International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:6, No:1, 2012

Creep Constitutive Equation for 2- Materials of Weldment-304L Stainless Steel

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***Abstract*—**In this paper, creep constitutive equations of base (Parent) and weld materials of the weldment for cold-drawn 304L stainless steel have been obtained experimentally. For this purpose, test samples have been generated from cold drawn bars and weld material according to the ASTM standard. The creep behavior and properties have been examined for these materials by conducting uni-axial creep tests. Constant temperatures and constant load uni-axial creep tests have been carried out at two high temperatures, 680 and 720 °C, subjected to constant loads, which produce initial stresses ranging from 240 to 360 MPa. The experimental data have been used to obtain the creep constitutive parameters using numerical optimization techniques.

***Keywords*—**Creep, Constitutive equation, Cold-drawn 304L stainless steel, Weld, Base material

I. INTRODUCTION

ENGINEERING parts, which operate at high temperature and under mechanical loads, have many applications in power generation and petrochemical plants. The trend to increase the thermal efficiency of these systems leads to the use of higher working temperature levels [1]. Therefore, it is necessary to study the creep behaviour of the high temperature alloys, which are used in these systems. Recently, methods to analyze the creep behaviour of the structures or materials have been improved significantly in three fields:

- Developing more realistic constitutive equations;
- Carrying out more tests to produce accurate constitutive parameters;
- Improving or modifying methods to analyze the creep behaviour of materials and reduce the simplifying assumptions.

In this paper both first and the second fields have been addressed. In other words, using a series of uni-axial creep tests, the creep behavior of two different materials: parent and weld of cold-drawn 304L stainless steel (CD 304L SS) have been determined. The material conforms to ASTM A276-05a specifications. Using the experimental data, creep constitutive parameters for two materials have been obtained, which can be used to estimate the creep behavior of welded joints at different operating conditions.

Constant temperature and constant load uni-axial creep tests have been carried out at two high temperatures, 680 and 720°C, under initial stresses of 240 to 360 MPa.

Over the past several decades, considerable efforts have been made to gain a fundamental understanding of the creep mechanisms and to develop an efficient engineering design criterion for high temperature components, which operate under multi-axial stress states. However, a realistic creep testing procedure requires tremendous effort and long time tests which are expensive and often unachievable. To overcome this shortcoming, usually, tests have been carried out at uni-axial condition under high temperature and stress levels.

Hald [2] and also Agamennone et al. [3] have quantified the microstructural evolution during the creep at 650°C of tempered martensite 9–12%Cr-steel modified with 2%W and 5%Co. Hayhurst et al. [4] have studied the creep deformation and rupture data of butt-welded pipes associated with 0.5Cr0.5Mo0.25V ferritic steel.

Kimura et al. [5] have studied long-term creep deformation properties of modified 9Cr–1Mo steel. They have shown that, with decrease in stress level, the magnitude of creep strain at the onset of accelerating creep stage decreases from about 2% in the short-term regime to less than 1% in the long-term region. They have also shown that the time to 1% total strain, that is an important parameter for design of high temperature components, lies in the transient creep stage in the short-term regime; whereas, it shifts to the accelerating creep stage in the long-term regime.

The effect of precipitation behaviour in the gauge lengths of the creep test specimens have been studied by Padilha et al. [6] for initially solution annealed type 316L(N) stainless steel at 550 and 600°C for periods of up to 85000 hr. Latha et al. [7] have studied the thermal creep properties of alloy D9 and 316 stainless steel tubes. They have compared their results with the properties of 20% cold worked type 316 stainless steel tubes and showed that alloy D9 has higher creep rupture strength, lower creep rate and lower rupture ductility than 316 stainless steel.

Hayhurst et al. [8] have obtained constitutive equations for time independent plasticity and creep of 316 stainless steel at 550°C.

II. NORTON POWER LAW CREEP CONSTITUTIVE EQUATION

Numerous authors, within the framework of the physical and metallurgical points of view, have proposed various types of creep constitutive equations for metals. Most of the constitutive equations are obtained by means of the generalization of the simple and classic time and strain-hardening laws. Once the types of the constitutive equations and their parameters have been determined, the stress and temperature levels, at which these equations are used, should be determined.

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A wide range of creep model equations are in use today to represent the high-temperature time-dependent deformation behaviour of engineering materials [9]. Many of these equations comprise components originating from a small number of classical representations of primary, secondary, and/or tertiary creep deformations. The selection of the proper form of a constitutive equation is a major task in studying the creep behaviour of materials and this can be achieved by comparing the experimental data with the predicted creep strains for the material obtained using the selected constitutive equation [10]. The most important and widely used types of constitutive equations to predict the secondary creep are Norton- Power Law [10]:

$$\dot{\varepsilon}_{ss} = A\sigma^{n} \exp(-\frac{Q}{RT}) \qquad (1)$$

in which $\dot{\varepsilon}_{ss}$ is the steady state creep strain rate, σ is stress, Q is the activation energy, R is Boltzman gas constant, t is time and T is absolute temperature. Other parameters are physical constant which should be determined based on creep test data for each material.

To study the creep rupture-time of metals, various physics-based equations such as Larson-Miller, Monkman-Grant, Orr-Sherby-Dorn, Goldhoff-Sherby, White-Le May, have been proposed [11]. Among them Larson-Miller equation can be expressed as:

$$P_{L-M} = (T)(C + \log_{10} t_r) \qquad (2)$$

This equation can be derived from Equation (1) with some simplifying assumptions. In this equation T is in Kelvin, t_r is rupture time in hours and C is a physical parameter which has been assumed to be 20. This value is an accepted amount for most engineering materials and steels [12] and therefore, has been used in this research work to estimate the creep behavior of the materials.

III. SPECIMENS AND CREEP TEST MACHINE

The test specimens have been machined out from the bars according to the ASTM E8M-04 [13] with gauge length of 100mm and diameter of 10mm (see Figure 1).

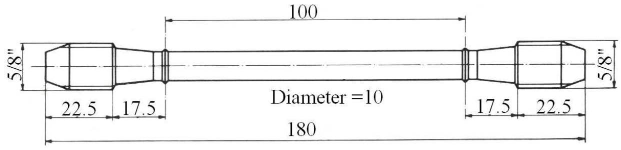

Fig. 1 Schematic creep test specimen, dimensions are in mm.

Uni-axial creep tests have been carried out using 5000 kg, AMSLER creep test machine according to the ASTM E139 [14] standard. Its lever-arm loading ratio is 25:1 with load accuracy of +/- 1%. Furnace or chamber temperature range of the machine is up to 1000^{o}C with the accuracy of +/-0.5^{o}C. It also provides displacement-time graphs with the accuracy of +/-0.5 µm. The maximum extension of the specimen is 10 mm.

IV. MATERIAL AND EXPERIMENTAL TESTS

Type 304 stainless steel is the most widely used alloy of the austenitic group. It is a variation of the basic 18-8 grade, Type 302, with a higher chromium and lower carbon content. Lower carbon minimizes chromium carbide precipitation due to welding and its susceptibility to intergranular corrosion. In many instances, it can be used in the "as-welded" condition, while Type 302 must be annealed in order to retain adequate corrosion resistance. Type 304L is an extra low-carbon variation of Type 304 with a 0.03% maximum carbon content that eliminates carbide precipitation due to welding. As a result, this alloy can be used in the "as-welded" condition, even in severe corrosive conditions. 304L has slightly lower mechanical properties than Type 304. The maximum temperature to which Types 304 and 304L can be exposed continuously without appreciable scaling is about 899°C. For intermittent exposure, the maximum exposure temperature is about 816°C. Type 304L is non-hardenable by heat treatment annealed by heating to 1038 - 1121°C, then cooled rapidly. Cold worked parts can be stress relieved at 399°C for 1/2 to 2 hours [15].

To study the creep properties of the base material, test samples have been obtained directly from new austenitic 304L stainless steel cold-drawn bars, which have been solution, annealed at 1050^{o}C. Chemical composition of this material is given in Table 1.

TABLE I
CHEMICAL COMPOSITION OF CD 304L SS IN PERCENT

C	Si	Mn	Cr	Mo	Ni	Cu	V
0.025	0.42	1.8	17.8	0.27	8.1	0.76	0.19

In this table, results of quant-metric measurements for the specimens under investigation are given. To study the creep properties of the base material, CD 304L SS, Uni-axial creep tests have been carried out at temperatures from 680 to720^{o}C under constant initial stress from 320 to 360 MPa. During the tests, the temperature and load levels remain constant.

To study the creep properties of the weld material, test samples have been obtained directly from the blanks machined out from the axis of the weld material zone of the weldment and in the direction parallel to the weld line. To avoid any material mismatch, the weld blanks were 3.5 mm apart from the fusion boundary (see Fig. 2). The material used was a CD 304L SS steel plate with a thickness of 30 mm. The plates were welded using Multi-layer TIG welding with 28 passes. X-ray inspection of the welded joint revealed no welding defects. Uni-axial creep tests have been carried out at two temperature levels of 680 and 720^{o}C under constant initial stress of 240 and 260 MPa.

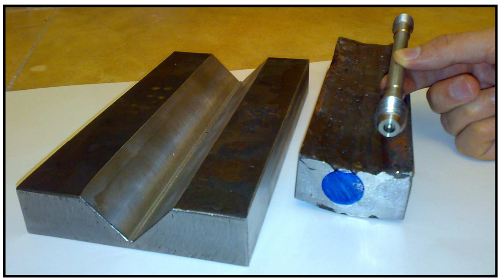

Fig. 2 The blanks machined out from the axis of the weld material zone of the weldment

V. EXPERIMENTAL RESULTS

Fig. 3 presents the true stress-strain curves for different material layers of the weldment: Parent and weld at 25, 680, 700 and 720°C obtained using experimental tests.

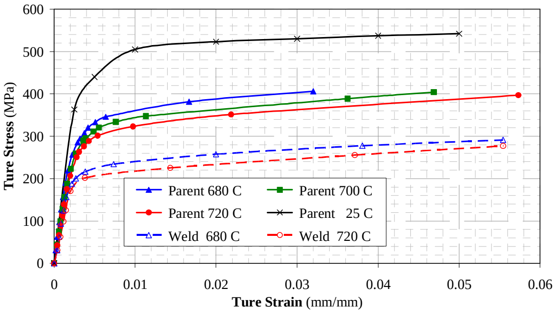

Fig. 3 True stress-strain curves for base (parent) and weld materials. Data have been obtained using experimental tests

A power law formulation has been used to model the uni-axial time independent elasto-plastic straining:

$$\begin{aligned} \varepsilon_{elastic} &= \sigma / E \quad && if\ \sigma \le S_y \\ \varepsilon_{plastic} &= B\sigma^m \quad && if\ \sigma > S_y \end{aligned} \tag{3}$$

where E, B and m are temperature dependent material constants. The Young's Modulus E, and initial yield stress, Sy, have been obtained from uni-axial experimental data. To obtain material constants, B and m, Least Square optimization scheme has been used. For this purpose theoretical strains have been calculated using Equation (3) and the experimental strains have been obtained directly from test measurements. Minimizing the error function, given constants B and m, for different material layers, which are given in Table II.

TABLE II
ELASTO-PLASTIC PROPERTIES OF THE BASE (PARENT) AND WELD MATERIALS (CD 304L SS) AT DIFFERENT TEMPERATURE LEVELS

Material	*Tem.* (°C)	*Elastic module* (GPa)	*Yield Stress* (MPa)	*B(MPa^{-m})*	*m(-)*
Base	25	179.5	426	3.555×10^{-65}	23.09
	680	145.2	319	2.339×10^{-26}	9.24
	700	116.2	305	1.059×10^{-28}	10.25
	720	116	290	8.658×10^{-24}	8.4
Weld	680	-	213	7.6837×10^{-25}	9.28
	720	-	194	5.2487×10^{-23}	8.64

Creep failure in engineering components can be regarded in two ways: when the time to rupture, t_r, has been reached or the time, $t_{Creep\ Strain=C\%}$, at which the creep strain reaches a critical level of C%. In most of the engineering components, the latter condition plays a major role; and therefore, it has been used in this study. Since the maximum extension of the specimen is 10 mm (total strain of 10%) in the creep-testing-machine, all the tests have been carried out until the true creep strain of 3% has been reached or $t=t_{Creep\ Strain=3\%}$.

TABLE III
UNI-AXIAL CREEP TESTING RESULTS FOR THE BASE (PARENT) AND WELD MATERIALS (CD 304L SS)

Material	*Temp.* (°C)	*Stress* (MPa)	$t_{Creep\ Strain=3\%}$ (hr)	*Min. Creep Strain Rate* $\dot{\varepsilon}_{ss}$ (1/hr)
Base	680	320	400	7.57187×10^{-05}
	680	340	348	8.59975×10^{-05}
	680	360	236	1.28547×10^{-04}
	720	320	98	3.07829×10^{-04}
	720	340	72	3.78703×10^{-04}
	720	360	55	5.55202×10^{-04}
Weld	680	240	2100	1.44733×10^{-05}
	680	260	1350	2.33645×10^{-05}
	720	240	452	6.69506×10^{-05}
	720	260	300	1.0844×10^{-04}

At this amount of deformation, most of engineering components would be regarded as failed. The summary of the creep test results have been given in Table 3. Also, the minimum creep strain rate, $\dot{\varepsilon}_{ss}$, for each test has been given in this table. The results given in Table 3 show that by increasing the stress or temperature, time to reach 3% creep strain decreases significantly. Also it shows that at the same temperature and stress level, the time to reach 3% creep strain for the Base material (parent) and weld materials are very close.

Fig. 4 shows the variation of minimum creep strain rate $\dot{\varepsilon}_{ss}$ with 1/T for different stress levels. Also Fig. 5 shows the variation of minimum creep strain rate $\dot{\varepsilon}_{ss}$ with stress at different temperature levels.

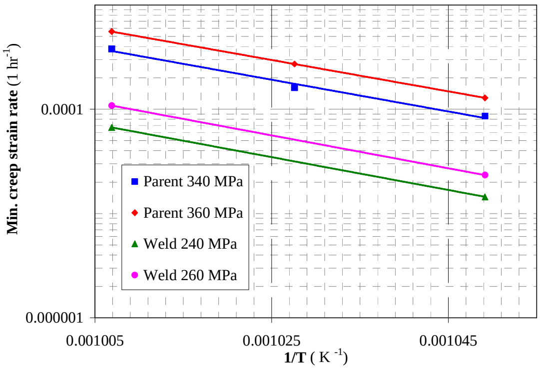

Fig. 4 Variation of the minimum creep strain rate (1/hr) with the inverse of temperature (1/K)

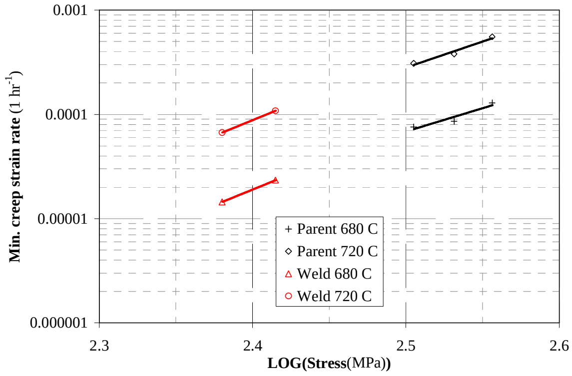

Fig. 5 Variation of the minimum creep strain rate (1/hr) LOG (stress (MPa))

The slope of the lines presented in Fig. 4 will give amount of "-Q/R" parameter; and also the slope of the lines in Fig. 5 give the amount the value of "n" power. The almost parallel lines in log-log scale in this figure proves that "n" is independent of the temperature level and also almost equal slope of the lines in Fig. 4 show that "-Q/R" is stress independent.

The nonlinear behavior of creep deformation often cause large scatter in creep test data. Also, errors due to the data recording and discrepancy of the test results lead to different values of constitutive parameters for each test. Therefore, the constitutive parameters which fit best with all test data should be obtained using numerical optimazation methods. Using these methods, the constitutive parameters can be obtained by minimising the difference between experimental data points and the calculated values. A computer code has been developed based on unconstrained nonlinear optimaization method. Using this code, the error function has been minimised to obtain the creep constitutive parameters, which are given in Table IV.

TABLE IV
CREEP CONSTITUTIVE PARAMETERS FOR THE BASE (PARENT) AND WELD MATERIALS (CD 304L SS)

Material	*A* *(MPa^{-n}hr^{-1})*	*Q* *(J/mol K) ×10^5*	*n*
Base	6.0121×10^{-5}	2.6	5.73
Weld	97.838×10^{-3}	2.6	4.59

VI. CONCLUSION

A set of constant load creep tests have been carried out to predict creep behavior, constitutive parameters and time to reach 3% creep strain for CD 304L SS weldment materials. The results show that at the same temperature and stress level, the time to reach 3% creep strain ($t_{Creep\ Strain=3\%}$) for the parent and weld materials are very close. Also it has been shown that at the same temperature and stress level, the minimum creep strain rate is minimum for the weld material and is maximum for base material.

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