ARTICLE IN PRESS

Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Fracture behaviour of Alloy 718 at high strain rates, elevated temperatures, and various stress triaxialities

Ted Sjöberg *, Jörgen Kajberg, Mats Oldenburg

Division of Solid Mechanics, Luleå University of Technology, SE-97187 Luleå, Sweden

ARTICLE INFO

Article history:
Received 7 July 2016
Received in revised form 21 April 2017
Accepted 22 April 2017
Available online xxxx

Keywords:
Mechanical testing
Failure mechanism
High strain rate
High temperature
Digital image correlation

ABSTRACT

A methodology for fracture characterisation at strain rates up to 1000 s^{-1}, temperatures up to 650 °C, and various stress triaxialities is presented. High-speed photography combined with digital image correlation is used to evaluate the strain at fracture. The methodology was successfully demonstrated on aged nickel based Alloy 718, commonly used in the containment structure of aircraft engines. Tensile specimens with four different geometries were loaded to get a wide range of positive stress triaxialities. All specimens originated from one single heat and batch to ensure consistent mechanical properties. The results showed evident stress state dependency on the failure strain, where lower failure strains were observed at higher stress triaxialities for all combinations of temperatures and strain rates. A coupled relationship between the temperature and the stress triaxiality controlling the fracture strain was found. However, any clear dependency on strain rate was hard to detect.

1. Introduction

As environmental goals for the aerospace industry become more and more demanding, such as Flight Path 2050 set up by the Advisory Council for Aeronautics Research in Europe (ACARE), manufacturers are pushing structures and materials closer to their limits in order to improve efficiency and save weight. Producers of metallic turbine cases for aircraft engines experience on-going competition with much focus on weight reduction. The goal of weight reduction is however not the only objective for manufacturers. For example it is also of great importance for the casing to maintain its containment capability; i.e. the prevention of damage of the surrounding structure in the event of released parts in accidents such as blade off events. This means that good knowledge of plastic deformation and failure close to service conditions are absolutely necessary when designing all parts of aircraft engine cases, including the hot parts. Practically speaking, this involves knowledge concerning mechanical material response from onset of yield to fracture, at both high strain rates and elevated temperatures. In the design process of aircraft engine casings, testing in pilot-scale and full-scale are common and often required for certification and use in civilian traffic. These tests are both time-consuming and expensive. However, with the increased computational capability of modern software a lot of design steps can be managed in a virtual environment by using finite element analysis. Many leading commercial codes, such as LS-DYNA, ABAQUS and PAM-CRASH, therefore put a lot of effort to meet the demands on reliable fracture criteria in order for the industry to be able to accurately simulate complex situations such as blade off events in turbines.

It is well known that one of the most important controlling factors in ductile fracture of metals is the stress state. Bao and Wierzbicki [1] performed experimental testing and numerical simulation on 2024-T351 Aluminium using a series of

* Corresponding author.
E-mail address: Ted.Sjoberg@ltu.se (T. Sjöberg).

http://dx.doi.org/10.1016/j.engfracmech.2017.04.036
0013-7944/

Please cite this article in press as: Sjöberg T et al. Fracture behaviour of Alloy 718 at high strain rates, elevated temperatures, and various stress triaxialities. Engng Fract Mech (2017), http://dx.doi.org/10.1016/j.engfracmech.2017.04.036

different tests in order to cover a wide range of triaxialities. Based on these tests they could find that the relation between stress triaxiality and equivalent strain at fracture seems to be divided into three distinct areas. For large triaxialities the dominating failure mode is void growth while for negative stress triaxiality shear mode is the dominant failure mode. In between these two regions, at low triaxialities, a fracture can develop as a combination of both modes. Wierzbicki et al. [2] used the experimental results obtained by Bao and Wierzbicki in order to calibrate and evaluate seven different fracture models implemented in multiple commercial FE-codes. The seven fracture criteria were formulated in either the space of strain, stress or mixed strain-stress. They found that most models can only be used when the stress triaxiality stays within narrow ranges. The model they found best able to predict fracture over wide ranges of stress states was the Xue-Wierzbicki model. It was concluded that in order to accurately deal with wide ranges of stress states the fracture model needs to be constructed in the three-dimensional space of invariants. Teng and Wierzbicki [3] used the same experimental data on 2024-T351 Aluminium and experimental data on Weldox 460 E steel obtained by Børvik et al. [4,5] to calibrate six fracture models for high velocity impact scenarios. In a similar manner as Wierzbicki et al. they found that a fracture criterion formulated in the space of stress triaxiality and equivalent strain at fracture is unable to accurately represent fracture properties of a material. This can be demonstrated by for example the axisymmetric and transverse plane-strain loading conditions, two cases having the same stress triaxiality and therefore not distinguishable for such models. The solution Teng and Wierzbicki proposed is to include the effects of the third invariant of the deviatoric stress, J_3, when modelling fracture.

To further improve the accuracy of fracture prediction over wide ranges of stress states Bai and Wierzbicki [6] proposed a new fracture locus in the space of equivalent strain at fracture $\bar{\varepsilon}_f$, stress triaxiality η, and Lode angle parameter $\bar{\theta}$. The suggested model is similar to the Xue-Wierzbicki model, but the fracture locus is asymmetric with respect to the Lode angle. Another fracture criterion put forward by Bai and Wierzbicki [7] is a modified version of the stress-based Mohr-Coulomb criterion [8]. The proposed version of the Mohr-Coulomb criterion is also a mixed strain-stress representation in terms of the fracture strain $\bar{\varepsilon}_f$, the stress triaxiality η and the Lode angle parameter $\bar{\theta}$. The aim was to thereby customise the classical criterion to also cover ductile failure.

Recently Algarni, et al. [9] studied the stress triaxiality and Lode angle dependencies of nickel based Alloy 718. Experimental testing was performed at room temperature and quasi-static loading using round specimens with different notch geometries as well as a plane strain specimen geometry. The fracture behaviour was then characterised by applying the modified Mohr-Coulomb model. The results from this study showed that the fracture of Alloy 718 was only moderately dependent on the Lode angle. However it should be noted that the authors found that the plastic behaviour was highly dependent on the Lode angle.

Chocron et al. [10] proposed the addition of a Lode angle dependent term to the Johnson-Cook plasticity model and failure criterion. This resulted in a model that is simple to implement while still being able to predict more complex failure modes than the standard Johnson-Cook model. Erice and Gálves [11] used the same Lode dependent term to modify the Johnson-Cook failure criterion and then coupled it with a elastoplastic damage plasticity model. The coupled model was then applied on Alloy 718. For calibrating the model a number of geometries, both axisymmetric (round) specimen with different notches and plane specimens, were subjected to quasi-static tensile loading at room temperature. In addition a tensile split-Hopkinson bar was used to dynamically load round specimens in uniaxial tension at strain rates of approximately $\dot{\varepsilon} = 1000\ \text{s}^{-1}$. The dynamic tests were also performed over a wide range of temperatures, from 25 to approximately 800 °C. The fracture strains for the round specimens were estimated by employing an optical profilometer, where the strain values up to failure were given by $\varepsilon = 2\ln(d_0/d)$. The failure strains for the plane specimens subjected to quasi-static loading were determined by using digital image correlation (DIC). Erice et al. [12] later used the resulting model to compare numerical results with outcomes from high velocity impact experiments of Alloy 718 performed at elevated temperatures.

DIC, providing full-field displacement and strain measurements, is a well-established technique that has been used in many high strain rate applications. For example Kajberg and Wikman [13] used DIC to evaluate the strains in dogbone specimens used in split Hopkinson pressure bar experiments while Tarigopula et al. [14] used DIC in split Hopkinson tension bar experiments. Pierron et al. [15] used DIC to obtain full field measurements of a three point bending impact test on aluminium and Zhang et al. [16] used DIC in characterisation of mechanical properties in rock material using different testing methods in a split Hopkinson pressure bar system. DIC has also been used at high temperature conditions by amongst other Lyons et al. [17] who evaluated the use of full field measurements on uniaxial tensile specimens heated to 650 °C in a furnace. Grant et al. [18] pushed the temperature higher and by using filters and blue LED light to suppress black-body radiation effects and were able to use DIC to measure strains while uniaxially loading a nickel based alloy at a temperature of 1000 °C. A study by Guo et al. [19] reached even higher temperatures by spraying carbon fibre specimens with tungsten powder to form a speckle pattern. The high melting point of tungsten enabled application of DIC at testing temperatures as high as 2600 °C.

In this paper the focus is on characterising the fracture behaviour of Alloy 718 sheets used in the fan case of an aircraft engine. An extensive experimental campaign was therefore launched reflecting the typical service conditions in the engine considering fracture behaviour at plane stress conditions at varying strain rates, temperatures, and stress states. Tensile tests of flat specimens were performed for four different geometries in order to obtain a wide range of positive stress triaxialities at fracture. All geometries were tested at four different strain rates and three temperatures. Unlike the extensive experimental study conducted by Erice and Gálves [11], all specimen geometries were subjected to the same ranges of temperatures and strain rates. Further, the deformation processes of the specimens were captured using a high-speed camera, enabling the

Please cite this article in press as: Sjöberg T et al. Fracture behaviour of Alloy 718 at high strain rates, elevated temperatures, and various stress triaxialities. Engng Fract Mech (2017), http://dx.doi.org/10.1016/j.engfracmech.2017.04.036