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Analysis and mathematical modelling of elevated temperature flow behaviour of austenitic stainless steels

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ABSTRACT

High temperature flow behaviour of various grades of austenitic stainless steels viz. 304L, 304, 304 (as-cast), 316L and 15Cr–15Ni–Ti modified austenitic stainless steels (alloy D9) were analyzed by performing isothermal hot compression tests in a wide range of temperatures (1073 K to 1473 K for 304L, 304, 304 (as-cast), 316L and 1123 K to 1523 K for alloy D9) and strain rates (0.001–1 s^{-1}). It has been observed that all these materials show strain hardening, strain rate hardening, thermal softening, coupled effect of temperature and strain, and temperature and strain rate on flow stress in the hot working domain. The modified Zerilli–Armstrong (MZA) model which considers the above significant effects on flow stress has been applied to predict the flow behaviour of these materials. The material constants of the MZA model for each material have been evaluated and subsequently applied to predict the flow stress. It has been demonstrated that the MZA model could adequately represent the elevated temperature flow behaviour of these materials over the entire ranges of strain, strain rate and temperature.

1. Introduction

Over the decades, finite element (FE) simulation has been successfully used as a tool to analyze and optimize the thermo-mechanical processes [1–3] like rolling, forging and extrusion. Constitutive equation is used as an input to the FE code for simulating the material's response under specified loading conditions [4,5]. Therefore, the accuracy of the FE simulation depends to a large extent on how accurately the deformation behaviour of the material is being represented by the constitutive equation [6]. Basically, constitutive equation is a mathematical representation of the relationship between the flow behaviour of the material and the process parameters like strain (ε), strain rate ($\dot{\varepsilon}$) and temperature (T). Additionally, the constitutive equation may also contain information related to the thermo-mechanical history and microstructural parameters depending on the requirement of the users [7,8]. These equations are used to predict the flow stress of material when other processing parameters are known [9,10]. The constitutive flow behaviour of materials is often found to be complex in nature [11,12]. A single equation may not be sufficient to describe the flow behaviour of all materials in a specified domain or of a specific material in all processing domains. Hence, it is of great importance to find out a suitable constitutive equation that can predict the flow behaviour of, at least, a particular class of materials in a specified domain of interest viz. cold, warm or hot working domain.

There are several constitutive equations available in open literature [10–25], starting from the most elementary and widely employed power law relationship to sophisticated mechanical threshold stress (MTS) model. Each constitutive model has its own advantages and drawbacks depending on flow behaviour of materials under investigation, working domain, accuracy needed, computational time required and number of data required to evaluate the material constants, etc. Constitutive equations could be broadly categorized into two groups: empirical and physically based constitutive models. Though physically based models could provide more accurate representation of deformation behaviour of material over a wide range of temperatures and strain rates [25], they are not always preferred as they often require more data from precisely controlled experiments [26,27]. More importantly, these models involve large number of material constants and properties than empirical models which may not be readily available in literature [9,28,29]. On the other hand, empirical models involve small number of material constants and require limited number of experimental data to evaluate those constants. Amongst the empirical and semi-empirical models, the Johnson–Cook (JC) [16,17] and Zerilli–Armstrong (ZA) [18] models have been successfully used to predict the flow stress of various materials and hence are being used in many commercially available FE software. However, it has been shown in the past that the JC model is not sufficient to provide the required accuracy in prediction of flow behaviour of many materials over a wider processing domain [28–31]. Albeit, the ZA model

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Table 1
Chemical composition (in wt%) of the materials under investigation.

Material	Cr	Ni	Mo	Mn	C	S	P	Si	Ti	Fe
304L	18.6	10.3	0.07	1.7	0.028	0.005	0.035	0.58	–	Bal.
304	18.6	10.3	0.07	1.7	0.08	0.005	0.035	0.58	–	Bal.
304 (as-cast)	18.6	10.3	0.07	1.7	0.08	0.005	0.035	0.58	–	Bal.
316L	18.2	11.6	2.3	1.7	0.2	0.007	0.04	0.77	–	Bal.
Alloy D9 (Ti/C = 4)	15.10	15.04	2.26	1.51	0.052	0.003	0.011	0.50	0.21	Bal.
Alloy D9 (Ti/C = 8)	15.12	15.27	2.26	1.50	0.051	0.003	0.012	0.52	0.42	Bal.

has been used for various materials over different strain rates at temperatures between room temperature and $0.6T_m$ [33–36] and is preferred to JC model as it incorporates the coupled effect of strain rate and temperature [37–39], it is not suitable for flow stress prediction in the high temperature [$T > 0.6T_m$] and lower strain rate domain [33–35,40].

Ideally, a constitutive equation should involve a reasonable number of material constants, which can be evaluated using limited number of experimental data and should be able to represent the flow behaviour of the material with adequate accuracy and reliability over a wider processing domain. Formulating or finding a suitable constitutive equation to adequately represent the flow behaviour requires a careful observation of response of the material in the specified processing domain which helps in understanding the individual and coupled effects of various process parameters on the flow behaviour. The objective of this study is two-folds. The first objective is to analyze the flow behaviour of various grades of structural materials that are extensively used in Generation IV reactors viz. 304L, 304, 304 (as-cast), 316L and 15Cr–15Ni–Ti modified austenitic stainless steels (alloy D9) and to observe the prominent flow characteristic in the hot working domain. The second objective is to mathematically model the flow behaviour of these materials over the specified hot working domain and subsequently evaluate the predictability of the model.

2. Experimental

The chemical composition of the materials under investigation has been given in Table 1. Flow stress data for these materials has been generated by performing hot compression tests on cylindrical compression test specimens of 10 mm diameter and 15 mm height. The hot compression tests were conducted using a computer-controlled servo-hydraulic testing machine (Dartec, Stoubridge, UK) with a maximum load capacity of 100 kN. The machine is equipped with a control system to impose exponential decay of the actuator speed to obtain constant true strain rates. A resistance-heating split furnace with silicon-carbide heating elements was used to heat the specimen to the desired temperature by surrounding both the platens and the specimen. Borosilicate glass paste was used to coat the samples before placing the samples between the platens. The glass paste acted as a lubricant and also prevented the hot specimen surfaces from extensive oxidation. The testing temperatures, strains and strain rates for various materials are given in Table 2. A Nicolet transient recorder was used to record the adiabatic temperature rise during hot deformation. Standard equations were used to convert the load-stroke data to true stress–true strain data. The flow stress data obtained at different processing conditions were corrected for adiabatic temperature rise, if any, by linear interpolation between $\ln\sigma$ and $1/T$, where σ and T are the flow stress and absolute test temperature, respectively.

Table 2
The test matrix for the materials under investigation.

Material	Temperature (K)	Strain	Strain rate (s^{-1})
304L, 304, 304 (as-cast), 316L	1073–1473	0.5	0.001–1
Alloy D9 (Ti:C = 4 and 8)	1123–1523	0.5	0.001–1

3. Results and discussion

3.1. Analysis of flow behaviour

Analysis of the flow behaviour of material is important before selecting the constitutive equation for flow stress prediction. Therefore, it is required to study the nature of the flow curves of the materials under investigation in the specified domain before selecting the suitable material model. The representative flow curves of 304 (as-cast) and 304 stainless steels at lowest and highest strain rates and temperatures of the specified domain (Table 1) are shown in Fig. 1. From this figure, it is clear that both the materials show thermal softening as well as strain rate hardening. The flow behaviour of the other materials under investigation, i.e. 304L, 316L and alloy D9 (Ti:C = 4 and 8) are found to be almost similar to that of 304 (as-cast) and 304 stainless steels and hence not presented here. To quantify the effect of temperature on the strain hardening, the slope of the stress strain curve (i.e. $\theta = \partial\sigma/\partial\varepsilon$) is plotted against the temperature. The plot of θ vs. T for 304 (as-cast) and 304 at strain rate 1 s^{-1} is given in Fig. 2. The figure indicates that the strain hardening gradually decreases with increase in temperature. Almost similar kind of behaviour has also been noticed at other strain rates and hence not emphasized here. Further, the variations of θ with temperature for other materials under investigation are found to be similar to that of Fig. 2. The θ value for other materials at different temperatures (at 0.1 and 0.5 strain) is given in Table 3. Similar kind of θ vs. T behaviour has also been observed in other FCC materials [40]. It could be observed that the effect of temperature on strain hardening is more significant at lower strain levels (see Fig. 2 and Table 3). The relationship between temperature and

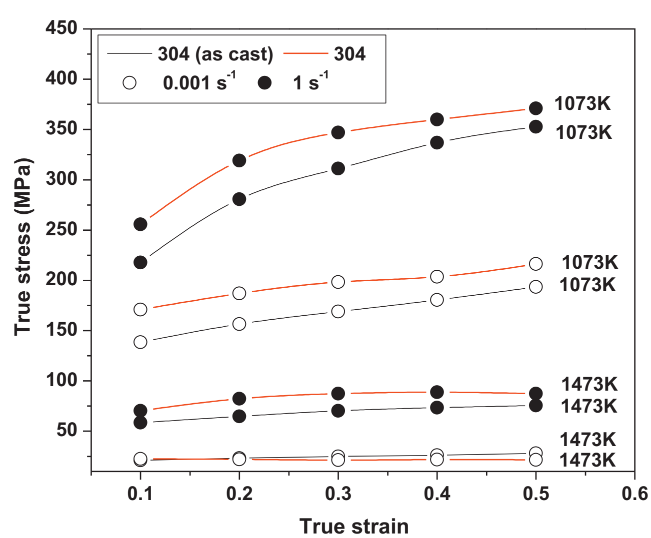

Fig. 1. Flow stress at temperatures 1073 and 1273 K at strain rates 0.001 and 1 s^{-1} for 304 (as-cast) and 304 austenitic stainless steel.