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Effects of surface roughness on thermo-mechanical fatigue life of a P91 power plant steel

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Abstract

P91 martensitic steel has now been widely used for power plant components such as steam pipe sections and headers. With the shift to renewable sources, traditional fossil power plants are increasingly expected to operate under so called "two shifting" conditions (high frequency start up/shut down cycles from a partial load condition) to match market demands. Such conditions increase the potential for large thermal stresses to be induced in thick walled components, making thermo-mechanical fatigue (TMF) and creep-fatigue interaction a life limiting concern. It is important to investigate the behaviour of P91 power plant steel under cyclic creep-fatigue interaction conditions in order to estimate the component remnant life under various possible operating strategies. Specimens used for TMF testing are commonly hollow (unlike solid specimens used in isothermal tests) to allow for higher cooling rates (with insignificant radial temperature variations) by injecting air. It is difficult to polish the internal surface to the same extent as the external surface of the specimen (with a roughness (Ra) of 0.8μm). Concerns have been expressed as to whether this type of uncontrolled surface roughness could significantly affect the fatigue life of the specimen since most fatigue cracks often initiate at the surface of the material. In this work, the roughness profile of the internal surface of the TMF sample is measured using Alicona optical profilometer. Resultant surface profiles are idealised and used to simulate distributions of stress and plastic strain under fatigue load using multi-axial visco-plasticity model. Concentration of stress and higher plastic stain accumulations are observed at the peak region of the roughness profile and crack initiations are expected to occur at those regions. Using accumulated plastic strain as a failure criterion for the fatigue, shorter fatigue lifetime is expected for specimen with rougher surface relative to the polished specimen. Optical and scanning electron microscopy (SEM) has been used to investigate the nature of the cracks initiating from the internal and external (polished) surfaces of a failed TMF test specimen.

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Keywords: P91 steel, surface roughness, visco-plasticity model, thermo-mechanical fatigue

1. Introduction

There is a trend in numerous industries to operate components in ways that ensure output is closely matched to demand. The reasoning for this is clear; by operating based on demand waste can be minimised and efficiency

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increased. A potential danger in this strategy however is that components operating under these conditions will necessarily experience rapidly fluctuating loads that may be both thermal and mechanical. Consequently, ensuring structural integrity against thermo-mechanical fatigue (TMF) is an important priority.

An example of this phenomenon lies in the power industry. The changing energy portfolio has resulted in an increased dependence on renewable energy sources for base load. Conventional thermal plant is therefore becoming required to pick up the deficit to maintain baseline frequency. Given the fluctuations in market demand and renewable energy generation, "two-shifting" operating procedures are increasingly popular (high frequency start up/partial load/shut down cycles) ((Beatt et al., 1983, Shibli and Ford, 2014)). Under such conditions, large thermal stresses can be induced in thick walled high pressure components (such as steam header). In summary, there is a shift in concern in many industries; from creep deformation observed during sustained operation to complex temperature dependent visco-plastic behaviour.

Experimental data is required to determine bulk material properties in order to characterise these behaviours at the continuum level. For cyclic loading conditions, visco-plastic deformation and damage may be approximated using, for example, the material models presented in (Chaboche and Rousselier, 1983a, Chaboche and Rousselier, 1983b, Lemaitre and Chaboche, 1994). While solid specimens can be used for isothermal testing, it is generally the case that hollow samples are used for scenarios where both mechanical and thermal loads fluctuate (such as during TMF). Very high heating rates can be achieved in the laboratory using induction heating or radiant lamps. To match these rates (and achieve regular loading waveforms that may be analysed) when cooling is required, forced air is typically injected through the specimen. External surfaces of the specimen may be easily polished to $R_a = 0.8m$m, meaning machining defects (that would cause highly localised stress concentration) can be removed. Internal surfaces that are drilled in hollow samples cannot be controlled so easily. A concern exists therefore in the validity of TMF experiments performed using hollow samples. The work of Whittaker et al. (2013) for instance demonstrates the initiation of cracks on the internal surface of a hollow nickel based superalloy specimen tested to failure under TMF loading conditions. If localised behaviour in the vicinity of machining marks is severe premature crack imitation may be observed and bulk gauge section results distorted. These concerns are intensified when the work of Murakami and Miller (2005) is considered. Their investigations into fatigue damage in 70/30 brass highlighted that, rather than the approach assumed by continuum damage mechanics (CDM) by designating a representative volume element (RVE), the loss in load carrying capability during fatigue loading was dominated by crack initiation at the surface only. If surface conditions on a specimen are poorly understood, it is foreseeable that "fatigue damage" will be over-estimated or misinterpreted. The present work looks to investigate the possible effect of machining surface features on localised cyclic visco-plastic behaviour by conducting a stochastic study of drilled (internal) and polished (external) samples, reconstructing representative unit cells and subjecting them to cyclic loading in finite element analysis (FEA) using a multi-axial viscoplasticity model. The lifetime for fatigue crack initiation was also estimated using accumulated plastic strain and stored energy approach.

2. Surface analysis

To achieve faster cooling and heating rates, TMF samples used by Saad (2012) have a 4mm diameter through hole and its geometry and dimensions are shown in Fig. 1. The internal surface of a hollow sample is complex with features being semi-periodic and several different orders of "roughness" superimposed. Simulation of individual features observed from micrograph would be of limited interest as the severity of the feature could not be compared to others in the sample. What follows in the present section therefore is a description of the stochastic approach employed to generate representative unit cells based on observed surface profiles.

3D surface maps have been determined for "polished" (representative of the external $R_a = 0.8m$m surface of a test specimen) and "drilled" (representative of the machined internal surface) test coupons using an Alicona Infinite Focus (http://www.alicona.com/en/products/infinitefocus, 2016.). Surfaces were imaged using a 10x objective lens, suggesting a vertical (z axis) resolution of 150nm. This is deemed to be appropriate given the scale of features expected on the external polished (control) surface. The 4mm diameter hole machined in the "drilled" test coupon was cut using a tool spindle speed of 600rpm and a feed rate of 0.1mm/rev. Standard white water soluble oil coolants were used during the process. These parameters are typical of machining processes performed on high strength steels such as P91. The post-processing of the measured roughness profiles were carried out using MATLAB.