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Creep rates of heat-affected zone of grade 91 pipe welds as determined by stress-relaxation test

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ABSTRACT

Cross-weld creep testing conducted at 650 °C under 69 MPa stress has reproduced either the Type I or Type IV failure mode in Grade 91 welds, depending on the post-weld heat treatment procedures. Welds post-weld heat treated below the A_{C1} temperature have ruptured in the Type VI failure mode, while welds heat-treated above the A_{C1} temperature of the alloy have ruptured in the Type I failure mode. Heat-treatments at lower temperatures and shorter durations have produced a reduced creep rate. The accelerated short term stress-relaxation test has been conducted to obtain the input creep rates for a finite element model for the cross-weld creep testing. The model predicted secondary creep rates are in good agreement with the results from the conventional cross-weld creep tests. From the finite element model, the creep damage by cavitation is believed to start at regions where the first principal stress and stress triaxiality concentrate.

1. Introduction

The creep-enhanced ferritic steel Grade 91 was designed for creep service at higher temperature and stress levels than those could be provided by P22 [1]. Due to the higher design stress provided by Grade 91, a reduced section thickness would enhance the component's thermal fatigue resistance under oxidation conditions. However, premature failures were reported in Grade 91 weldments due to creep damage in the heat-affected zone [2,3]. In such Type IV cracking, initially reported by Shuller et al. [4], creep voids form in the fine-grained and inter-critical heat-affected zone of high-Cr ferritic heat resisting steels, leading to early failure compared with creep tests on the base material [5,6]. Openly reported creep results on Grade 91 cross-weld specimens became abundant most recently, for instance, by Parker et al. [7,8,10] and in reviews by Abson and Rothwell [9] and David et al. [11]. Data on Type IV creep failure as a function of post-weld heat-treated at various temperatures and times are in great demand [11,12].

Although most of the total creep deformation comes from the fine-grained HAZ in Type IV damage of cross-weld specimens of Grade 91, some researchers have assumed the total creep strain to be additive of contributions from a composite material of base, weld and heat-affected zones. Using this additive assumption, Li, Shinozaki, and Kuroki [13] studied the coarse-grained and fine-grained heat-affected zones in a two-dimensional finite element model and concluded that the first principal stress controlled the formation of voids in Type IV failure, which agreed with previously reported conclusion. Watanabe et al. [14] considered three different regions - weld metal, base metal, and fine-grained heat-affected zone - in a finite element model and concluded that the stress triaxiality controlled the creep void formation. Both studies used estimated high temperature material properties in their models, and the models did not include all regions in the heat-affected zone.

To measure the creep law from specific heat-affected zones, simulated microstructure needs to be reproduced according to the measured thermal history during the actual welding. To test the simulated specimens using conventional constant load creep testing, however, takes a long time and great cost. A short-term accelerated creep test that produces usable creep law data is desired. Yet it has to be understood that the creep rates obtained from short-term tests are derived from the current status of the material. Long-term damage such as aging, oxidation, and the

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interactive microstructure evolution during creep is not considered in the short-term test. Woodford showed that the creep rates could be generated from a stress relaxation test [15]. Rao et al. [16] recently proved that the crest rates from stress relaxation tests with a 0.8% initial strain are in good agreement with the results from conventional creep tests for a 10% Cr cast steel. Jung et al. [17] compared the data from compressive stress relaxation tests of a zirconium alloy with 2–10% initial strain, and concluded that the minimum creep rates from relaxation tests matched well with the creep rates from the conventional creep tests.

This paper will study the finite element modeling of the cross-weld creep in Grade 91 joints as affected by post-weld heat-treatment (PWHT) below and above A_{C1} temperature. The study will consider cross-weld creep specimens that are consisted of base metal, weld metal, and three regions of the heat-affected zone. The input data will be obtained from an accelerated creep test using the stress-relaxation method.

2. Experimental Procedure

2.1. Welding and heat treatment

The ASTM A335 P91/ASME SA335 P91 pipe had an 8.625-inch (219 mm) outer diameter, 1.143-inch (29 mm) thickness, and was normalized for 8 min at 1060 °C and tempered for 45 min at 786 °C in its as-received condition. The chemical composition of the Grade 91 pipe and filler metals are given in Table 1. Two 8-inch (203 mm) long pipes were welded together by gas-tungsten arc welding (GTAW) and flux-cored arc welding (FCAW) processes. The double-V weld groove had a 60° included angle with 1.5 mm root face. GTAW was used for the root pass with 300 A DC and 1.27 m/min wire feed speed, and FCAW was used for the filling passes with 26.5 V arc voltage and 7.0 m/min wire feed speed. Pure argon shielding was used for GTAW and mixed 75 Argon/25 CO_2 shielding was used for FCAW. The filler metal was 1.2 mm diameter ER90S-B9 for GTAW, and ER91T1-B9 for FCAW. The 0.14 m/min linear travel speed was maintained for GTAW and 0.292 m/min for FCAW by a stepper motor controlled fixture. Sixteen Type-K thermocouples were placed on different locations from the edge of the weld groove to measure the temperature profile. Two 8-channel data loggers were used to record the temperature measurements with a sampling frequency of 5 Hz. After welding, the locations of the thermocouples were re-measured relative to the fusion line, which was assumed to have experienced the melting temperature. The microstructure from the HAZ of the as-welded specimen was then analyzed and the HAZ locations were identified and measured from the fusion line. The interpass temperature was maintained with a use of ceramic pad heater and surface temperature probe, with an accuracy of temperature control at ±10 °C. The preheat temperature was between 150 and 250 °C. The interpass temperature during welding was between 200 and 300° C. A pneumatic descaler and wire brushing were used for slag removal. A post-weld bake out at 250 °C temperature for 4 h was conducted with temperature-controlled oven. Subsequently, the as-welded joints were post-weld heat-treated in an air furnace with a heating rate of 10 °C/minute, holding for 2 or 8 h at various temperatures both below and above the A_{C1}, and air cool to room temperature.

2.2. Creep test

The cross-weld creep specimens were extracted from the welded and heat-treated pipe samples as shown in Fig. 1a. The dog-bone shaped creep specimen had an effective gauge length of

Table 1
Chemical composition of Grade 91 base and filler metals (wt.%).

	ER90S-B9 GTAW	E91T1-B9 FCAW	Base metal
C	0.097	0.10	0.11
Mn	0.56	0.79	0.37
Si	0.25	0.28	0.37
S	0.004	0.008	0.002
P	0.006	0.02	0.016
Cr	8.83	9.1	8.47
Ni	0.307	0.55	0.08
Mo	0.928	0.88	0.94
Nb	0.064	0.03	0.071
N	0.03	0.05	0.048
O_2	47 ppm		
Ti	0.001		
Al	0.002	0.001	0.002
V	0.197	0.2	0.19
Cu	0.013	0.04	
As	0.003	0.002	
Sn	0.003	0.008	
Sb	0.003	0.002	
B	0.0007		
Zr	0.001		
CO	0.028		
Ca	0.003		
Ta	0.001		
W	0.005		
H_2	3 ppm		

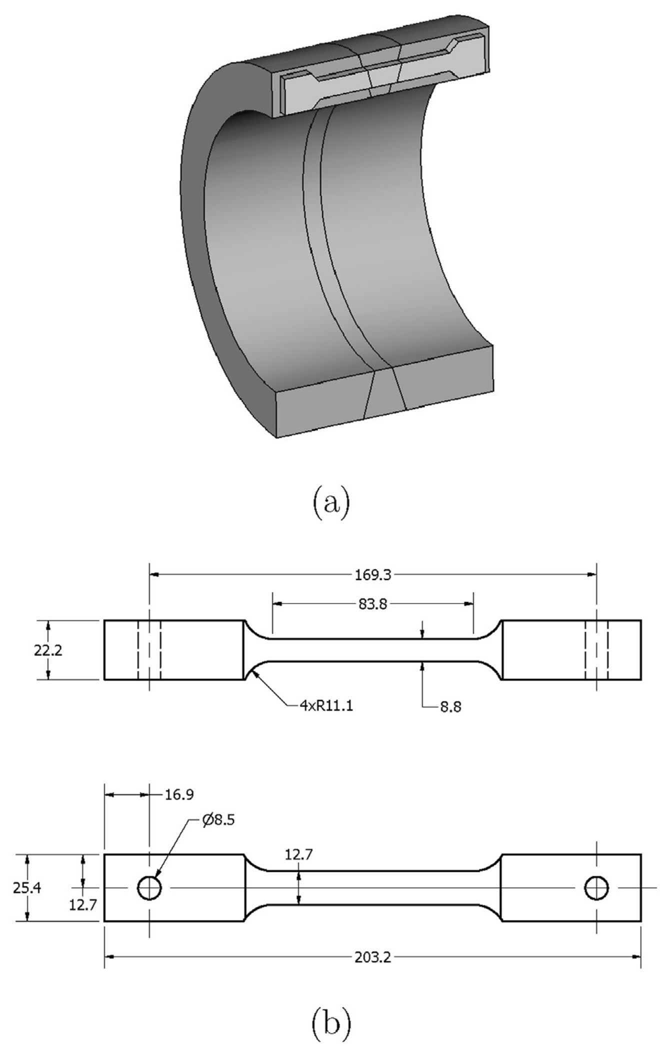

Fig. 1. Schematic of cross-weld creep test specimen extraction from the welded pipe (a), and the dimensions of the creep rupture specimen (in mm) (b).