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Fatigue Assessment of Ti-45Al-2Mn-2Nb^{XD} Sub-Element Specimens

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ABSTRACT

A novel test technique is described for the sub-element fatigue assessment of dovetail geometric features commonly employed as a fixture for blade/disc assemblies in steam and gas turbines. Once developed, the test method was employed to assess the performance of a model dovetail geometry employing the gamma titanium aluminide Ti-45Al-2Mn-2Nb^{XD}. In addition to generating information describing fatigue crack initiation, crack growth and ultimate failure, associated wear processes were also characterised.

KEYWORDS: TiAl; Dovetail fixtures; Fatigue; Wear

INTRODUCTION

Intermetallic gamma titanium aluminide alloys are proving themselves as capable replacements for nickel-based superalloys in low-pressure turbine aerofoils in gas turbine engines, offering low density, high specific strength as well as good oxidation resistance [1,2]. Following traditional design philosophies, these gamma blades are attached to the nickel-based superalloy turbine disc via a simple dovetail or slightly more complex fir-tree interlocking feature. In-service stressing governing the component life is naturally complex [3,4], including a major fatigue cycle induced through the alternating centrifugal force of the take-off and landing sequence plus the superposition of high frequency vibration. In turn, these stresses are concentrated by the stress raising effects of the geometric features, in addition to supplementary contact stresses resulting from blade/disc fretting mechanisms, often alleviated by the use of lubricants and coatings [5,6].

Laboratory studies of the fundamental static and fatigue properties of gamma titanium aluminides are regularly reported in the scientific literature and these data form the basis of finite element analysis of engineering components to predict safe in-service mechanical behaviour. More specialist testing to characterise the effects of localised fretting on fatigue strength have also been performed [7,8]. These studies often apply a two stage approach, first introducing fretting damage into the specimen through a sliding contact process, then subsequently testing the pre-fretted specimen to evaluate fatigue strength. It would be preferred if coincident wear and fatigue damage could be applied during the same experiment.

Ultimately, complete stages of a turbine assembly and a full engine test would be performed to satisfy regulatory authorities. However, understanding the more complex stress states at blade/disc fixtures for example would benefit from sub-element laboratory scale testing. To this end, the current paper will describe a novel test technique developed during a recent fatigue assessment of Ti-45Al-2Mn-2Nb^{XD}. The tests described simulated the behaviour of a model single dovetail blade root geometry and the interaction to a nickel-based superalloy disc rim fixture. The wear damage accrued under such multi-axial stress was inspected, sites of fatigue crack initiation established and the ultimate fatigue strength at room and elevated temperature evaluated.

EXPERIMENTAL METHODS

Specimen Design

Initial design studies were conducted to optimise a specimen design that incorporated a single, nominal dovetail geometry to one end of a laboratory test piece that could be gripped in an axial assembly intended for fatigue loading. However, the final design constituted a double ended dovetail geometry. This enabled a degree of self alignment once the load train was subjected to tensile loads and maximised the number of blade/disc contact points evaluated during a single test to four. It was envisaged that this arrangement would provide the opportunity to inspect sub-critical cracking at the opposing three contact locations from that which promoted failure, subsequently borne out during testing and described later. The double ended dovetail blade root specimens were machined and finally ground from Ti-45Al-2Mn-2Nb^{XD} alloy in the centrifugal cast plus HIPped condition, Figure 1, containing a near fully lamellar microstructure, Figure 2. The pedigree of this material matches that previously reported [9].

Test Rig Design

To interface with this specimen design, a pair of IN 718 “disc segments” were machined, each with an axial dovetail notch to mate with the blade. These segments were in turn attached to pull rods via a clevis and split pin, Figure 3, again providing an element of self alignment whilst under static or cyclic tensile loads. This setup provides a sub-element representation of an in-service blade/disc assembly and an advance when compared to two-dimensional specimen testing [10,11]. The specimen/disc interactions described here were assessed without the employment of a lubricating coating (i.e. metal to metal interfaces).

Blade-Disc Wear

A limited assessment of wear was conducted using the same specimen and load train assembly as for the fatigue testing. The main aim of this investigation was to characterise the fretting damage produced over the bedding area between the IN718 disc and the Ti-45Al-2Mn-2Nb^{XD} blade. A preliminary test was conducted at room temperature, interrupting the test after 2 x 10^6 cycles at R = 0.82 and 165 MPa peak stress. Subsequent tests were then conducted at 650^{o}C, at an R-ratio of 0.1 and 300 MPa peak stress, with inspections conducted after 10^5 cycles. In both cases, these were selected as purely indiscriminate loading conditions.

Fatigue Step Testing

The constant amplitude fatigue testing was conducted employing a single Instron servo-hydraulic test frame, with load cell calibrated to International standards. Two temperatures were assessed; room temperature (20^{o}C) and 675^{o}C. The elevated temperature was achieved through the use of a split, three zone radiant furnace encapsulating the load train. Two calibrated, type N, mineral insulated thermocouples were placed in intimate contact with diagonally opposing faces of the dovetail specimen. A step test technique was employed to evaluate fatigue strength to failure, using a sinusoidal waveform at a frequency of 2Hz. The peak stress was increased by 25 MPa on the successful completion of every 10^5 cycles, with the peak stress level for the initial block deliberately chosen at a relative low level to ensure failure did not occur in the first block. It has been previously reported by Nicholas and co-workers that similar step testing applied to this class of intermetallic alloy does not impose a history effect upon the eventual strength recorded or induced failure mechanism [12], whilst Lerch et al have published a similar conclusion specific to cast TiAl variants [13]. A stress ratio (minimum stress/ maximum stress) of R = 0.1 was employed throughout. Failure was defined by a loss of load bearing capacity, which typically resulted from cracking at and the detachment of a single lobe of one dovetail, Figure 4.

RESULTS AND DISCUSSION

Stress modelling

Subsequent to specimen manufacture and prior to testing a three dimensional, axi-symmetric, finite element analysis was performed to predict the distribution of stress in the assembly and in particular the critical region where failure could be expected in the dovetail specimen. Proprietary materials data were employed for the physical and mechanical properties of the IN718 disc and Ti-45Al-2Mn-2Nb^{XD} blade root specimen. Figure 5 illustrates stress contour maps generated assuming an axial tensile load of 1KN. Careful inspection of the different perspective plots indicates that the peak tensile stresses are located at the dovetail specimen surface, in regions displaced from the area of contact bedding, i.e. offset towards the shank of the dovetail. Sliding contact was predicted across an area 0.3mm wide under this magnitude of load. Near identical levels of peak stress were predicted in the individual blade and disc segments.

Wear Properties

The wear properties of the Ti-45Al-2Mn-2Nb^{XD} material at room temperature were primarily assessed by a single test, performed at the arbitrary test conditions of 165 MPa peak stress, R = 0.82, terminated and inspected after completing 2 million cycles. When comparing to the ultimate fatigue strength measurements this level of applied cyclic stress was relatively low, but notably closer to the nominal load employed for the FE modelling. A minor scar patch was observed, initially by eye, along one of the four dovetail lobes. The scar, extending for approximately 6mm in length from one corner of the specimen, measured approximately 300μm at the widest point, viewed under scanning electron microscopy in Figure 6. Although restricted to a single lobe, the scale of the damage zone was consistent with the area of contact bedding predicted by the FE results. Wear on the other three contact lobes was less prominent, illustrated by Figure 7. In these cases small scar patches were isolated and the detail of the machined specimen surface remained evident, indicating only minor plasticity during contact fretting. In all of these examples of room temperature scarring, without prior knowledge of the stress system it would be difficult to identify the orientation of relative sliding.

The wear damage on specimens tested under 300MPa at 650°C, Figure 7, contained more obvious shear deformation to the specimen surface plus associated metallic debris and oxides [7]. Notably, the level of applied stress for this test was more significant, at approximately 75% of the ultimate fatigue strength measured at this temperature. The scar patches were obvious on all four lobes, continuously along the whole contact area. The combination of relatively large applied stress range and elevated temperature are presumed to be responsible for the increased width of the scar at approximately 1mm. The ability of this intermetallic to readily deform via plastic flow (creep) at such temperatures has been previously reported [9]. Due to the prominence of these scars, the specimens were carefully inspected, however, no surface breaking cracks were observed either within or juxtaposed to the scar damage.

The corresponding wear damage within the contact areas of the IN 718 disc posts was also inspected. It should be noted that any specific pair of disc segments was usually employed for multiple wear tests, hence these components accumulated a relatively high number of test cycles (in some cases approaching 4 million cycles) compared to the individual dovetail specimens. Contact bedding surfaces appeared very similar to those of the gamma specimens, with shear deformation extended across the mating areas. Once again, no evidence of cracking was observed in any disc posts.

Fatigue Strength

Six dovetail blade specimens were assessed under step fatigue loading to measure ultimate fatigue strength, three each tested at room temperature and 675^{o}C. The maximum fatigue strength achieved by any specimen at the two temperatures was identical. That stress level has been employed in Figure 9 to normalise the peak strength achieved during the step block that induced failure, plotted against the number of cycles endured during the ultimate load block. The results demonstrate a relatively consistent cyclic strength at both temperatures. This was viewed as an encouraging result, indicating that strength is retained up to 675^{o}C without any detrimental effects due high temperature oxidation. The number of cycles accumulated within the final loading block by the individual specimens ranged from approximately 10,000 to almost 100,000 cycles. This indicates a degree of damage tolerance in the alloy, exemplified by the transition in oxidation tinting associated with the sub-critical growth of a crack at 675^{o}C as illustrated in Figure 10. However, it is recognised that the proportions of life spent initiating the critical crack and sub-critical crack growth can not be partitioned accurately by employing this test technique.

Initial observations of the exposed fatigue fracture surfaces indicated a bright lustrous appearance indicative of brittle fracture. Closer inspection of the failed specimens illustrated that fatigue fractures did not initiate at the contact bedding sites. Instead, the initiation and sub-critical growth of trans-lamellar fatigue cracks occurred on a plane displaced from the bedding, Figures 10 and 11, correlating well with the finite element model predictions for the peak stress locations towards the shank of the specimen (Figure 5). The opposing three lobes, still intact after test termination, often contained sub-critical cracks, again indicating a degree of damage tolerance. Isolated “chips” along the edge of the nickel disc locating feature, Figure 12, were occasionally observed if the TiAl dovetail segment was allowed to rupture. If this form of damage was noted post test in any disc segment that specific pair of segments was retired from further testing.

Consistent with our experience of standard laboratory specimen designs, identifying the exact site of fatigue crack initiation along the dovetail surface was difficult at room temperature. The presence of multiple initiation sites, coupled with the brittle nature of the material almost makes it impossible to pinpoint microstructural features or damage zones responsible for fatigue initiation. However, at high temperature this process was marginally easier. For example, inspection of the crack highlighted in Figure 11 emphasised an arc of oxidation tinting, which under higher magnification illustrated that the earliest stages of cracking occurred from a site mid-way along the flank of the dovetail on one lobe, i.e. displaced from the corners of the specimen. The early trans-lamellar mode of fracture, extending approximately 0.5mm in this example, later transferred a mixed mode prior to ultimate tensile overload.

CONCLUSIONS

The following conclusions can be drawn from the present study:

- A novel specimen geometry and load train assembly has been designed as a means of assessing wear and fatigue characteristics of model TiAl aerofoil dovetail root fixtures.
- Whilst the present study concentrated on a specific gamma aluminide, the technique could be modified to assess actual component aerofoil/disc assemblies, sampling more complex fir-tree geometries and different alloy combinations.
- The degree of wear damage accumulated on cast Ti-45Al-2Mn-2Nb^{XD} dovetail lobes was sensitive to changes in temperature across the range 20 to 650^{o}C. However, wear scars did not initiate coincident fatigue cracking.
- The fatigue strength measured in Ti-45Al-2Mn-2Nb^{XD} dovetail specimens was relatively insensitive to temperatures across the range 20 to 675^{o}C.
- Early stage fatigue crack growth, initiated from regions remote from wear damage but associated with greatest stress concentration, demonstrated a trans-lamellar mode.
- A finite element stress model successfully predicted the location and extent of contact bedding plus the location of highest stress.

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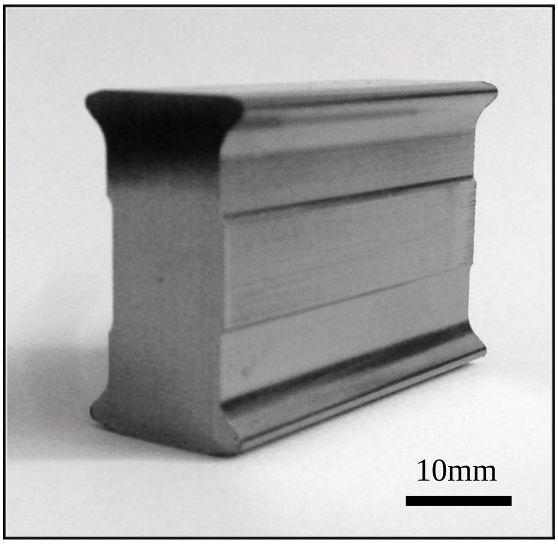

Figure 1. Double-ended dovetail Ti-45Al-2Mn-2Nb^{XD} blade root specimen.

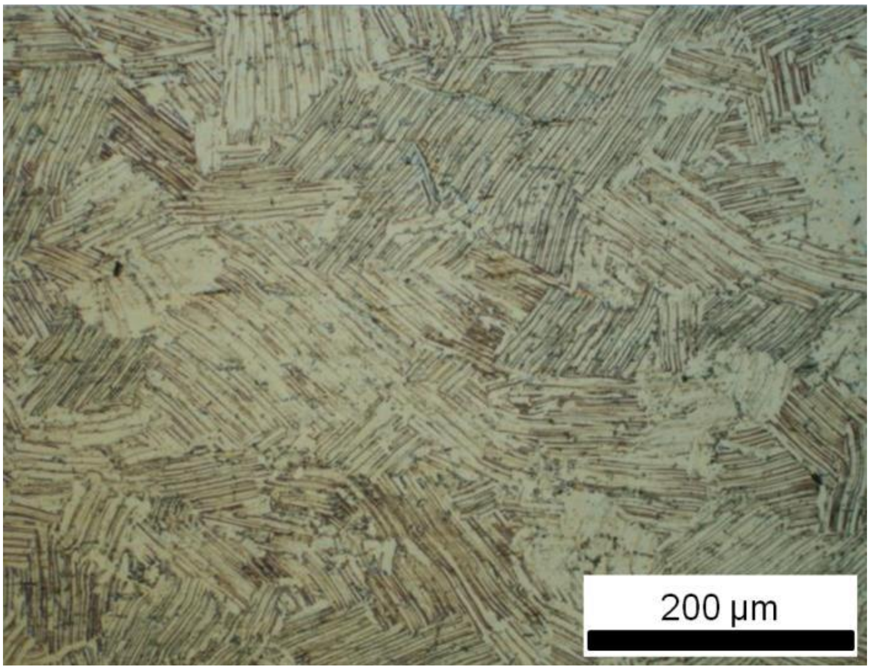

Figure 2. Ti-45Al-2Mn-2Nb^{XD} with fully lamellar cast and HIP'ed microstructure.

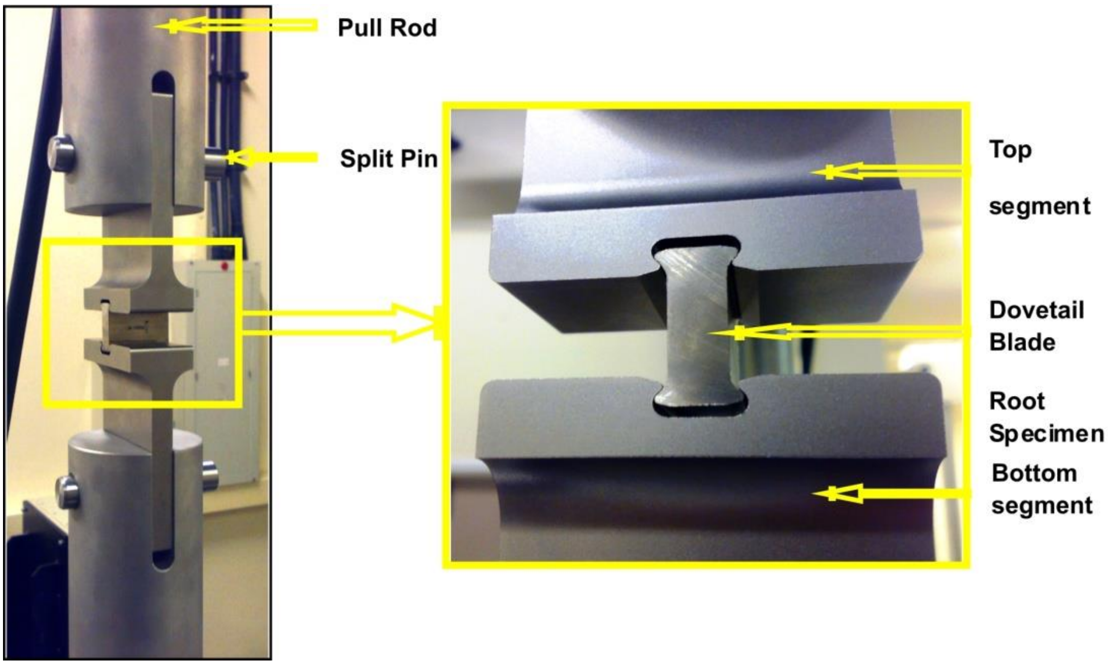

Figure 3. Specimen gripping and load train assembly.

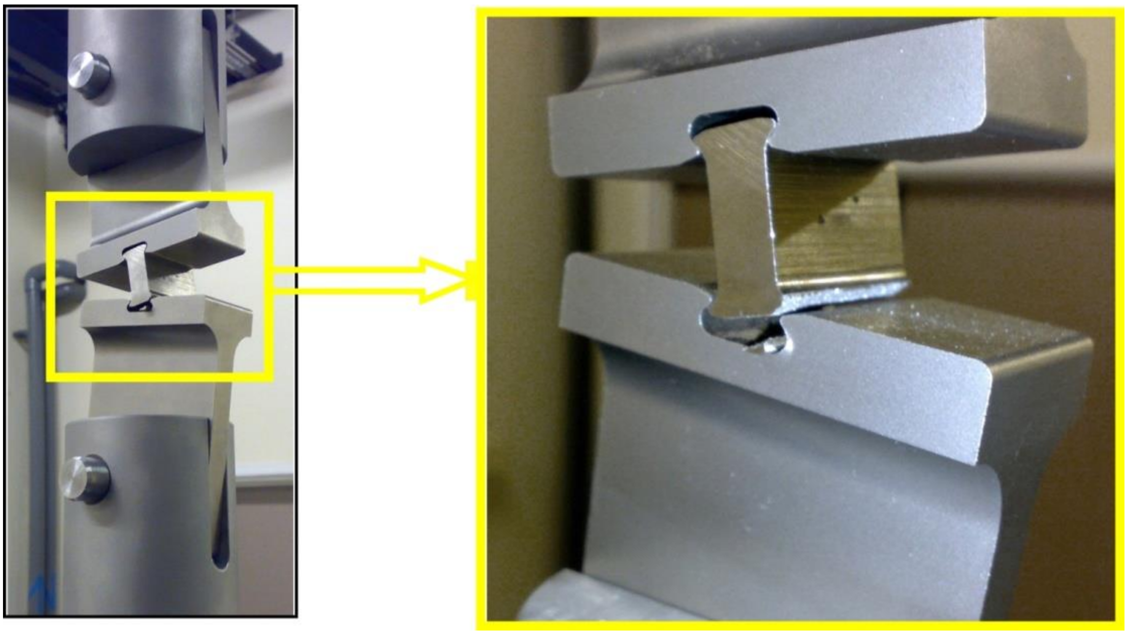

Figure 4. Fatigue failure generated at one dovetail lobe.

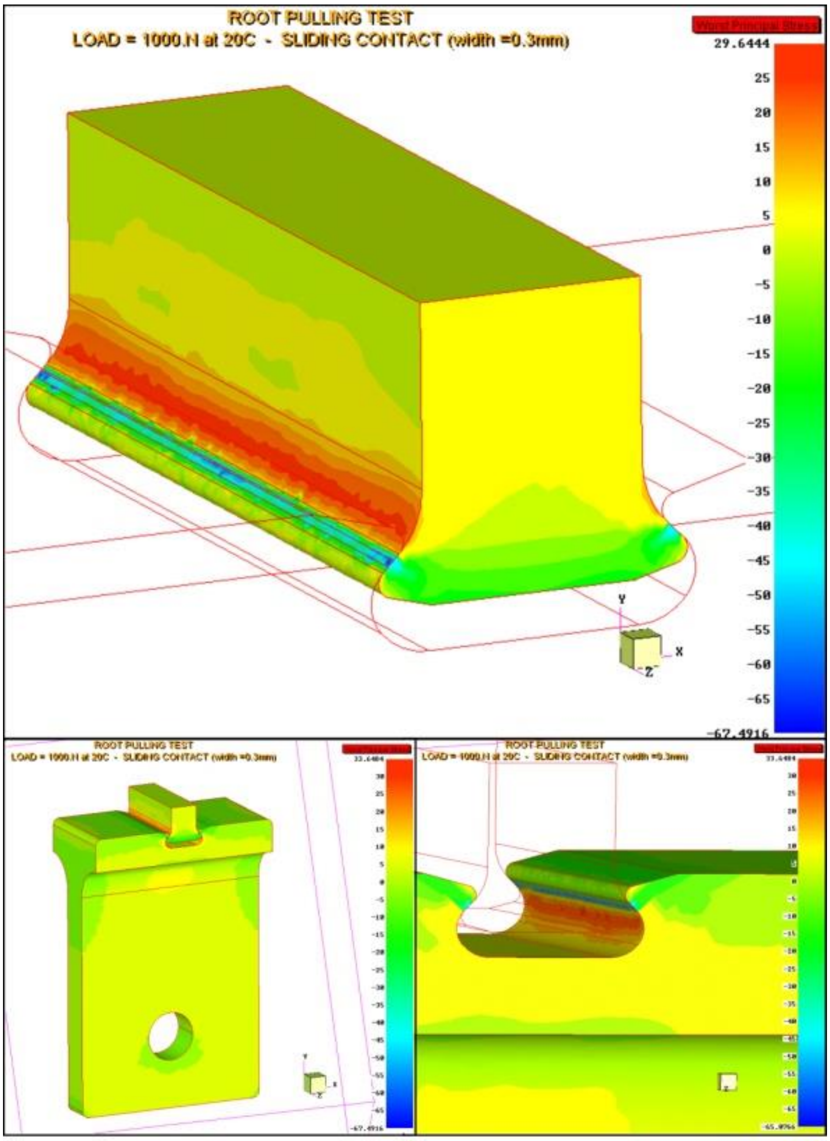

Figure 5. Finite element stress modelling of the dovetail blade-disc interaction.

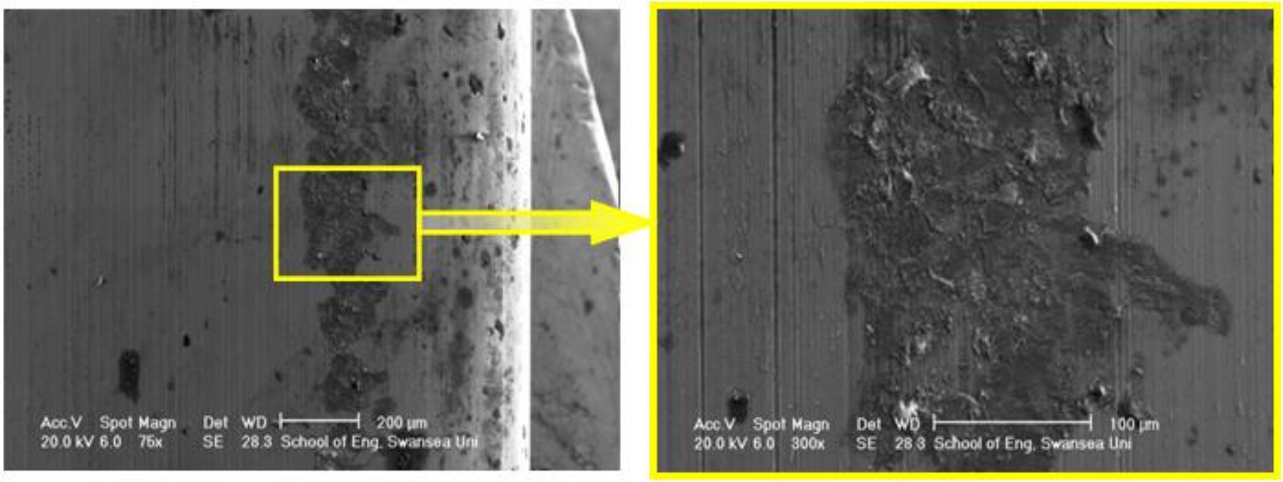

Figure 6. Wear scar on a dovetail lobe, room temperature, low and high magnification.

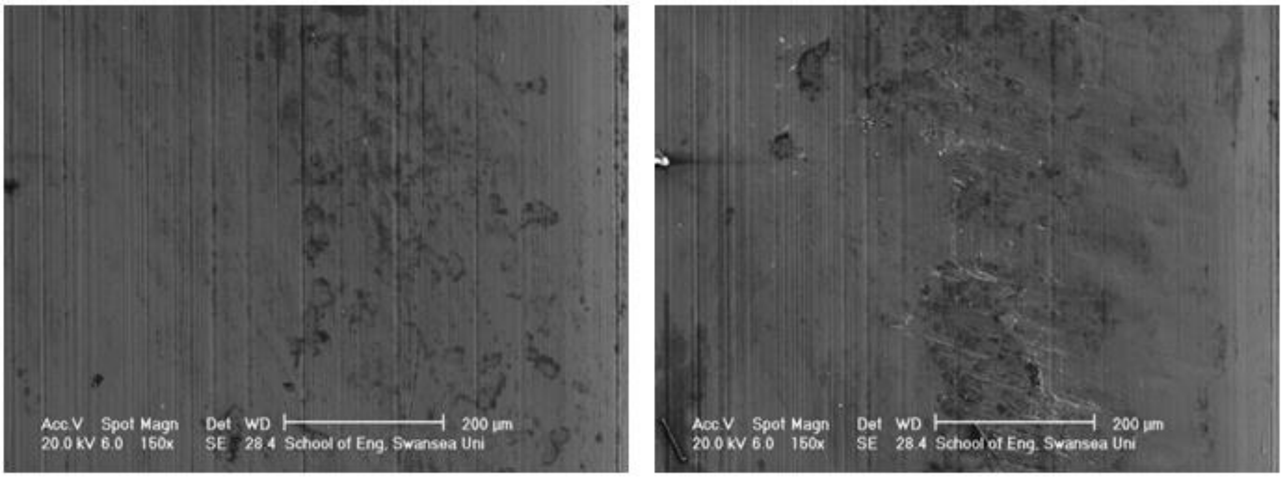

Figure 7. Minor wear observed at additional contact areas at room temperature.

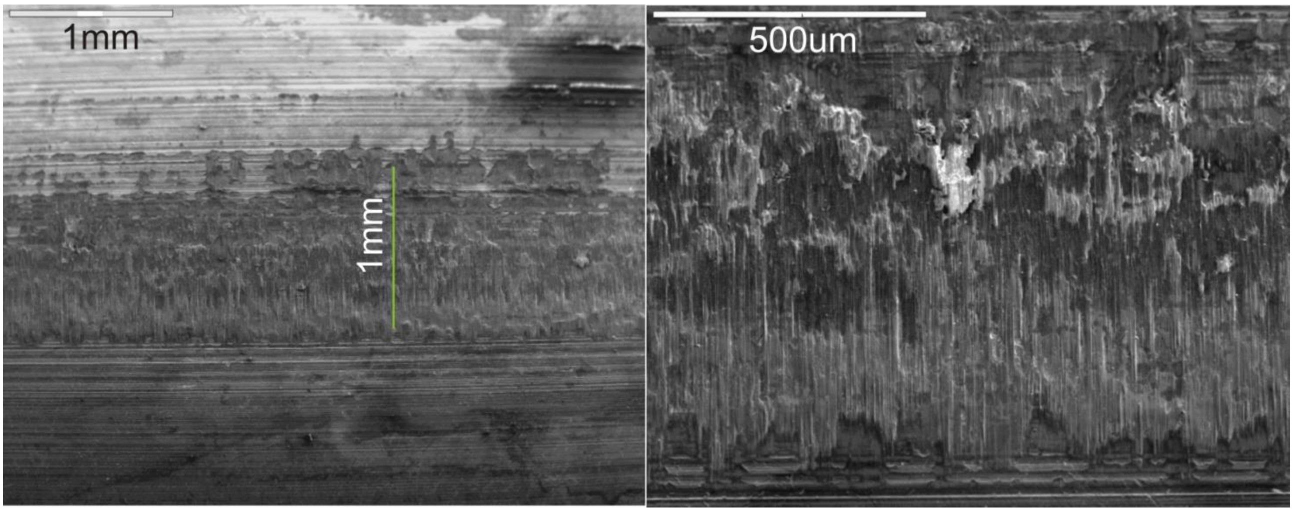

Figure 8. Wear scars generated at 650^{o}C.

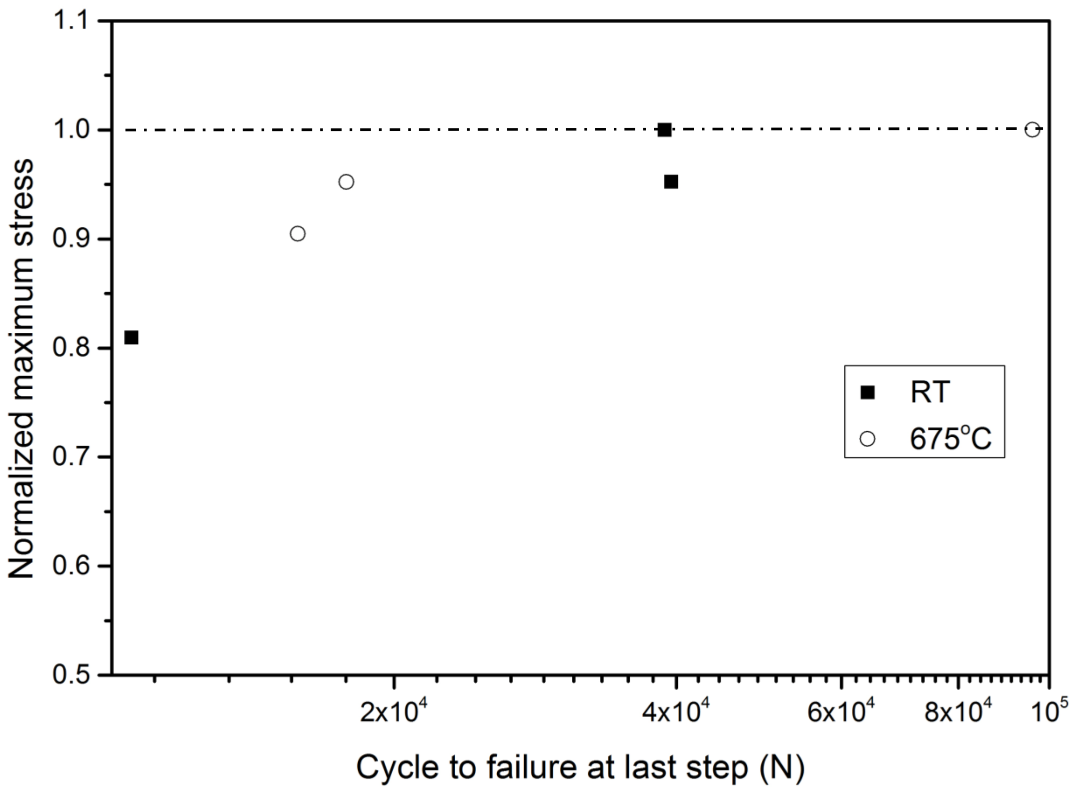

Figure 9. Normailsed fatigue strengths measured at room temperature and 675°C.

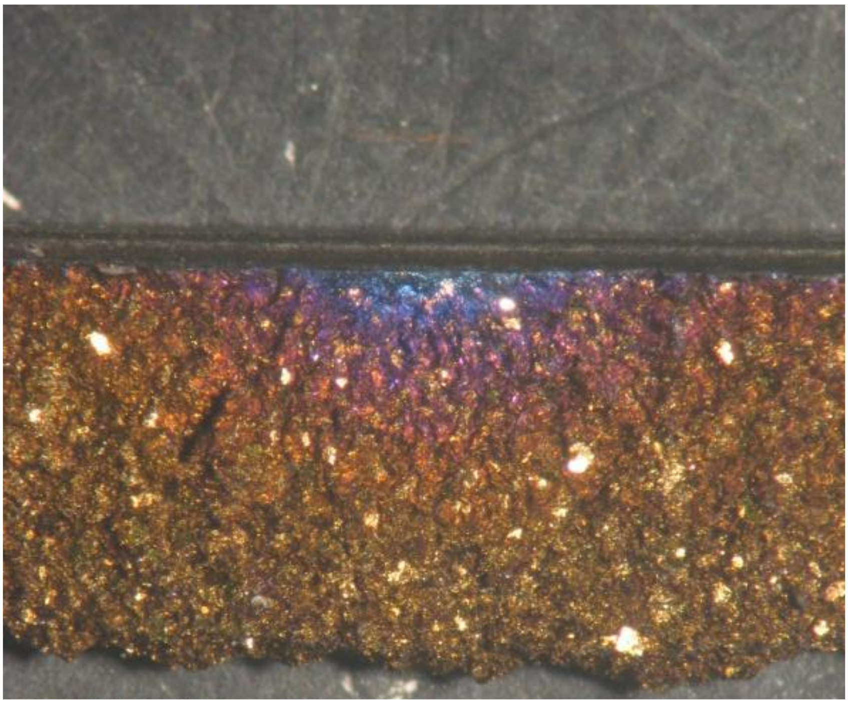

Figure 10. Crack initiation and sub-critical growth at 675°C.

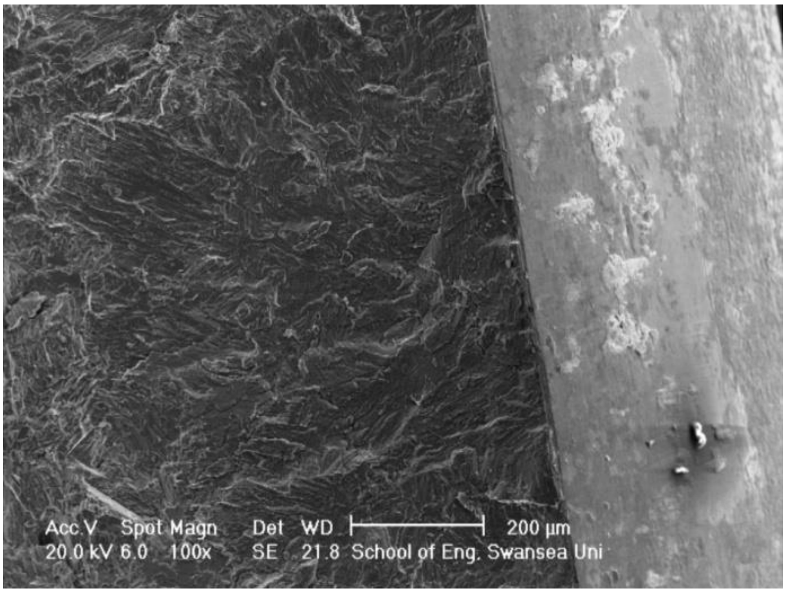

Figure 11. Early stage trans-lamellar crack growth, 675^{o}C.

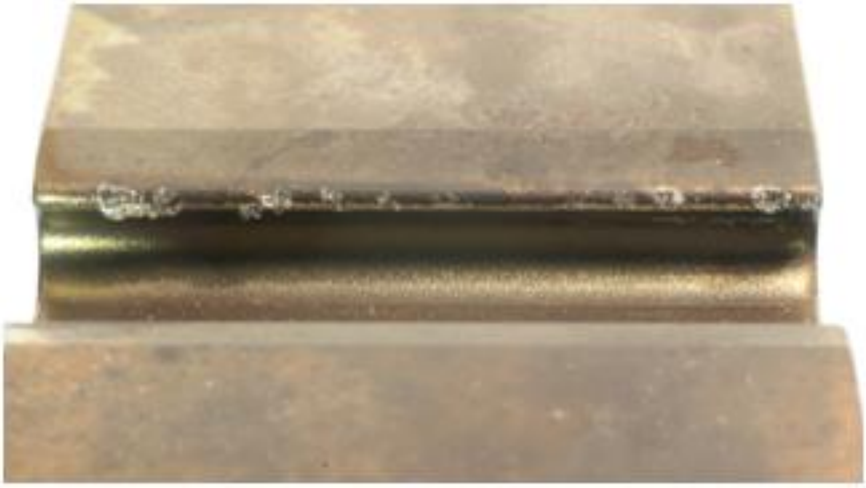

Figure 12. Damage to a nickel disc segment following failure of the TiAl dovetail.