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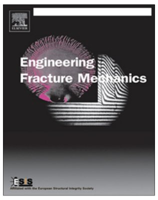

Modelling of creep rupture of ferritic/austenitic dissimilar weld interfaces under mode I fracture

Jia-nan Hu [a,b,*], Takuya Fukahori [c], Toshihide Igari [c], Yasuharu Chuman [c], Alan C.F. Cocks [a]

[a] *Department of Engineering Science, University of Oxford, Parks Road, OX1 3PJ, UK*
[b] *Sente Software Ltd, Surrey Technology Centre, Guildford GU2 7YG, UK*
[c] *Research & Innovation Centre, Mitsubishi Heavy Industry. Ltd, 717-1, Fukahori-machi, 5-chome, Nagasaki 851-0392, Japan*

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ABSTRACT

Dissimilar metal welded structures (DMWs) have been used extensively in conventional and nuclear power generation plants. Evaluation of creep rupture properties of DMWs is critical to the structural integrity assessment. Failure of DMWs can occur in the base metal, the heat-affected zone (HAZ), or the dissimilar interface between the two welded materials, depending on the operating stress and temperature. The primary focus of this work is on interface failure in systems consisting of a ferritic steel (P91 or P22) and an Inconel filler material, which has an austenitic structure. A planar damage zone is introduced within a finite element (FE) framework to model the response of the interface. A traction-separation constitutive law with a Kachanov-type damage accumulation relationship is employed to describe the interface response, with the material parameters calibrated against available creep rupture data in which failure occurred at the dissimilar weld interface. It is found that the difference in damage accumulation along the interface of different DMW systems can be attributed to the mismatch in creep properties of the continuum materials either side of the interface. Diversion of the crack path into the HAZ is also captured as a result of damage accumulation in the heat affected zone (HAZ). The relationship between the empirical damage accumulation model and the major microstructural features that are responsible for interface failure is also discussed.

1. Introduction

Dissimilar metal welded joints (DMWs) are used extensively in many high temperature engineering applications in which different materials are used in different regions of a plant to satisfy the mechanical, environmental and/or economical requirements of the design [1]. In conventional or nuclear power generating plant, DMWs between ferritic low alloy steels and austenitic stainless steels or between different grades of ferritic steels are commonly used [2–4]. Due to the thermo-mechanical mismatch between the two materials, filler metals (such as Inconel) are often used and buttered on one material before being joined to the other. This, ensures the mutual solubility between the two welded materials, and also helps mitigate against the residual stresses that can be produced when the DMWs are heated to elevated temperatures in service [3,4].

Evaluation of the creep rupture properties of DMWs is critical to the structural integrity assessment. A variety of failure modes associated with DMWs have been identified during monotonic uniaxial creep rupture tests of planar components or

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[*] Corresponding author at: Sente Software Ltd, Surrey Technology Centre, Guildford GU2 7YG, UK.
E-mail address: jianan.hu@sentesoftware.co.uk (J.-n. Hu).

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Nomenclature

α	coefficient of thermal expansion (CTE)
ε_{ij}^{e}	elastic strain of continuum material
ε_{ij}^{cr}	creep strain of continuum material
ε_{ij}^{th}	thermal strain of continuum material
$\dot{\varepsilon}_0(\dot{\varepsilon}_{0H})$	strain rate in the base metal (heat affected zone) at a reference stress σ_0
n	power-law creep stress exponent of continuum material
h	softening constant for heat affected zone
b	nucleation constant for heat affected zone
N	number of nucleated cavities in heat affected zone
X	triaxiality factor
δ_n (δ_t)	normal (tangential) separation of interface zone
T_n (T_t)	normal (tangential) traction of interface zone
a	elastic constant of interface zone
$\dot{\delta}_0$	creep separation rate of interface zone at a reference traction T_0
δ_c	critical crack opening separation
δ_n^{cr}	normal separation of interface zone resulted from creep
ω	damage variable of interface zone
m	power-law creep constant of interface zone

solid pipes [3,5,6]. There are three major categories of failure (Fig. 1), namely: base metal failure (Type V); heat affected zone (HAZ) failure (Type IV); and failure at the interface between one metal and the filler metal (Type VI or VII), whereby Type VII refers to failure along the interface, and Type VI failure initiates where the interface meets the free surface, but eventually diverts into the HAZ or even the base metal. Similar crack path changes have also been observed in similar metal welded (SMW) components [7,8] which have been simulated by examining creep crack growth (CCG) in SMW models containing an initial crack at different positions [7–12]. These studies demonstrate that, the effect of mismatch in creep properties surrounding the crack, applied load level, initial crack position, specimen geometric constraint and even the width of the HAZ, etc, can all contribute to the crack path change by promoting the initiation and propagation of a secondary crack in the soft material to the side of the initial crack [7,8]. These factors may help explain the Type VI failure mode shown in Fig. 1 for DMW components, but studies on intact DMW components without an initial defect have not been extensively conducted. Moreover, changes in environmental conditions such as the operating temperature and applied stress level may lead to a change of the dominant failure mode. A comprehensive understanding of the DMW failure mechanism and when a given mechanism dominates is yet to be achieved.

In this work we are interested in the creep failure at dissimilar welded interfaces when one metal is ferritic 9Cr-1MoVNb (designated P91) steel or 2.25Cr-1Mo (designated P22) and the filler metal is an austenitic Inconel alloy (designated Inco). Monotonic uniaxial creep rupture tests of different DMWs have been carried out by different research groups at 550 °C [3,5,6]. Laha et al. [3] adopted Inco182 as the filler metal, while other researchers [5,6] employed Inco82. Fig. 2 summarizes the results of experiments on P91/Inco182/Alloy 800 and P22/Inco182/Alloy 800 DMWs conducted by Laha et al. [3] and P91/Inco82/SUS304 conducted by Yamazaki and Yamashita et al. [5,6]. Results of creep tests on the pure base metals of P91 or P22 and the trend lines for all the data obtained by Laha et al. [3] are also shown in the figure. At most applied stresses, DMWs are found to be weaker than the counterpart base metals. Also P22 DMWs are found to be weaker than P91 DMWs in all these uniaxial tests. In the double logarithmic plot of Fig. 2, a transition of slope of the trend lines can be clearly seen when the mode changes to interface failure, which dominates at relatively low stresses and long times to failure, and has occurred predominantly at the ferritic/austenitic interface, despite the use of different Inconel fillers. Note that the interface failure life of the P91 DMWs tested by the different investigators is observed to be similar within the tested stress range. Further, metallurgical observations of the tested samples have revealed a sharp transition in microstructure, physical properties and chemical composition across the interface, which leads to discontinuous mechanical properties, such as hardness, and the generation of residual stresses [3]. Elongated precipitates and cavities have also been observed along the

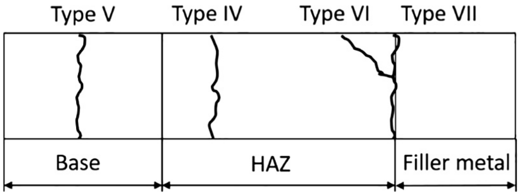

Fig. 1. Typical failure modes associated with dissimilar metal welded systems.

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