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Small punch fatigue testing of a nickel superalloy

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Abstract: Miniaturised mechanical test approaches, specifically small punch testing, are now widely recognised as a means of obtaining useful mechanical properties to characterise the creep, tensile and fracture characteristics of numerous material systems from a range of industrial applications. Limited success has been found in replicating fatigue properties through the use of a small punch disc. This paper will discuss the ongoing research and progress in developing a novel small punch fatigue testing facility at the Institute of Structural Materials at Swansea University. Experiments have been performed on the nickel superalloy C263 at ambient room temperature, investigating three different alloy variants; two orientations produced through additive manufacturing and the cast equivalent. Fractographic analysis has been completed to interpret the complex damage mechanisms in the test method along with the differences in performance amongst the alloy variants.

Keywords: small punch; small punch fatigue; C263; additive manufacturing.

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1. Introduction

A fundamental understanding of the mechanical performance of a material is essential when looking to implement them into any high temperature component, as is often the case within the aerospace industry. Advanced materials and processes are continuously under development in an attempt to improve performance whether through a reduction in weight, improved strength, enhanced temperature capability or streamlined design. An extensive assessment of mechanical performance of these advancements through traditional means is typically expensive and, coupled with the challenge of often limited material availability, has led to a commitment in developing more appropriate test techniques. The miniaturised test method being discussed here is the Small Punch (SP) test, the general arrangement for which is given in the European Code of Practice [1].

Primarily, the SP test is used to obtain creep, tensile and fracture data from small discs of material, providing useful mechanical property information from small material quantities [2,3]. The approach is carried out by deforming a disc specimen under an applied compressive load transferred through an indenter, where the test may be either constant load, which exhibits a creep type response, or constant displacement rate which promotes tensile type behaviour. During SP testing the specimens are considered to deform under a biaxial stress state and data sets for both the constant load and constant displacement rate regimes have been correlated to equivalent conventional test methods through various means [2,3]. The test method has been applied across a range of industries and alloy systems for different purposes including the residual life assessment of power plant steels [4], ascertaining local properties of welded joints [5] and ranking the performance of aerospace alloys [6]. As a result, SP testing offers a feasible option for determining mechanical properties at the early stages of development in novel alloys and processing, potentially assisting with down selection through means of ranking.

The advancement and worldwide implementation of the SP technique has highlighted the necessity to understand the behaviour of the arrangement under cyclic deformation, particularly in aerospace alloys where fatigue performance is a life limiting parameter. Thus far, efforts have seen a SP test with a cyclic loading capability [7,8] implemented using compressive loading ratios (R>0), whilst a second arrangement has been developed to accommodate positive loading regimes (R=0.1) and fully reversed cycles (R=-1) by means of a twin indenter layout [9,10].

This research discusses the progress made at the Institute of Structural Materials (ISM) at Swansea University in developing the aforementioned SP fatigue testing methodology. Experiments were performed on nickel superalloy C263, produced through different processes; either casting or built through additive layer manufacturing (ALM), over a range of maximum load conditions using a positive R ratio of 0.1. The differences in fatigue lives between the variants was assessed and post-test fractographic analysis was conducted to determine whether any evidence of fatigue crack growth could be identified.

2. Materials and Methods

2.1. Material

Nickel-based superalloy C263 is a commercial alloy used in the aero-engine industry for static components such as combustion chambers due to its performance at high temperature along with its resistance to creep and corrosion. The nominal composition for C263 is summarised in Table 1 [11].

Table 1. Chemical composition of C263 (wt%).

	Co	**Cr**	**Mo**	**Al**	**Ti**	**C**	**B**	**Zr**
C263	20.0	20.0	5.9	0.5	2.1	0.06	0.001	0.02

Its relatively low γ’ content means that C263 has good weldability and lends the material well to ALM processes. ALM provides the opportunity to manufacture near net shape components, offering the potential for considerable benefits in terms of design capability and material wastage. Disadvantages of ALM include the inherent microstructural anisotropy due to the re-melting of previous layers as well as the possibility of the presence of features such as porosity or lack of fusion during the build. One such method is Laser Powder Bed Fusion (LPBF) in which a 3D component is built through successively melting layers of powder through a computer controlled laser. As a result, an understanding of the relationships that exist between the process, microstructure and mechanical properties is essential, especially when considering applications in structural components. This is where exploiting miniaturised test techniques proves valuable since multiple test samples may be extracted from much smaller quantities of material allowing a more cost-effective means of down selection in terms of LPBF process parameter input such as power, hatch spacing and velocity or post-process conditions such as orientation or heat treatments [12].

The microstructures for each of the variants of C263 under investigation are given in Figure 1, displaying the microstructure of the punch contact surface. In the first instance, LPBF variants were built as traditional round bar test specimens in two orientations under the same process parameters, either vertically (90°) where the gauge length is parallel to the build direction or horizontally (0°) SP specimens were extracted from the thread ends of larger test pieces in each orientation. The clear anisotropic microstructure produced by LPBF can be seen in Figure 1b and 1c, where elongating grains are present in the build direction. Cast C263 material was used as a reference material although the bi-modal grain structure makes the miniaturised sample challenging since the number of grains present in each sample can vary. Table 2 provides the grain sizes and aspect ratios of the corresponding microstructures.

Cast SP specimens were obtained by electrical discharge machining Ø9.5mm cylinders from a cast ring which were subsequently sectioned in to ~800 µm segments. The sections were then ground and polished to obtain a final thickness of 500 µm ± 5 µm with a 1200 grit finish. In the case of the LPBF specimen the Ø9.5 mm cylinders were obtained by the turning of threaded ends from larger test samples.

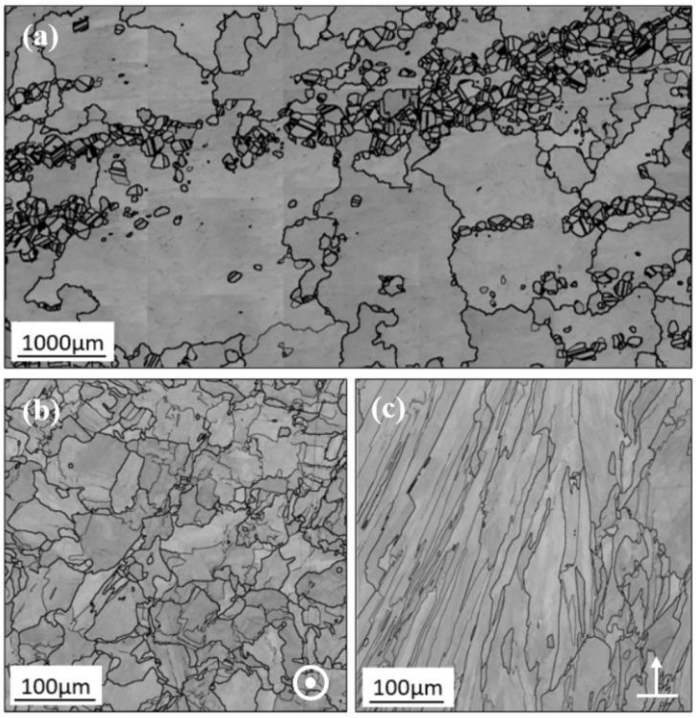

Figure 1. Microstructures of C263 alloys showing the punch contact face; (a) cast (b) LPBF vertical (90°) and (c) LPBF horizontal (0°).

Table 2. Grain sizes and aspect ratios.

C263 Variant	Average Grain Size [µm]	Aspect Ratio
Cast	101.7/921.8	0.55/0.52
LPBF 90°	22.8	0.99
LPBF 0°	29.6	0.23

2.2. Small Punch Fatigue

Figure 2 shows the SP fatigue test setup which for testing positive R ratios, as in the case in this research, is consistent with that of a traditional SP test under a constant displacement rate, as a result the dimensions are as those prescribed by the European Small Punch Code of Practise [1]. Previous work in the authors' research group has gone into more comprehensive detail regarding this unique test arrangement [9,10]. Tests were performed with an R=0.1 load ratio at a 1Hz frequency using a sinusoidal waveform.

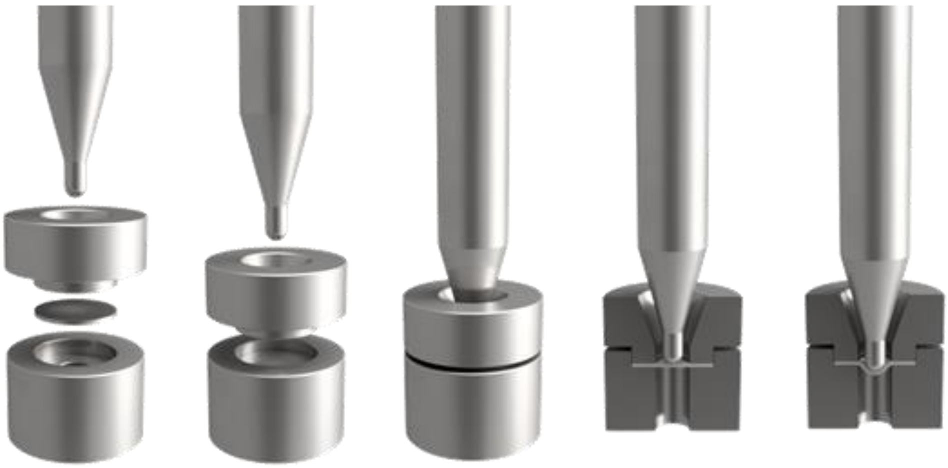

Figure 2. Small punch fatigue test configuration for an R > 0.

Figure 3 displays the commanded and actual load response for the first three cycles for two different maximum load tests, highlighting the control and repeatability of the setup to produce accurate and reliable fatigue cycles.

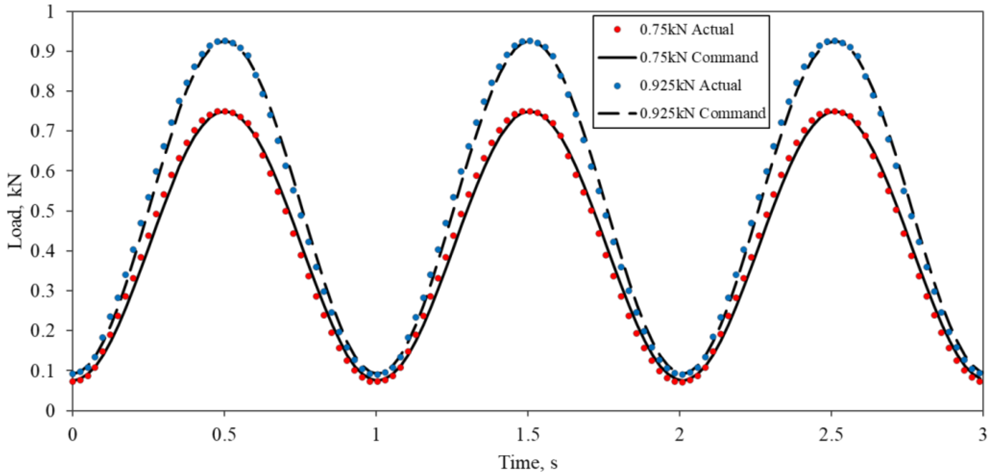

Figure 3. Commanded vs. Actual load response for the small punch fatigue test apparatus.

3. Results & Discussion

At the time of publication, a total of three SP fatigue tests have been performed on each of the material variants at different maximum load conditions to generate a series of representative load (L) – number of fatigue cycles to failure (N_f) curves, or an L-N curve. Figure 4 shows the L-N curves for the three C263 variants plotted as the maximum load against cycles to failure. The observed behaviour is akin to that from a series of uniaxial fatigue tests and the resulting uniaxial stress against number of cycles to failure curve, with an increasing maximum load reducing the number of cycles to failure. Nevertheless, the difference in stress state, biaxial in SP fatigue compared to uniaxial stress in conventional uniaxial fatigue, means any direct comparison requires a deeper understanding of the evolution of the stress and the material mechanisms that take place.

A key challenge in producing L-N curves for this arrangement comes from determining a consistent and repeatable failure criterion, since unlike a traditional uniaxial fatigue test there is no obvious or audible fracture that occurs. Therefore, the failure criteria need to be based upon the specimen displacement. From a series of initial interrupted trials, it was revealed that after 250 µm of displacement, a clearly defined fracture comparable to that seen in small punch tensile testing was observed. As such, this value was used as the failure criteria for all experiments.

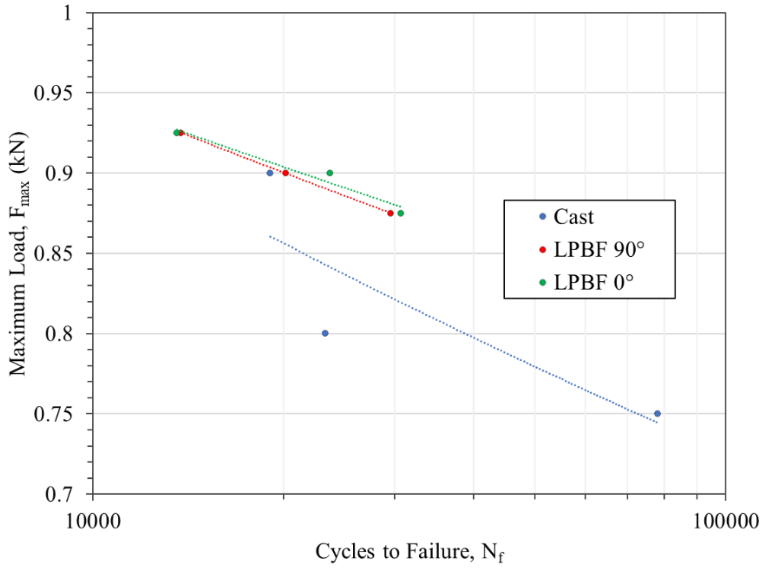

Figure 4. Room temperature small punch fatigue L-N curves (R=0.1, 1Hz sinusoidal waveform).

The L-N curves in Figure 4 clearly show that for the relatively limited data sets generated, LPBF materials outperform the cast material in this unique test type, with the LPBF 0° and 90° exhibiting near identical behaviour. It is believed these differences can be largely attributed to the grain size since the cast material has a grain size 5-50x greater than that of the LPBF materials and therefore fatigue life would be expected to decrease. The large scatter in the cast curve could then be attributed to the bi-modal grain structure which within a Ø9.5 mm x 500 µm specimen means the number of grains through thickness could potentially be just one. The LPBF 0° and 90° average grain sizes are within 5µm although there is a large difference in the aspect ratio due to the epitaxial grain growth from the additive process. Nonetheless, the grain size appears to be the dominant factor since the L-N response of the LPBF materials sit upon one another. Further SP fatigue tests with $N_f < 10000$ cycles and $N_f > 50000$ cycles may enhance the influence of the elongated grain structure further.

Figure 5 shows the load-displacement response for the first cycle and cycle 1000 for the three variants. The first load – displacement cycle helps to provide some means of confirmation as to whether the unique SP fatigue test setup is producing genuine results, in particular the displacement measurements being taken and how they compare to those from a small punch tensile test on the same material [13]. Furthermore, this explains the debit in performance seen the cast material when compared to the additive variants.

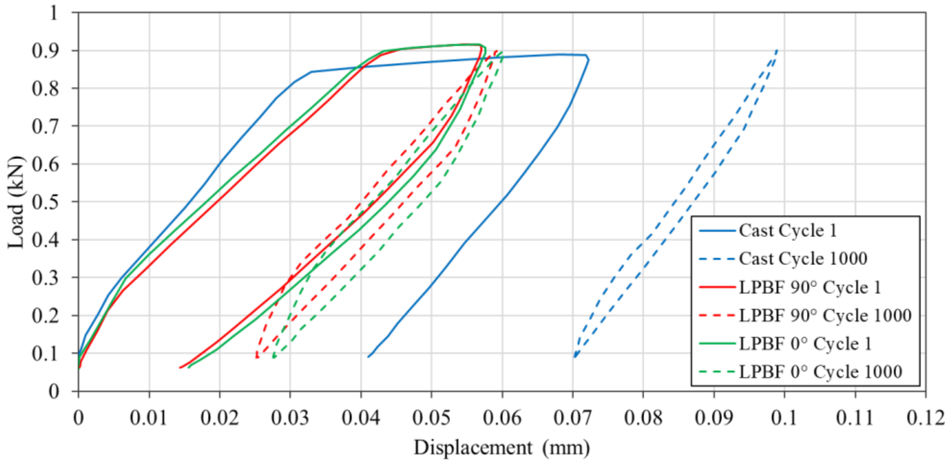

Figure 5. Load vs. displacement hysteresis response at $F_{max} = 0.9$kN; cycle 1 and cycle 1000.

3.1. Fractography

Fracture surfaces were assessed through scanning electron microscopy to determine the means and mechanisms by which the specimens had failed. Figure 6 shows the overall fracture morphology together with images taken at higher magnification of the through thickness for each of the C263 variants. Figures 6a), c) and e) show star-type cracking across the three materials where the cracks grow radially from the centre of the specimen. For the LPBF materials this is somewhat different to that observed in small punch tensile testing of these materials where a dominant circumferential crack occurs [13], therefore there must be a clear change in failure mechanism.

Figures 6b), d) and f) reveal features that relate to fatigue damage in each of the materials tested, specifically striations. Striations are features that occur along the crack path that represent the increment of crack growth that occurs in a single fatigue cycle as a result of the plastic blunting process. It is the presence of these features that gives confidence to the small punch fatigue testing methodology in terms of the mechanisms that are taking place, although a comprehensive understanding of the stress state is the next step moving forward.

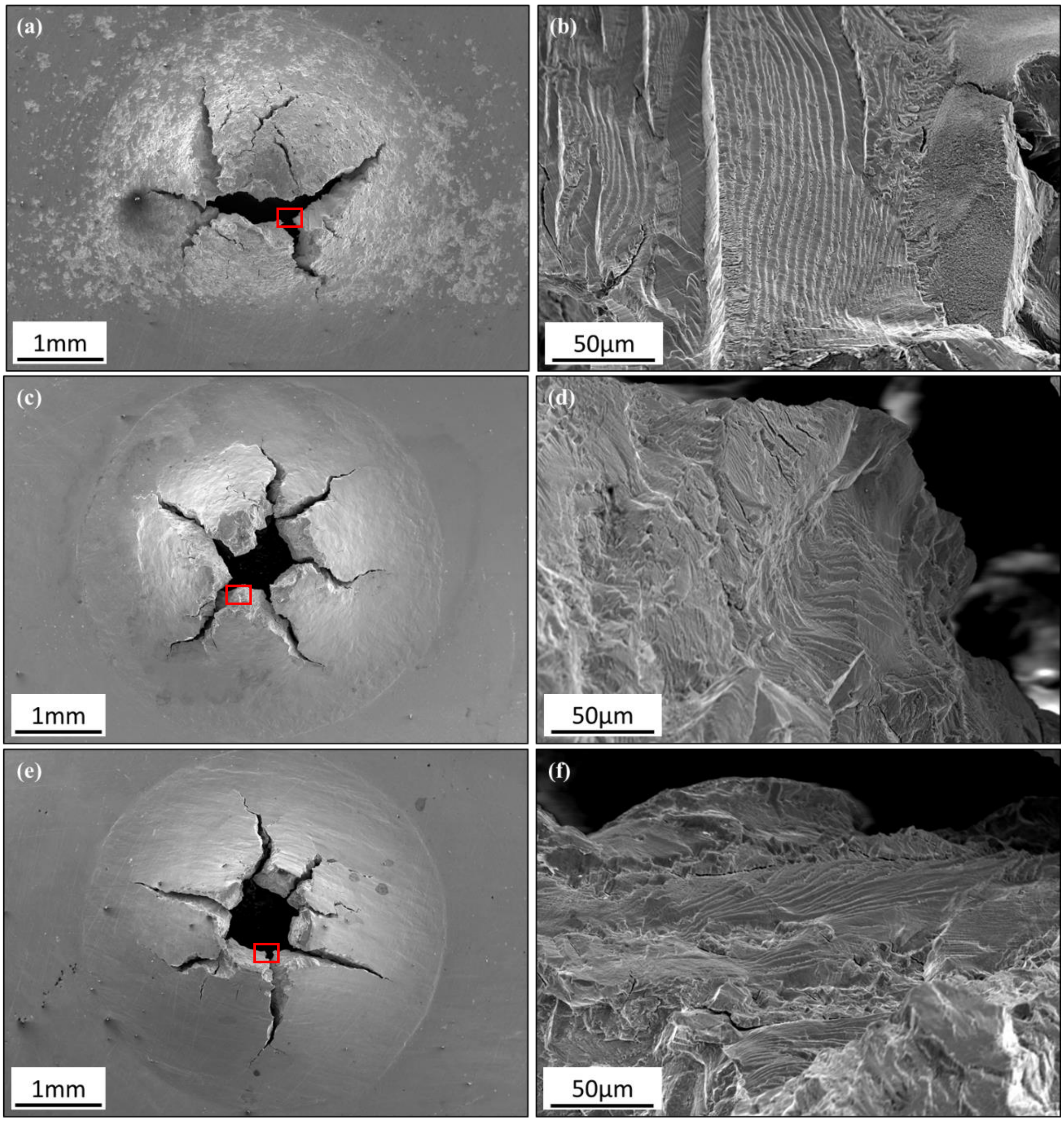

Figure 6. Fractographic images of small punch fatigue tests of (a-b) cast (c-d) LPBF 90° and (e-f) LPBF 0° C263 material showing clear evidence of striations.

4. Conclusions

Ongoing research into a bespoke small punch fatigue capability being conducted at Swansea University has been detailed in this paper resulting in the following conclusions:

- The small punch fatigue response of the C263 variants has shown a sensitivity to grain size in line with that expected under uniaxial fatigue conditions.
- Evidence of striations give confidence of the apparatus and the resulting fracture mechanisms that are taking place in the material variants.
- Further work into understanding the evolving stress state is a crucial step moving forward when aiming to compare or interpret the results with uniaxial fatigue data.

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