

# The Influence of Manufacturing Anomalies on Fatigue Performance of Critical Rotating Parts in the Aero-Engine

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## Abstract

Manufacturing anomalies introduced during machining of critical parts have become a significant cause of gas turbine disc cracking events in the aero-engine. A European funded programme 'MANHIRP' has been set up to address this issue and some initial results from the programme, particularly those related to machining of titanium alloys will be presented in this paper. Three machining processes have been investigated: hole making, turning and broaching. For two of these processes, data are presented of fatigue response, where it can be seen that the anomalies introduced have reduced fatigue strength in most cases relative to datum specimens.

## 1 Introduction

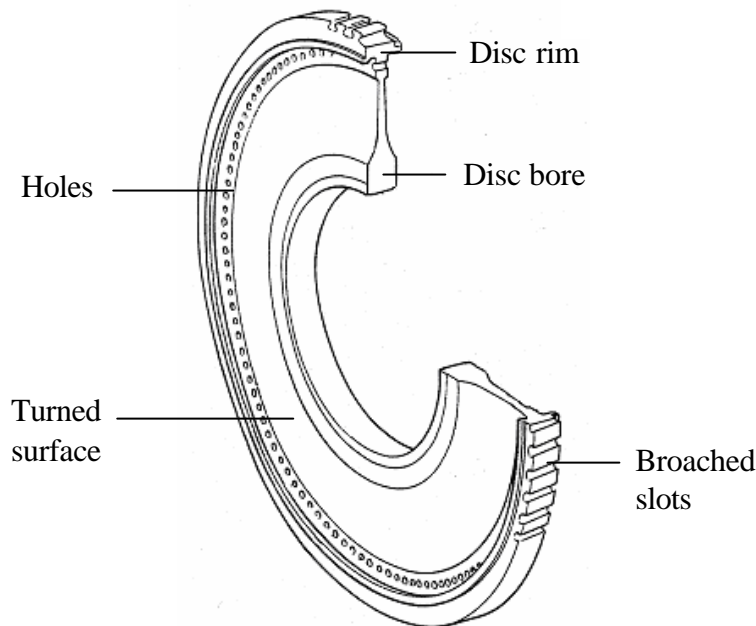
The most common Hazardous Effect for aircraft engines as defined in the Joint Aviation Regulations (JAR-E) is uncontained high-energy debris being ejected from the engine. Critical parts are those, which have to achieve and maintain a high level of integrity to avoid Hazardous Effects and mostly consist of rotating high-energy discs and spacers. An analysis of events in service discs, which includes both cracking and burst, shows that manufacturing anomalies, mostly caused by machining abuse or rare events during machining, are rising and in the 1990s have become the biggest cause of disc burst.

The 'MANHIRP' programme is a Framework V Growth Programme set up to reduce the risk of disc burst from manufacturing anomalies. The key objectives of the programme are:

- A scientific basis on which to control manufacturing process development, change and sentencing of non-conforming product in terms of the required surface condition in the materials.
- The ability to specify process controls to achieve a specified low level of the risk of burst from machining anomalies.
- A reduction in the probability of burst of a disc from a manufacturing anomaly by a factor of ten.

The work in MANHIRP is examining three features of a disc which together account for nearly 90% of all reported causes of manufacturing anomalies. A schematic diagram showing typical locations of the above features is shown in Fig. 1. These features are:

- (i) Turned surfaces, including the bore, diaphragm and drive arms.
- (ii) Holes, embracing those in the diaphragm, rim and in flanges.
- (iii) Broached slots in the rim of the disc.

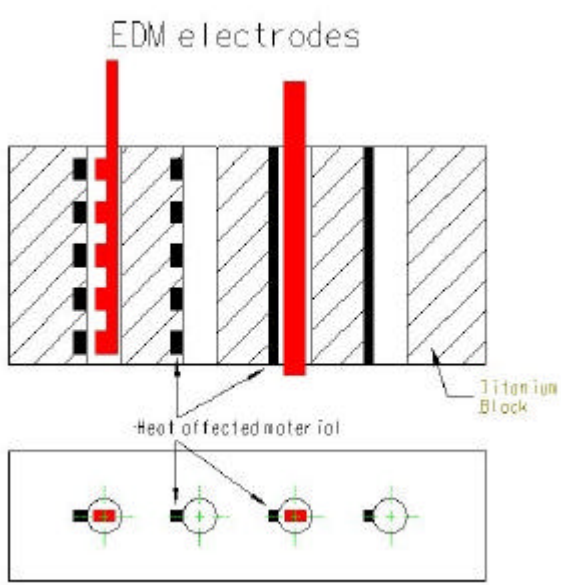


**Figure 1.** Schematic diagram to show nomenclature and typical features in gas turbine discs.

## 2 Experimental Procedure

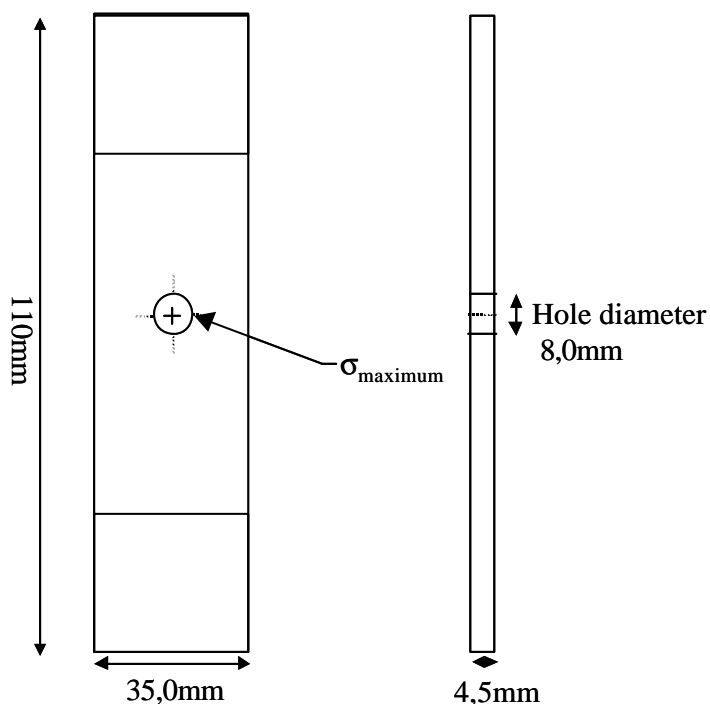
### 2.1 Hole Manufacture and Fatigue Testing in Ti6Al-4V

A series of specimens were produced at Volvo Aero from a Ti6Al4V disc forging to specification PWA1228. An artificial technique was used to introduce 'overheating' type of anomalies (anomaly type 1[1]). This was carried out using an Electro Discharge Machining (EDM) process. This method was used to produce point anomalies using a 0.8mm thick by 2mm wide copper electrode. The fatigue samples were produced from titanium blocks with the dimension 110 x 40 x 25 (mm). A hole of diameter 7.5mm was rough drilled in the centre of the block. The EDM anomalies were then produced in the hole (Fig. 2). The EDM electrode removed approximately 0.5 mm. After the EDM the hole was rough drilled to achieve a smooth surface and to remove most of the re-cast layer produced by the EDM machining. To improve the surface roughness the holes were honed to remove approximately a further 0.2 mm on the hole diameter. After the honing the titanium block was sliced by wire EDM into flat fatigue specimens and then ground to remove re-cast layer from the wire EDM. 'Datum' specimens were produced by drilling and honing alone.



**Figure 2.** Point and line anomalies by EDM machining.

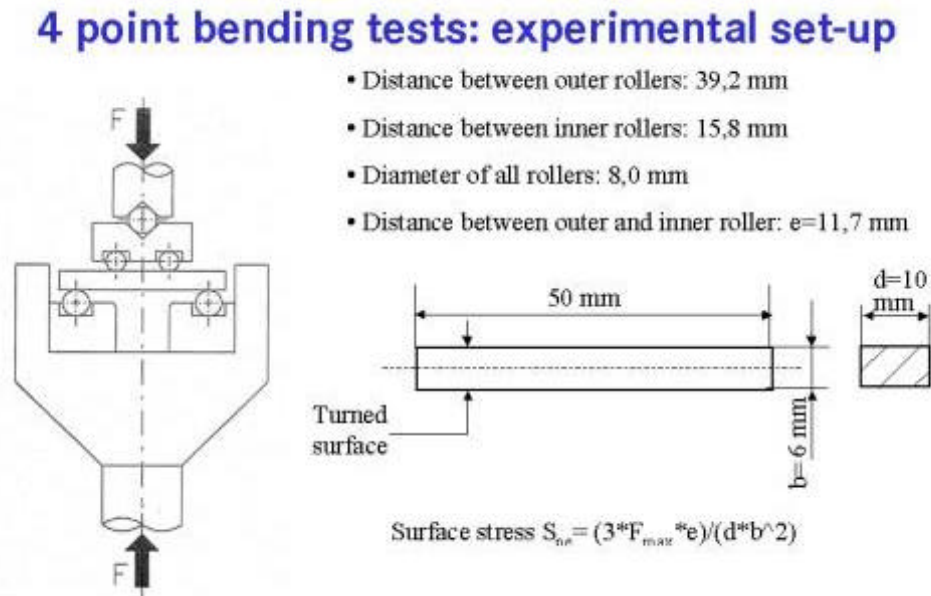
The fatigue specimens were of the dimensions shown in Fig. 3. The peak stress at the hole was calculated using handbook formulae and compared to prediction from ANSYS modelling. Fatigue testing was carried out at room temperature at a frequency of 1Hz using an R ratio (where  $R = \text{maximum load}/\text{minimum load}$ ) of 0.1 and a sinusoidal waveform under load control. Fatigue testing was carried out using both an MTS and an INSTRON servo-hydraulic machine both with 100kN load cells and fitted with MTS647 hydraulic wedge grips rated to 100kN. Specimens were tested at predominantly two stress levels in order to establish scatter.



**Figure 3.** Schematic diagram of fatigue specimens used for hole feature testing.

## 2.2 Turned Specimen Manufacture and Fatigue Testing in Ti6Al-4V

A series of specimens were produced by MTU using Ti6Al4V disc forging material to specification PWA1228. The specimens were machined from discs turned using similar turning parameters as specified in 2.2.1. The specimens were all tested according to the set up and details given in Fig. 4.



**Figure 4.** Fatigue testing set up used for 4 point bend testing

### 2.2.1 Datum Specimens

These specimens were made using production turning parameters in order to provide a baseline. Tool geometry: CNMG 120412 with tool radius=1.2 cutting speed (vc)=90 m/min, feed (f)=0.2 mm/rep, cut depth (ap)=0.3 mm.

### 2.2.2 Redeposited Material (anomaly type 6 [1])

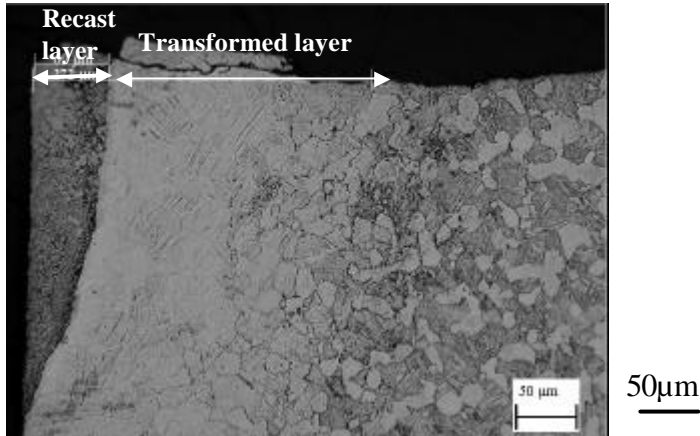
These specimens were produced by taking a finish machined surface and introducing chip material between the specially prepared cutting insert and the machined surface while the disc was rotating.

### 2.2.3 Smearing by Contact of Tool Fixture with Rotating Work Piece (anomaly type 4[1])

These specimens were produced by pressing a tool fixture against the rotating surface of the disc. The aim of this work was to understand how deep the damage would be from this type of event during manufacturing. In fact the damage produced was very severe and would definitely be rejected during inspection. In future, it is intended to remove all visible damage by rework and assess the fatigue response of the remaining material. This surface condition would be more representative of real anomalies, which could occur during manufacturing.



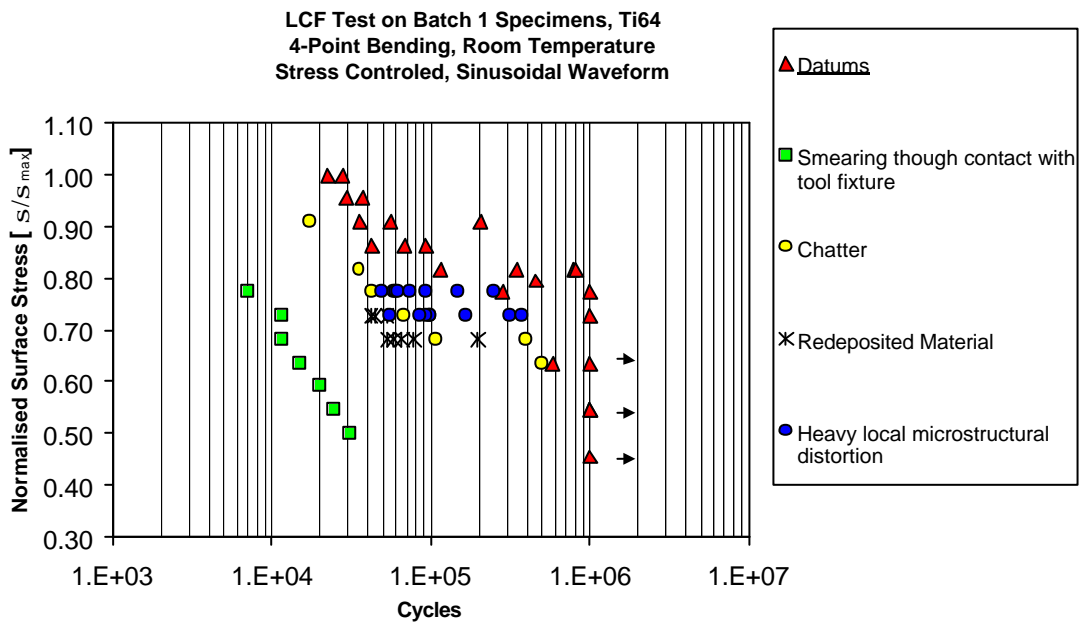
transformed beta microstructure (see Fig. 6). At the very surface a recast layer is formed, and varying amounts of this layer remain after honing of the hole. If the total depth of overheated material is measured, there is some correlation between a larger depth of overheated material with a lower cyclic life of the specimen, particularly at the higher stress level employed.



**Figure 6.** Micrograph of overheated area taken through fracture surface of specimen tested at normalised stress of 0.875 which failed at 34,971 cycles.

### 3.2 Fatigue Testing of turned specimens in Ti6Al-4V

Results of the fatigue testing are shown in Fig. 7.



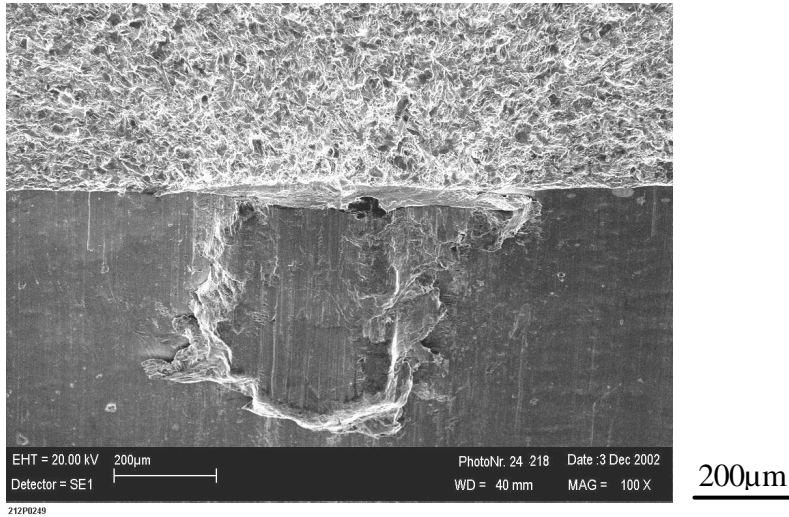
**Figure 7.** Low cycle fatigue results from turned specimens in Ti-6Al-4V.

#### 3.2.1 Datum Specimens

The datum specimens can be seen to exhibit fairly typical S-N type behaviour.

### 3.2.2 Redeposited Material (anomaly type 6 [1])

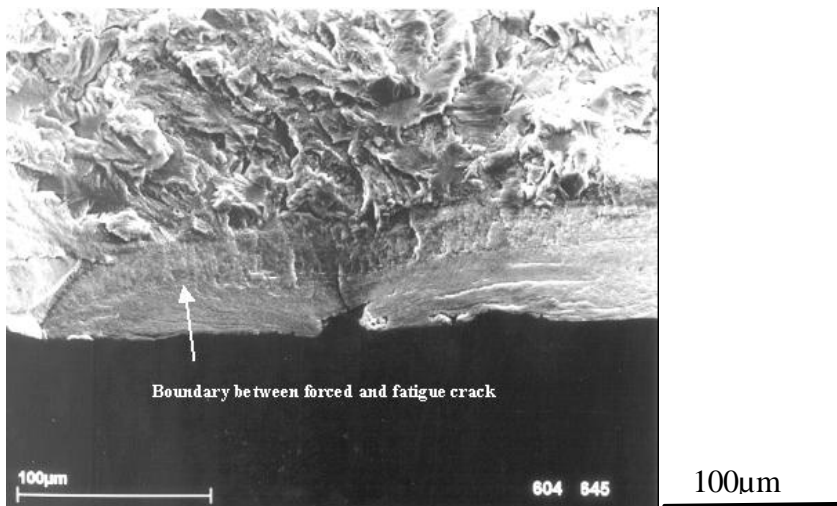
Redeposited material can be seen to reduce the fatigue strength below that of the datum specimens. In some cases, fatigue crack initiation started from smearing features (see Fig. 9), but in other cases initiation started from 'scratch' like features which were associated with the smeared material due to the artificial method used to create the redeposited material.



**Figure 9.** Fatigue crack initiation site associated with redeposited material.

### 3.2.3 Smearing by Contact of Tool Fixture with Rotating Work Piece (anomaly type 4[1])

Examination of the specimens after fatigue testing revealed that pre-cracks existed in the smeared material even prior to fatigue cycling and therefore fatigue life consisted of crack propagation only (Fig. 10). This explains the very large debit on fatigue strength caused by this anomaly.



**Figure 10.** Scanning electron microscope image showing fracture surface, where heavily distorted microstructure showing boundary between 'forced' pre-crack (present prior to fatigue testing) and fatigue crack growth during fatigue testing.

### *3.2.4 Chatter Marks*

The fatigue debit resulting from chatter is expected to be related to the increased surface roughness and/or changes in surface residual stress, which have not yet been investigated. Note that these specimens were well outside any acceptance criteria or standard usually employed to assess these anomalies. Nevertheless the chatter marks were not crack initiating as all fatigue cracks started at the specimens edges. Efforts are currently underway to avoid edge cracks on future tests.

### *3.2.5 Heavy Local Microstructural Deformation*

The fatigue debit from specimens turned containing heavy local microstructural deformation was unexpectedly low. It expected to be due to local tensile residual stresses concentrated around the tool impact area. However, as for the case of chatter marks, the specimens here failed from edge cracks and are undergoing further investigation.

## **4 Conclusions**

From the fatigue data presented, it can be seen that anomalies typical of those, which can be produced during disc manufacture, can give rise to a fatigue deficit. Other work in this programme is focussed on quantifying and improving the detectability of these anomalies by NDI techniques and also detecting them during the machining operation by the use of process monitoring (e.g. power and force monitoring, acoustic emission, vibration, and acceleration). Results from this work cannot be included here due to space restrictions.

## **5 Acknowledgments**

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## **6 References**

1. K. M. Fox, MANHIRP Internal Document No. MANHIRP-01-0000006-WP1-RPT, issue 3, 2002