore, Figure 5 shows the relationship between the experimentally measured strains and the numerical predictions. The close correlationship validates the numerical model.

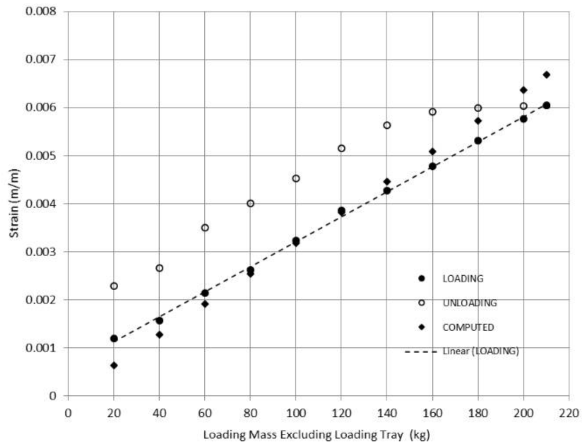


Figure 5 - Mass vs strain response of machine

3 NUMERICAL MODEL

3.1 Introduction

Numerical simulations in this work were conducted using the general Finite Element Analysis (FEA) package Abaqus 6.13 [7]. Abaqus provided two approaches to model cracked components. One approach is to model the crack geometry as accurately as possible by using extensive localised mesh refinement in the crack tip zone to capture the large stress gradients. This is implemented in Abaqus using the seam approach. This is a time consuming process both in terms of pre-processing, processing and post-processing but yields more information on the crack tip stress field. An alternative approach is the crack enrichment technique. In this case the crack is modelled as an enrichment feature without the need to refine the mesh in the crack tip zone in order to capture stress gradients. This technique is implemented in Abaqus 6.13 as extended finite element method (XFEM). XFEM was selected for crack size - strain calibration simulations due to its limited complexity and lower processing resources for non-propagating cracks.

3.2 Material Model

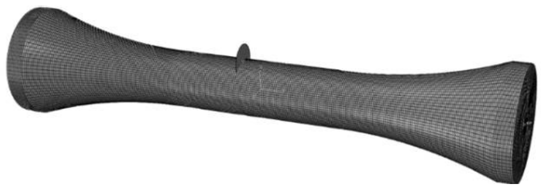
The material was modelled using a modified Jonson-Cook model to capture nonlinear behaviour [8]. The parameter modifications were made to match available material properties data. The parameters used are shown in Table 2 against the Johnson-Cook standard parameters.

Parameter	A (MPa)	B (MPa)	n	C	m
Current work	*939.39*	*461.09*	*0.34*	*0.012*	*0.8*
Johnson-Cook	862	331	0.34	0.012	0.8

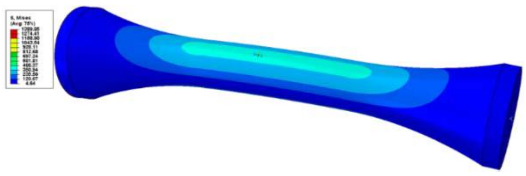
Table 2 - Johnson-Cook material parameters [8]

3.3 Model Geometry

The specimen was modelled as a 3D body built-in at one end and subjected to a point moment at the free end of magnitude 150 000 N-mm. The extended clamping sections on the two ends of the specimen were removed to reduce element count. After a mesh sensitivity study, an element size of 0.5 mm was selected. The initial crack was modelled as a circular disk of 1 mm diameter. Although there was an option to activate crack propagation, all cracks were considered stationary. Figure 5 shows the meshed specimen (a) and stress distribution (b). The uniformity of the stress distribution over the gauge length of the specimen is evident providing for the random crack initiation at any point along the gauge section of the specimen.



(a)



(b)

Figure 5 - Specimen model (a) Meshed (b) Stress distribution

3.4 Strain Response with Crack Growth

The crack size was varied in 0.5 mm increments of radius from 0.5 mm to 10 mm. In addition, the position of the crack was varied in increments of 5 mm from the centre of the specimen. The variation of strain with circumferential position for a crack located 5 mm from the centre of the specimen is shown in Figure 6.

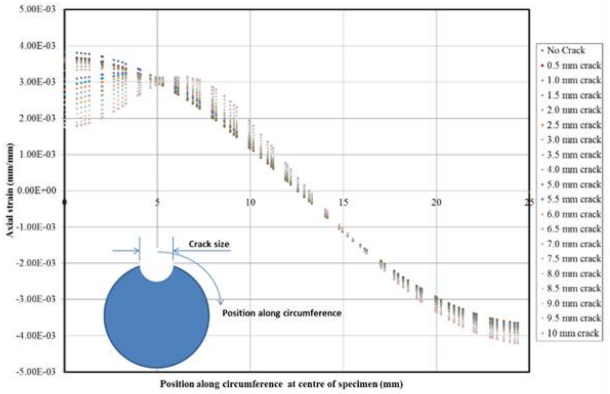


Figure 6 - Variation of strain with circumferential position for crack located 5 mm from the centre

When the deviation of the strain from the uncrack specimen response is considered, the strain distribution is shown in Figure 7.

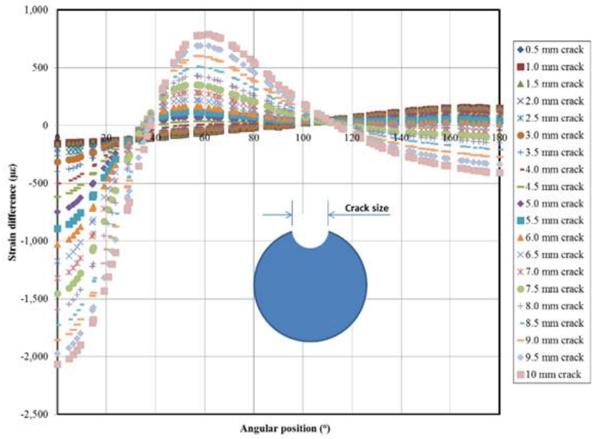


Figure 7 - Strain variation as a function of position along the circumference for different defect sizes (5 mm off centred in gauge length)

If the variation of the strain is now considered for a single location, the result is the response shown in Figure 8. This shows that as the crack propagates, the strain increases thus providing a means to monitor crack growth.

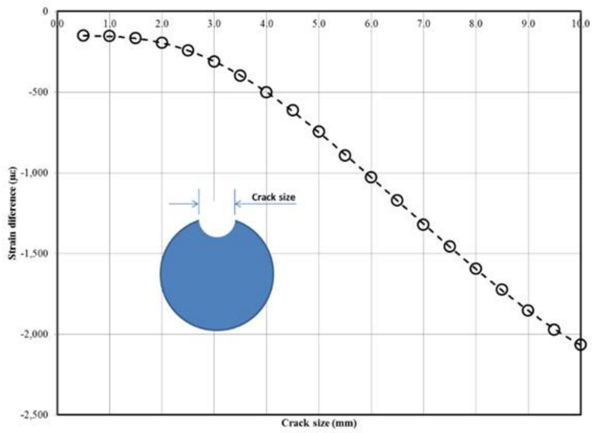


Figure 8 - Variation of strain at single point in line with crack initiation point as a function of crack size

4 FATIGUE TEST RESULTS

Figure 9 shows the fatigue signal for a titanium specimen subjected to a load of 160 kg (equivalent to 585.49 MPa on the gauge section). This represents 62.33 % of the yield strength of the material. This ensured a finite fatigue life since endurance limit for Ti6Al4V has been reported to lie in the range 529-566 MPa. The specimen failed after 51444 cycles. Data logging was conducted continuously at 128 Hz while the machine was running at 10 Hz. The figure also shows the expected change in strain as the specimen cracks and crack propagation progresses. This variation of strain (change in compliance) therefore provides opportunity to monitor crack growth during rotating bending tests. As expected, the crack initiation occupied a significant portion of fatigue life.

The quality of the signal is important to the success of this technique. For the current tests, no signal conditioning was applied.

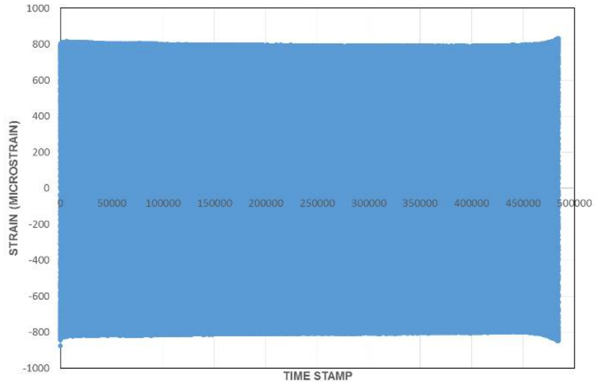


Figure 9 - Sample strain-time response during tests

The quality of the signal as obtained can be seen in an extract of a portion of the signal presented in Figure 10. Overall, the signals received were largely noise free. Minor errors occurred when resolving the peaks (turning points) because of the sampling rate that may not capture the exact maximum and minimum values. This was deemed insignificant when considering the total number of cycles evaluated.

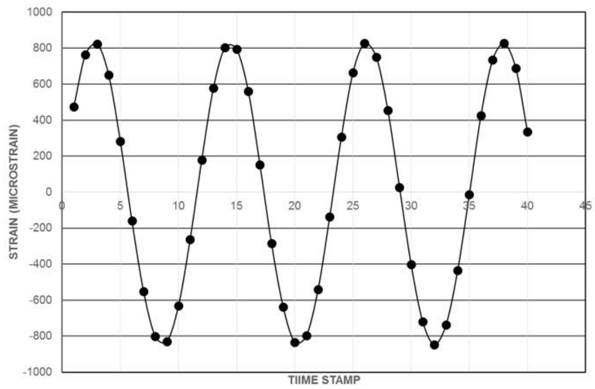
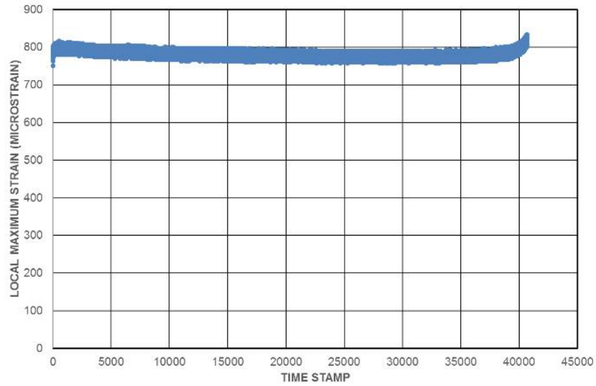
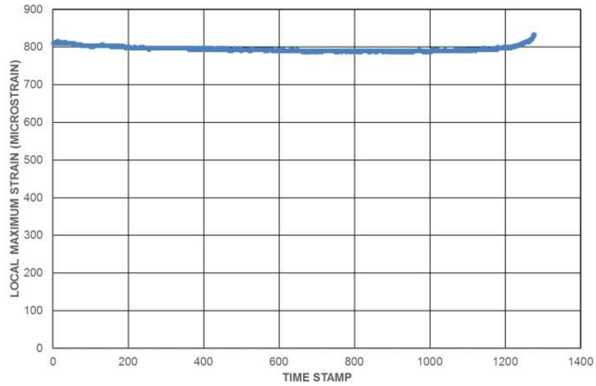


Figure 10 - Extract of the fatigue strain signal

To extract the crack growth information, the local maxima (positive) or local minima (negative) can be extracted. For this work, this was done by writing a simple analysis program in Matlab. Another simple tool that can be used is the VBA macros in Microsoft Excel. Data reduction in this case implies sequential maxima extraction. Simple averaging or filtering of the extracted maxima and minima values is inappropriate as it guarantees lower offset results. The result of the first maximum data point extraction run is presented in Figure 11(a). The result of a subsequent second extraction using the results of the first run as input data is presented in Figure 11(b). The banded nature of the signal in both figures shows the presence of secondary higher frequencies. These higher frequency signals could be caused by a variety of factors such as power transmission components (e.g. bearings and universal joints) or out of balance forces arising from strain loggers that were strapped to the collets. Spectral analysis will reveal more information.



(a)



(b)

Figure 11 – Maximum strains vs time

Further simplification of the local maximum strain signal yields the result shown in Figure 12.

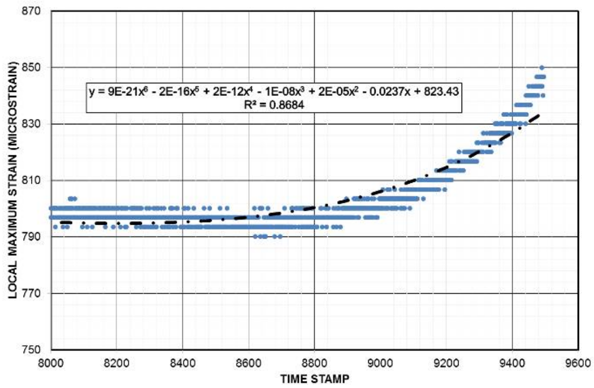


Figure 12 – Strain variation during crack growth

This variation in strain can therefore be used to track the progress of crack growth. The variation of the strain measured (change in compliance) at a known location is related to the size of the defect before final fracture occurs. When compared with the results of the finite element simulation the crack growth rate may be tracked. The fracture surface of the specimen is presented in Figure 13 at a magnification of 0.7. The image shows that this specimen failed due to the initiation and growth of a single crack as evidenced by the smooth surface. The beach marks towards the point of fast fracture suggest a change in rate of crack growth, possibly linked to the increased local stress levels due to decreased loaded area.

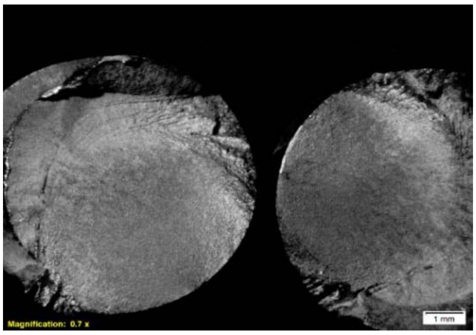


Figure 12 – Strain variation during crack growth

Furthermore, it can be deduced that stable crack growth consumed almost two thirds of the section. For a specimen of 16 mm gauge diameter, this represents close to 10 mm penetration. However, the oval nature of the stable crack growth area poses complications in relating the simulation to actual crack growth.

From Figure 12, the local strain close to the point of fast fracture is 850 micro strain. The deviation of this strain from the uncracked specimen is 2979.7 micro strain. From Figure 7, this corresponds to a crack radius of 11.5 mm which corresponds to a crack diameter of 23 mm. The actual measured penetration of the crack prior to fast fracture was found to be 10.3 mm from the surface. This gives an error of 11.65% according to simulation prediction. This is acceptable for practical engineering applications.

5 CONCLUSIONS AND RECOMMENDATIONS

In this paper, the crack behaviour during the rotating bending fatigue testing of grade 5 titanium alloy was studied using both numerical and experimental techniques. The crack behaviour was modelled using XFEM tool implemented in commercial FEM software Abaqus 6.13 while the strains were monitoring on the rotating specimen using strain gauges.

Based on the results obtained, the following can be concluded:

1. The tool that was developed can be used to monitor crack growth during rotating bending fatigue tests.
2. The tool is not sensitive enough to detect the onset of crack initiation
3. A crack with a penetration of 10.3 mm can be detected with an accuracy of 11.65 % on crack penetration

Further work is required to further refine the technique through more tests and the use of higher resolution strain measurements which can be achieved using fibre optics. This method can also be tested on other materials such as steel.

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7 BIOGRAPHY

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