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The contribution of small punch testing towards the development of materials for aero-engine applications

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ABSTRACT

This paper, invited for presentation at the 33rd Meeting of the Spanish Group on Fracture and Structural Integrity, March 2016 in San Sebastian, Spain, reviews the recent work carried out in the authors' laboratory, addressing the elucidation of tensile and creep characteristics of materials for aero engine components. Two specific applications of the Small Punch (SP) test assessment technology were identified, the first of these takes on board the unique potential of the SP test for testing small quantities of materials which are either in development or through their directional structure cannot easily be produced in quantities which would allow conventional mechanical testing. This goal also required the development and procurement of new SP test facilities capable of operation up to 1150 °C. The examples given in this paper are TiAl intermetallic alloys and nickel based single crystals, all studied utilising the Code of Practice for SP Creep Testing. The second application illustrates the use of SP testing to assess both the tensile and creep properties of additive layer manufactured (ALM) alloys such as IN718 and Ti-6Al-4V using the Code of Practice for SP Tensile and Fracture Testing. Due to the unavailability of sufficient material to facilitate conventional testing for comparison of materials property data, SP testing is unable to provide absolute data for all of these applications, nevertheless the ranking capabilities of SP testing are demonstrably proven.

1. Introduction

In the 1980s the original intention of the Small Punch Test was to assess the degradation of nuclear reactor components as a result of irradiation damage [1,2]. This was mainly aimed at determining tensile and fracture properties of the reactor pressure vessel steels [3,4]. A decade later the technique was encouraged for application to study the degradation due to creep of conventional fossil fuel fired energy plant components [5]. Mainly for these two types of applications, a European Code of Practice (EUCoP) for SP tensile, fracture and creep testing was developed early in the 21st century and launched by CEN in 2006, revised in 2007 [6].

This rigid foundation for the methodology encouraged a major engagement by many laboratories, particularly in Europe, to exploit the technique further and extend to other industrial sectors. In particular, the aero-engine community have recognised the unique potential of the SP creep test for testing small quantities of novel candidate materials which cannot be produced in quantities which would allow significant conventional mechanical testing due to prohibitive cost. Here the continuous evolution of the jet engine has led to the need to develop new alloys to withstand the increasing temperatures experienced in service, providing a major challenge to materials scientists and engineers. Recent advances have led designers to re-evaluate the suitability of traditional alloy systems for high temperature components, particularly as operating temperatures approach the limitation of many currently employed nickel based superalloys. Although improved component design, advanced cooling procedures and thermal barrier coatings continue to ameliorate various issues, research into materials which are envisaged to replace established structural metallic systems for elevated temperature turbine disc and blade applications within a twenty year horizon, now constitutes a major research activity.

For the assessment of these novel candidate materials, either metallic or intermetallic in nature, the small punch (SP) test technique immediately serves as a cost effective, front-runner amongst presently available miniaturised test techniques. To date, the vast majority of interest in the SP technique has focussed on relatively ductile alloys. However, prior to the application of SP tests to potential new alloys, some of which may be brittle in nature at least at ambient temperature, a thorough assessment of the technique for an archetypal brittle alloy must be considered. As important as alloy development is the ability of SP testing to assess the

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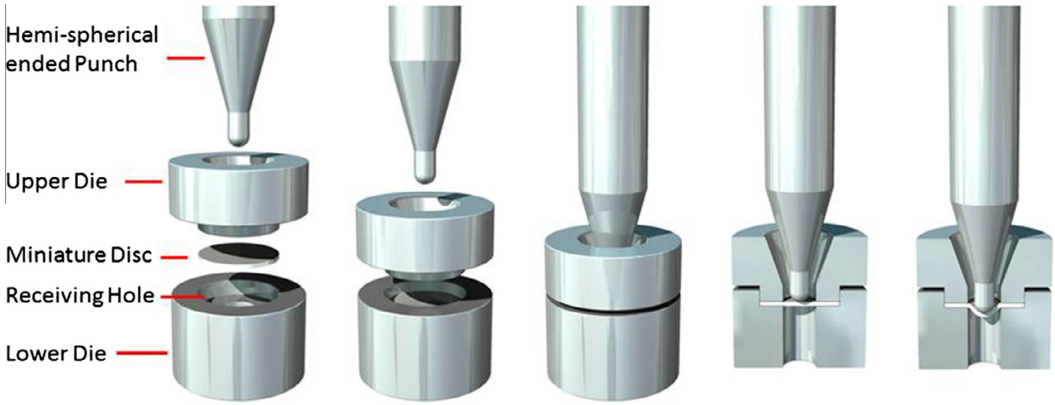

Fig. 1. Schematic representation of disc retention and punch application.

potential of the various techniques of additive layer manufacturing (ALM) aimed at gas turbine component repair and in the future for complete component manufacture. Here the advantage of being able to test small build volumes in tandem with process optimisation is complemented by the ability to assess mechanical properties in different orientations. This is also advantageous when characterising anisotropic materials such as single crystal alloys.

The present paper will serve to review the following four "case studies", selected examples from our recent research portfolio, where SP testing has been employed to address the range of requirements detailed above:

- CMSX-4® – an established single crystal turbine blade alloy, demonstrating notable directional mechanical properties.
- γTiAl – a brittle intermetallic at room temperature, intended for aerofoil applications in the low pressure turbine.
- IN718 – assessed as a developmental additive material for future aerofoil repair applications.
- Ti-6Al-4V – comparing conventional wrought and cast variants to novel electron beam melted material.

Throughout, evidence is provided to support the use of SP testing to define constitutive behaviour, demonstrating a sensitivity to microstructure and micro-texture variations, illustrating high temperature creep characteristics and correlations to conventional creep data.

2. Experimental approach

Two distinct small punch rig designs are required for (i) tensile and fracture testing and (ii) creep testing. However, both rely on loading a hemispherical ended punch or a recessed punch holding a spherical ball onto a thin disc specimen held in a clamped ring above a 4 mm receiving aperture, as displayed in Fig. 1. The deflection of the disc is continually monitored and is recorded against either increasing load under a constant rate of displacement in a tensile test or a constant applied load against time in a creep test. Tensile testing is usually conducted under higher loads than the creep test and a bespoke high temperature SP test jig has been designed for location within the load train of a universal, servo-actuated test frame. For higher temperature but lower load SP creep testing, a new free standing facility has been commissioned, which can operate at temperatures up to 1150 °C. The choice of punch material and diameter is determined by the loads required and test temperature. Normally, 2–2.5 mm diameter punches manufactured from Nimonic 90 are applied for tensile tests both at room and elevated temperature, with ceramic punches employed for very high loads and for creep tests at high temperatures. The other main difference between the equipment concerns the need for inert gas protection of the thin disc in the SP creep tests to resist oxidation under prolonged exposures. Depending upon the form of the as received stock material, discs are extracted using electrical discharge machining, then ground and polished to 500 μm ± 5 μm thickness. To reiterate, all testing was carried out according to the provisions set down in the EUCoP [6].

3. Results and discussion

3.1. Nickel based single crystals

Research has been completed to determine the suitability of the SP creep test when applied to single crystal forms of nickel based superalloy. The alloy selected was the established turbine blade alloy CMSX-4®,[1] tested at elevated temperatures of 950 °C, 1050 °C and 1150 °C. These temperatures in themselves mark a significant extension in SP capability when compared to the original intentions for SP techniques during the 1980s. The results were correlated with conventional uniaxial creep test approaches and used to demonstrate the implementation of long term lifing techniques to the relatively short term SP creep data. It is noteworthy that SP evaluation was capable of replicating the effects of microstructural evolution that prevails in this system across this temperature range.

It is inevitable that the characteristic, anisotropic nature of single crystal superalloys, where an improved creep response is found in a specific orientation, would influence the SP creep test. The biaxial stress distribution imposed during a SP creep test and the FCC unit cell of CMSX-4® are illustrated in Fig. 2. SP disc specimens were sectioned from a cylindrical rod of CMSX-4® grown in the ⟨0 0 1⟩ direction and therefore tested with load applied onto the orthogonal [1 0 0–0 1 0] plane.

Employing conventional, uniaxial creep testing, previous workers have demonstrated that under intermediate temperatures (700 °C) anisotropy is prominent in this alloy; crystals grown in the [0 0 1] orientation typically exhibited the strongest uni-axial creep resistance when stressed parallel to this orientation, followed by crystals loaded in the [0 1 1] orientation, with the [1 1 1] orientation demonstrating the weakest response. The strength effect is most pronounced during the primary creep phase [7,8]. However, at elevated temperatures, >980 °C, creep behaviour is seen to be far more isotropic. For example, at 1050 °C and 120 MPa, [0 0 1] orientated crystals exhibit a creep life between 468 and 705 h, [0 1 1] orientation a life of 536 h and [1 1 1] orien-

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

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