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Development of a high temperature flow stress model for AerMet 100 covering several orders of magnitude of strain rate

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ABSTRACT

Constant strain rate, constant velocity and Hopkinson Pressure Bar compression tests were carried out on AerMet 100 martensitic steel between 1130 °C and 1250 °C spanning strain rates from 0.01 s^{-1} to 4000 s^{-1}. The results were used to generate a predictive flow stress model over the entire range of test conditions. The effect of initial austenite grain size on flow stress was found to follow the Hall–Petch relationship. This dependency was then removed through innovative heat treatments. The morphology of the flow stress curves were also dependent on mechanisms of microstructural evolution which were controlled by the test method, strain rate and temperature. Friction and adiabatic heating also had a major contribution. A novel method was proposed in order to define the flow stress, which was then used to determine the work hardening exponent of the Zener–Hollomon equation. It was found that a deviation from the linear trend was observed in Hopkinson Pressure Bar tests and reasons were given. An artificial neural network approach was used to determine a more accurate predictive flow stress model which included the effects of test method, temperature, stain rate and initial austenite grain size. The method showed that it was possible to predict the flow stress between 50 and 2000 s^{-1} where mechanical testing's results were absent.

1. Introduction

In manufacturing of high performance components, the rate of deformation or strain rate is a design constraint dictated by the property of the materials. AerMet 100 is a martensitic steel specifically developed and heat treated [1] to be stronger and tougher than existing maraging steels. As such, it is used in high performance aerospace applications such as landing gear and engine shafts [2]. It is the material itself and its applications that have driven this research. This paper investigates two methods of hot compression testing for the application of developing a predictive flow stress model concerning elevated temperature forming operations that span several orders of magnitude in strain rate (SR). One method uses modified servo-hydraulic machinery [3] and the other utilizes the Hopkinson Pressure bar approach [4]. The methods are further broken down into two control modes namely, constant strain rate (CS) and constant velocity (CV). The strain rates in each test are described in Eq. (1) for CV, and, Eq. (2) for CS

$$\dot{\varepsilon} = \frac{\mathrm{v}}{\mathrm{h}} \tag{1}$$

$$h = h_0[\exp(-\dot{\varepsilon}t)] \tag{2}$$

$\dot{\varepsilon}$ is the strain rate, t is the duration of the test, v is the velocity of deformation, h and h_0 are the instantaneous and initial specimen height respectively.

Many materials such as steel are sensitive to strain rate. Increasing strain rate causes the material to respond quite differently to what might be expected in a creep test or quasi-static test. Traditionally it is assumed that a linear relationship exists between the logarithm of peak flow stress and strain rate when the test temperature remains constant. This can be represented by the Zener–Hollomon relationship [5,6] although this relationship is likely to break down at strain rates of 10^3 s^{-1} where flow stress increases more rapidly with applied strain [7]. Obtaining a true constant strain rate is important since increasing the strain rate could cause an uncharacteristic increase in the flow stress response due to continual work hardening [8]. Constant strain rate in practise may be achieved by controlling ram velocity in a nonlinear manner which will be influenced by the strength of the specimen, individual machine components (power supply capacity, hydraulic hoses, actuator, etc) and computer processor power

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high to allow a closed-loop feedback [8,9]. Najafizadeh et al. [10] and Stewart et al. [11] utilized a closed-loop feedback approach to achieve strain rates between 0.01 and 1 s^{-1}. CS tests also have a history of being performed using Gleeble thermo-mechanical simulator [12,13]. CS tests are generally limited to strain rates below or up to 10 s^{-1} since the inertia of the actuator and moving parts makes it very difficult to decelerate the actuator to maintain strain rate with any level of accuracy. CS tests are of great use for an experimenter wanting to study dynamic recovery (DRV)/re-crystallization (DRX) since the presence of a peak stress value and an inflection point in stress-strain curve should only be attributed to these two types of phenomena [14]. As Poliak et al. [13] very neatly explains, “The understanding and interpretation of DRX is still largely grounded on laboratory simulations performed at constant strain rates that are considerably lower than in most industrial hot working processes”. The author uses hot rolling as an example of how such a process yields variable strain rate conditions and how this can complicate mechanical behaviour which is not replicated by CS tests. Laboratory based constant velocity ramps may be used to replicate the higher strain rates akin to industrial forming operations. Strain rates in the region of 0.001 s^{-1} to 250 s^{-1} are possible because of the relative ease of linear machine programming (Eq. (1)). The strain rate in Eq. (1) remains relatively constant up to 0.5 true strain [15] but increases thereafter. This means that for a given equivalent initial strain rate, the final flow stress for a CV test is likely to be higher than for CS due to continual work hardening [8]; along with an absence of peaks attributed to DRV/DRX. The absence of these peaks on the flow curve does not necessarily rule out DRX on a microstructural level [13] but can make it difficult to practically compare stress values for each test. Achieving strain rates of 250 s^{-1} and upwards requires using the Hopkinson Pressure Bar technique which is governed by a different set of principles and is the study of shock physics [4]. ASM handbook volume 8 [16] suggests that HPB method can be exploited for strain rates between 200–10^4 s^{-1}. A cam plastometer is suggested for use between 0.1 and 500 s^{-1} although these machines are very rare. There is not an abundance of work showing compression testing in the strain rate range of 100–10^2 s^{-1}. It is common to find that each laboratory is usually specialized in one or two forms of testing-be it servo-hydraulic, Gleeble or Hopkinson Pressure Bar. This might explain why there is a general lack of published investigations covering strain rates of several orders of magnitude combined into a single study. To cover strain rates of different orders of magnitude, the three aforementioned test methods needed to be employed in this study which consequently produced results that were not immediately comparable. This paper explores a method of using numerical techniques to bridge this gap.

1.1. Model: artificial neutral networks

The understanding of flow behaviour in metal forming operations has long been studied using the traditional constitutive equations [17]. Given strain rates donot remain constant in CV and HPB tests, phenomenological or physical based constitutive models can become ambiguous as they assume constant strain rate and temperature. To address this, a new flow stress model was developed here using artificial neutral networks (ANN). This is a technique of statistical learning algorithms that take numerous inputs and implements a machine learning and pattern recognition to identify dependencies between inputs and outputs.

Even though artificial neural networks are not a new idea (first introduced by McCulloch in 1943 [18]) their application to mechanical testing has been very limited although they are becoming more popular with authors tending to do back to back comparisons with constitutive equation analysis and consistently favouring the ANN approach [19,20]. Senthilkumar et al. [21] performed a compression testing study on Al/Mg based nanocomposites and found that an ANN solution was more accurate than a constitutive relationship in predicting flow stress based on strain, strain rate and temperature. Ji et al. [19] used a very similar approach on AerMet 100 at strain rates up to 50 s^{-1}, again using similar input variables. Kajberg et al. [22] performed compression tests at strain rates of 1000 s^{-1} and 4000 s^{-1} between 900 and 1200 °C to strain of up to 0.7 using a Split Hopkinson Bar method. They also conducted tests at 1 s^{-1} on another device. They split the equations into two different categories; one being phenomenological constitutive models namely the Johnson–Cook (1983) and Hensel–Spittel (1978) and two physical based models namely the Zerilli–Armstrong and the Voyiadjis–Abed model (2005).Their conclusion was that the more recent microstructural based Voyiadjis–Abed model provided the best fit with the data. It was also suggested that in order to optimize the parameters of the equation further; additional intermediate strain rate data of order 10^1–10^2 s^{-1} was required, and a Gleeble device was suggested. This last conclusion is rather important since it highlights the need for these types of studies. Therefore to correlate the data from all the test techniques, a ZH and a ANN model was proposed to handle the effects test mode (CV,CS,HPB), initial austenite grain size (D_0), strain rate and temperature (T).

1.2. Material: AerMet 100

AerMet 100 is a product of the Carpenter Technology Corporation. It is an ultra-high strength martensitic Ni–Co secondary hardening steel used widely in the aerospace industry for turbine shafts and landing gear components [23,24]. The hardening and toughening phenomena of this material is described by Ayer and Machmeier in great detail [1]. The composition of AerMet 100 is given in Table. 1 [25]. The material used in this study was partially aged at 315 °C for 8 h. The A_c3 temperature was taken as 801 °C [26].

2. Experimental procedure

2.1. Servo-hydraulic (CS and CV tests)

Testing in the regime of 0.01–50 s^{-1} was carried out on an Instron servo-hydraulic test frame equipped with two 100 KN capacity load cells. A schematic diagram is shown in Fig. 1.

A piezoelectric and strain gauge cell load cell was used for force measurement. The platens were made of MARM002 nickel based alloy and were shrouded by a radiant furnace. CS tests were conducted at 0.1, 0.5, 1, 2 and 5 s^{-1} to a true strain of 1.5. CV test were conducted at initial strain rates of 0.01, 1, 5, 10, 20 and 50 s^{-1} to a true strain of 0.9. As discussed earlier, Eq. (1) describes the change in strain rate with respect to strain for CV tests. The test temperatures were 1130, 1200 and 1250 °C. Specimens were 12 mm in length, 8 mm diameter and were coated with boron nitride to reduce friction. The furnace was set to the test temperature controlled by two R-type thermocouples. The specimen was then inserted into the furnace and onto the platen for a pre-determined soak time. This was to fully austenitize the specimen and control the austenite grain size at each temperature. Specimens were then

Table 1
Composition of AerMet100.

Element	C	Cr	Ni	Co	Mo	Va	Si	P	Mn	Fe
Wt%	0.23	3.1	11.1	13.4	1.2	–	–	< 0.005	–	Balance