

Constitutive Modelling of Ingot Breakdown Process of Low Alloy Steels

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Abstract

In industrial ingot forging processes, the materials are subject to complex strain, strain-rate, and temperature histories. Understanding the behavior of the cast ingot during ingot breakdown operation during which the cast microstructure is converted into a wrought one, is of critical importance as it has a determining effect on the quality of the forged product. Finite element modeling (FEM) is a powerful numerical tool that can be used for the design or optimization of the ingot breakdown processes. However, the success in the application of FEM codes relies in the definition of accurate plastic constitutive model used for the investigated alloy. Phenomenological constitutive models provide a definition of the flow stress based on empirical observations and their descriptions in the form of some mathematical functions. In this research, Arrhenius-Garofalo's equation is used as constitutive model to generate the stress-strain curves of the forged material from the dendritic microstructure of a cast ingot made of medium carbon low alloy steel. The hyperbolic law in Arrhenius equation is most widely used to describe the relationship between the strain rate, flow stress and temperature, especially at high temperatures which can be represented by Zener-Hollomon parameter. In the current study, activation energy and other material constants are described as a polynomial equation to quantify the dependence of these parameters on strain. In order to provide accurate predictions of the thermal and mechanical parameters in the actual ingot breakdown operation, hot compression tests were carried out on GleebleTM 3800 thermomechanical simulator with uniform temperatures ranging from 1050°C to 1200 °C and strain rates from 0.25 s⁻¹ to 2 s⁻¹, these being representatives of the operating conditions of the application case. In particular, static and dynamic recrystallization which depend on energy stored in the grains were observed during hot deformation. The results show that the true stress-strain curves exhibit a peak stress at low strain rates when deformed at high temperatures, characteristic of dynamically recrystallized materials. Deformation at lower temperatures and at low strain rates resulted in strain hardening with no softening at any strain. The results demonstrate the significant influence of the choice of ingot breakdown parameters on the flow stress behavior such as

peak flow stress, steady state stress, deformation corresponding to peak and steady state stresses.

Keywords: Constitutive Modelling, Hot Compression, Flow Behaviour, FEM Simulation

Introduction

Hot workability is usually defined as the amount of deformation that a material can undergo without cracking and reach desirable mechanical properties and microstructure at a given temperature and strain rate. It is an important property to estimate the material's plastic deformation ability, which is generally evaluated by various parameters like strain rate, strain and temperature. In order to give a material a desired shape and property, hot deformation process is applied. The beginning stage of material processing starts with the casting process, after which forging is done till the desired shape.

Forging of a cast ingot starts with ingot breakdown process which is generally performed at very high temperatures (0.75 of melting point " M_P ") so as to breakdown the chemical (macrosegregation) and microstructural (as-cast dendritic) inhomogeneity [1]. Flow characteristic of a hot forging process consist of strain hardening and softening due to dynamic processes like recrystallization and recovery which basically determines the quality of a forging product. Constitutive relations are often used to model forging process in order to describe the plastic flow properties of metals and alloys. Arrhenius equation is a phenomenological model which is mostly practiced due to the fact that it has reasonable number of material constants with limited experimental results. It was proposed by Jonas et al.[2]. It is based on simple relation on three variables like strain, strain rate and temperature. However, the effect of strain was not introduced in the equation which was later modified by Sloof et al. [3]. This new model proved effective in predicting both hardening and softening characteristics. Many research groups have attempted to develop constitutive equations using Arrhenius model to describe the flow behaviour of various alloys using experimental data. [4-8]. Despite large efforts being made on the development of constitutive equations for 42CrMo, further investigation has to be done describing the behaviour of 42CrMo in its as-cast structure at very high temperatures ($\sim 0.7M_p$) so as to describe the flow behaviour during the ingot breakdown process. Therefore, the objective of this study is to investigate the nature of the influence of strain rate and temperature on compressive deformation characteristics of as-cast 42CrMo using hot compression tests. A model describing the relationship between

flow stress, strain rate, strain and temperature is proposed and used to simulate real time analysis of the process using Forge NxT 1.0[®] software which has not been done till date with the present model. The simulation results thus generated using the constitutive relations will be further used to analyze the adiabatic heating and force calculation in order to validate the model.

Experimental

The material used for the current investigation was an as-cast 42CrMo high strength steel. The composition of the alloy is shown in Table 1. The materials were provided by Finkl Steel Co., Sorel Tracy, Quebec, Canada. Cylindrical specimens were machined with a diameter of 10mm and a height of 15mm. Hot compression tests were performed in Gleeble 3800 Thermomechanical Simulator at four different temperatures (1050, 1100, 1150 and 1200°C) and four strain rates (0.25, 0.5, 1 and 2s⁻¹). The heating rate was 2°C/sec till 1260°C where it was maintained for 300sec so as to get homogenous temperature over the specimen. The specimen was then cooled to a respective deformation temperature at a cooling rate of 1°C/sec.

Table 1: Composition of as-cast 42CrMo (Wt.%)

C	Mn	Si	Mo	Cr	Ni	Other
0.35	0.85	0.40	0.45	1.85	Added	Microalloying

Results and Discussions

In the present paper, results from deformation temperature of 1200 °C and 1150 °C at strain rates of 0.25s⁻¹ and 2s⁻¹ are considered. Stress- strain curve of hot compression tests (Fig. 1 (a&b)) reveals that at low strain rates, dynamic softening mechanisms get activated and results in a stress drop after a peak stress. This is a typical recrystallization curve [9] which comprises of four four stages due to the effect of work hardening and softening mechanisms as shown in Fig. 1 (c).

Stage I: Work hardening due to DRV (Work Hardening is higher than softening rate)

Stage II: Transition Stage (Work hardening is compensated by DRV and DRX)

Stage III: Softening (Stress Drops steeply due to mechanisms like DRV and DRX)

Stage IV: Steady state (Stress becomes steady due to balance between softening and hardening).

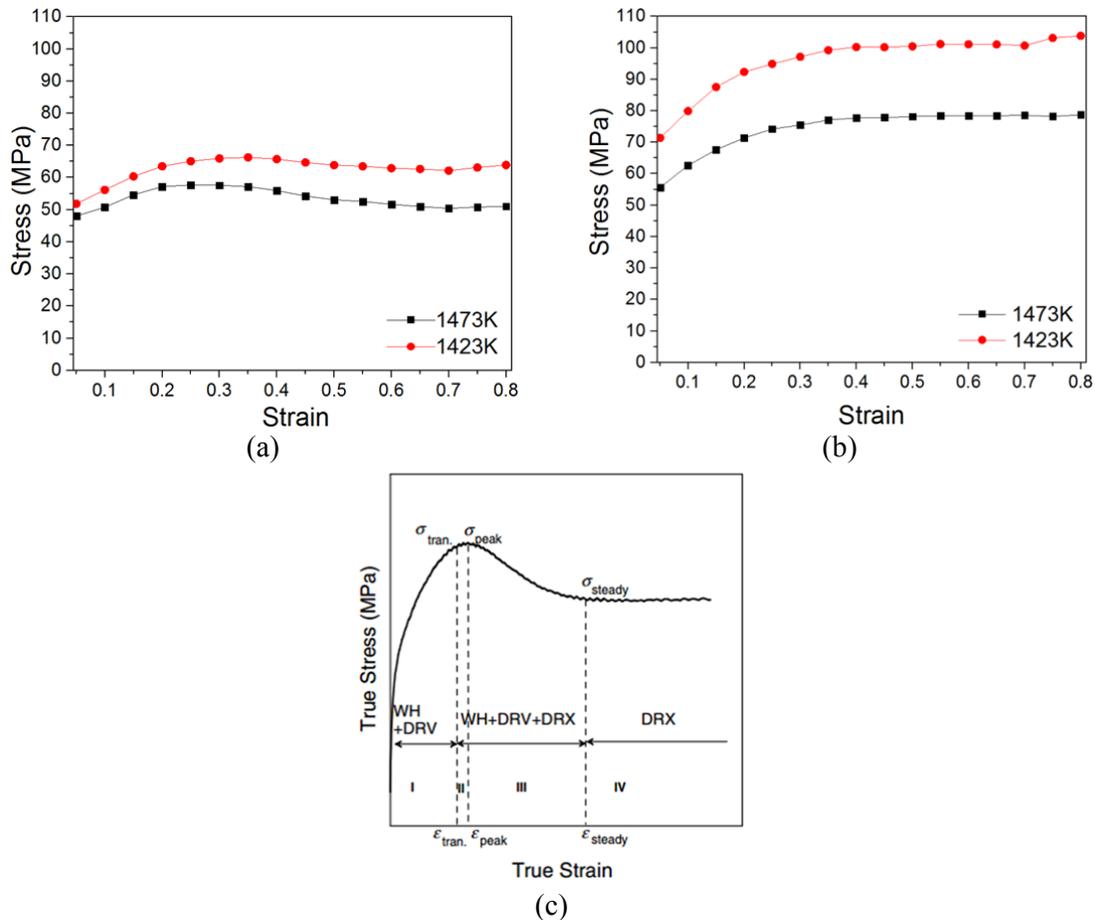


Fig.1: Experimental flow curves at a temperature of 1473K and 1423K at strain rate of $0.25s^{-1}$ (a) and $2s^{-1}$ (b). Typical flow stress curve at the elevated temperature (c)[4].

At high strain rates, the flow curves rises sharply and then attains a steady state. This type of flow curve resembles to that of recovery behavior due to which the flow stress attains a steady state due to dislocation generation and annihilation process running simultaneously. Dislocations are particularly needed to build a reservoir of stored energy. This stored energy along with the thermal energy is required for breaking down the coarse grains and generating much finer recrystallized grains. High temperatures along with dissolution of precipitates provides sufficient driving force for dislocation annihilation and thus softening can be seen as in Fig.1 at strain rate of $0.25s^{-1}$. However higher strain rates do not show softening even at high temperatures due to the fact that critical driving force has not reached because of high

Zener Hollomon factor, Z [9]. Low strain rates promote sufficient driving force for dislocation annihilation and thus softening can be seen in Fig 1(a).

Constitutive Equation of the flow stress

To investigate the deformation behavior of as-cast 42CrMo steel, there is a need to develop constitutive equations in order to simulate the process of ingot breakdown process. Material constants of the constitutive equation can be derived from the stress-strain data obtained from the hot compression tests. To simulate bulk metal forming, Forge NxT 1.0[®] software is used which generally uses thermo- viscoplastic constitutive models under hot conditions.

The effect of deformation temperature and strain rate on the deformation behavior can be expressed by Zener – Hollomon parameter (Z) [9] in an exponential form as follows:

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) \quad (1)$$

where, $\dot{\epsilon}$ = Strain Rate, T = Deformation Temperature (K), Q is the activation energy for deformation (KJmol^{-1}), R is the universal gas constant ($8.314\text{Jmol}^{-1}\text{K}^{-1}$).

Arrhenius-type model [8] is used to describe the relationship between flow stress, deformation temperature and strain rate during high temperature deformation. It is given by

$$\dot{\epsilon} = AF(\sigma)\exp\left(-\frac{Q}{RT}\right)$$

Where,

$$F(\sigma) = \sigma^{n_1} \quad (\alpha\sigma < 0.8) \quad (2)$$

$$F(\sigma) = \exp(\beta\sigma) \quad (\alpha\sigma > 1.2)$$

$$F(\sigma) = [\sinh(\alpha\sigma)]^n \quad (\text{for all } \sigma)$$

Where, A , n_1 , n , α and β are the material constants, with $\alpha = \beta/n_1$.

It can be noted that the Eq. (2) does not take into the account deformation strain which has a significant impact on the flow stress, especially at the initial stage of deformation. In order to compensate this, effect of strain accounted in order to increase the accuracy of the prediction and will be used in Eq. (7). In the present research, the data of flow stress, temperature and strain rate for the true strain between 0.05 to 0.8 with an interval of 0.05 were used for the construction of constitutive equations.

In order to find the constants, the value of $F(\sigma)$ is put into Eq. (2) which gives the relationship of low-level stress ($\alpha\sigma < 0.8$) and high-level stress ($\alpha\sigma > 1.2$).

$$\begin{aligned}\dot{\epsilon} &= B\sigma^{n_1} \\ \dot{\epsilon} &= B' \exp(\beta\sigma)\end{aligned}\tag{3}$$

B , B' and n_1 are material constants which are independent of deformation temperatures. These constants can be calculated by taking logarithm on both sides of Eq. (3).

$$\begin{aligned}\ln \sigma &= \frac{\ln \dot{\epsilon}}{n_1} - \frac{\ln B}{n_1} \\ \sigma &= \frac{\ln \dot{\epsilon}}{\beta} - \frac{\ln B'}{\beta}\end{aligned}\tag{4}$$

In the present research, the strain of 0.05 is shown in order to show the solution procedures of the material constants. Plotting graphs of $\ln \sigma$ vs $\ln \dot{\epsilon}$ and σ vs $\ln \dot{\epsilon}$, by linear regression method gives the values of n_1 and β . The values are calculated using the average values of slope of parallel lines from different temperatures. Putting these values, value of $\alpha = \beta/n_1$ can be found.

To calculate the value of Q , taking logarithm on both sides of Eq. (2) of the function for all values of stress and assuming it as independent of temperature.

$$\ln[\sinh(\alpha\sigma)] = \frac{1}{n} \ln \dot{\epsilon} + \frac{Q}{nRT} - \frac{1}{n} \ln A\tag{5}$$

Taking $\ln \dot{\epsilon}$ and $1/T$ are considered as two independent variables. Differentiating the above equation,

$$\begin{aligned}Q &= nR \frac{\partial \ln \dot{\epsilon}}{\partial \ln[\sinh(\alpha\sigma)]} T \\ n &= \frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial \left(\frac{1}{T}\right)} \dot{\epsilon}\end{aligned}\tag{6}$$

(T and $\dot{\epsilon}$ taken as independent variables)

Using this equation, plots of $\ln[\sinh(\alpha\sigma)] - \ln \dot{\epsilon}$ and $\ln[\sinh(\alpha\sigma)] - \left(\frac{1}{T}\right)$ can be generated and subsequently the value of n and Q can be found using regressed analysis of results from Fig. 3(a) & (b). The value of the constant $\ln A$ can be found from the intercept of $\ln[\sinh(\alpha\sigma)] - \ln \dot{\epsilon}$ plots.

After calculating the constants (α, n, Q and A) in the above equation, the flow stress can be obtained. Eq. (8) does not take into account the effect of strain. Effect of strain is apparent on the flow stress due to the effect of strain hardening and softening. Therefore, in order to predict the flow stress, strain is compensated in material constants (α, n, Q and A) by:

$$\begin{aligned}\alpha &= B_0 + B_1\varepsilon + B_2\varepsilon + \dots + B_m\varepsilon^m \\ n &= C_0 + C_1\varepsilon + C_2\varepsilon + \dots + C_m\varepsilon^m \\ Q &= D_0 + D_1\varepsilon + D_2\varepsilon + \dots + D_m\varepsilon^m \\ \ln A &= E_0 + E_1\varepsilon + E_2\varepsilon + \dots + E_m\varepsilon^m\end{aligned}\quad (7)$$

The order (m) of the polynomial is varied from one to nine. Selection of this polynomial should be done on the basis of analysis correction and generalization. In the present research the value of the polynomial is taken as $m=6$ and are shown in Fig.4 (a)-(d).

Using hyperbolic sine function, the constitutive model which relates flow stress and Zener-Hollomon parameter can be written as [10]:

$$\sigma = \frac{1}{\alpha} \ln \left\{ \left(\frac{Z}{A} \right)^{1/n} + \left[\left(\frac{Z}{A} \right)^{\frac{2}{n}} + 1 \right]^{1/2} \right\} \quad (8)$$

Then, flow stress values were predicted with varying temperature, strain and strain rate were predicted through Eqs. (1), (2), (7) and (8) and are presented in Fig. 5 in this present research.

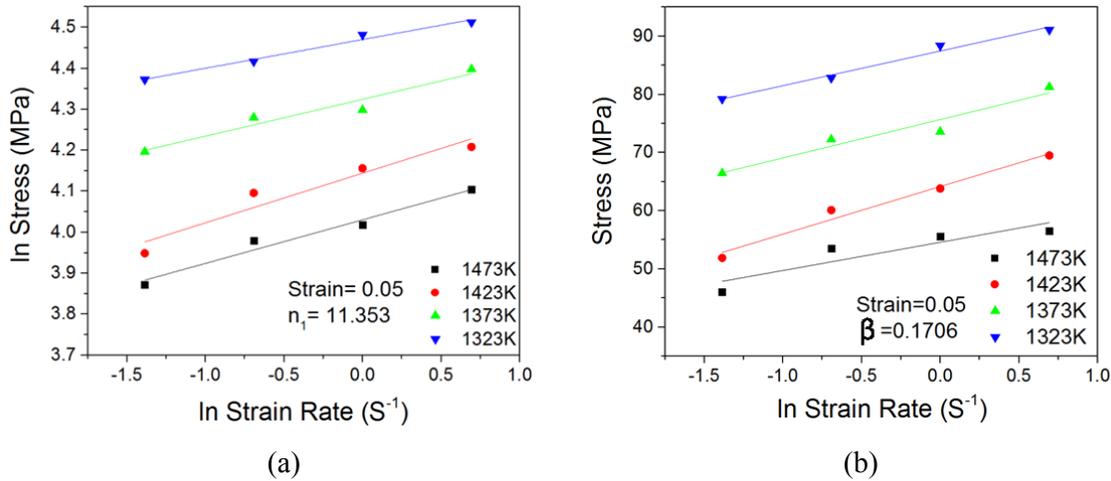
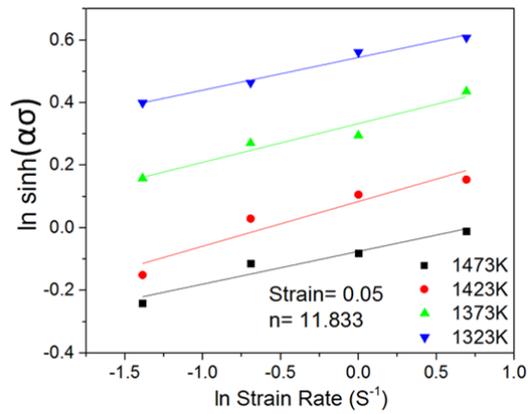
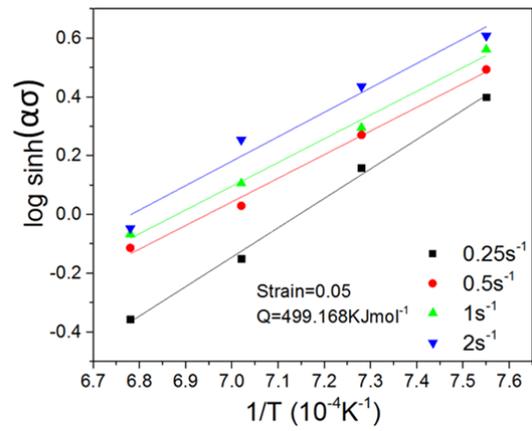


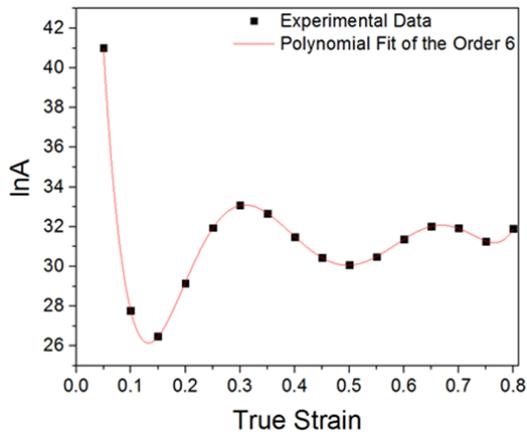
Fig.2 : Relationship of (a) Ln(σ) and Ln($\dot{\varepsilon}$), (b) σ and Ln($\dot{\varepsilon}$).



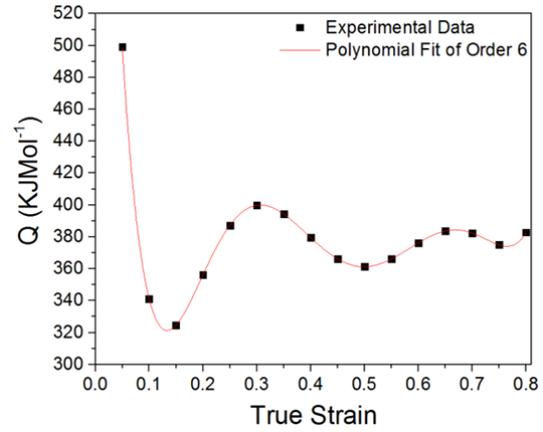
(a)



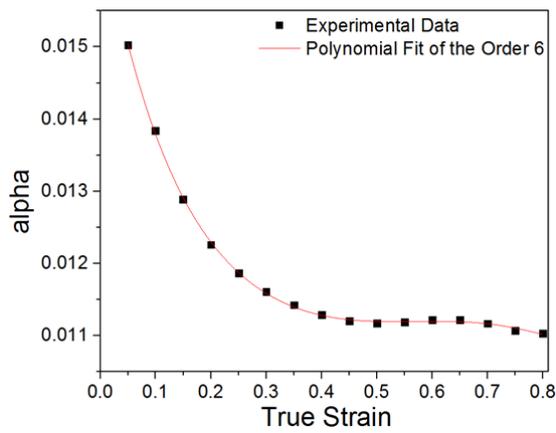
(b)

Fig.3: Relationship of (a) $\ln \sinh(\alpha\sigma)$ and $\ln(\dot{\epsilon})$, (b) $\ln \sinh(\alpha\sigma)$ and $1/T$.

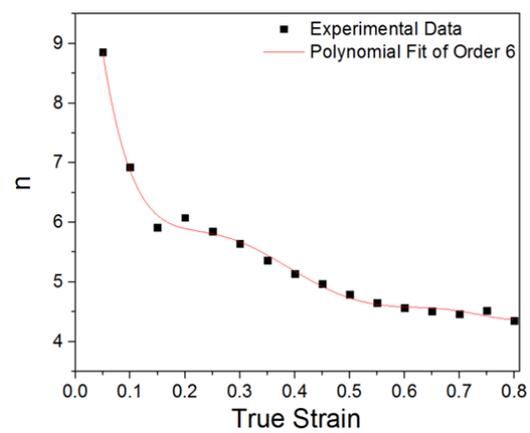
(a)



(b)



(c)



(d)

Fig.4. Polynomial fit of variation of (a) $\ln A$, (b) Q , (c) α and (d) n with strain.

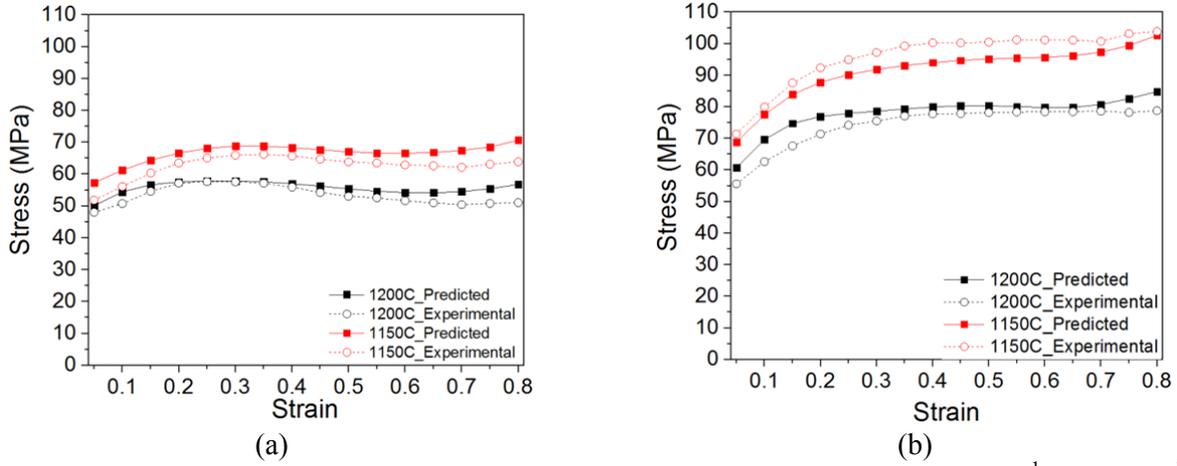


Fig. 5: Predicted and Experimental flow curves of 42CrMo at a strain rate of (a) $0.25s^{-1}$ and (b) $2s^{-1}$.

The plots of the predicted and experimental values at temperatures of $1200^{\circ}C$ and $1150^{\circ}C$ and strain rates of $0.25s^{-1}$ and $0.5s^{-1}$ are shown in Fig. 5. It is observed that the Arrhenius equation predicts the stress values throughout the flow curves. It is very interesting to note that the model predicts the softening as well as friction behavior for all experimental data. The difference in the values of predicted and experimental data do not exceed beyond $\sim 6.5\%$ at all the points in the flow curves.

Numerical simulation of 42CrMo hot forging

Numerical simulations generally consist of various elements which presents the real process. Among the various elements, includes the geometrical models of ingot, dies, material model and a set of boundary and initial conditions. The die temperature was kept similar to the deformation temperature. The density of the alloy is $7386.80465 \text{ Kg/m}^3$ and specific heat is $661.94 \text{ J/Kg/}^{\circ}K$. Arrhenius Model was introduced in Forge NxT 1.0[®] software and two simulations at different strain rates, $0.25s^{-1}$ and $2s^{-1}$ at a constant deformation temperature of $1200^{\circ}C$ were conducted. The temperature distribution map for final stage of deformation for strain rate of $0.25s^{-1}$ and $2s^{-1}$ with deformation temperature $1200^{\circ}C$ is shown in Fig 6. It is apparent from the Fig. 6 that temperature distribution in case of higher strain rate is more homogenous than at lower strain rate. Deformation heating is usually generated in any alloy during deformation and is the function of strain rate [1]. This heat generated is usually termed at adiabatic heating and causes higher heat in the sample thereby reducing the flow stress. Adiabatic heating is represented by the following equation:

$$\Delta T_{Adiabatic} = \frac{0.95 \int \sigma d\epsilon}{\rho C_p} \quad (2)$$

Where ΔT is the change in temperature, $\int \sigma d\varepsilon$ is the area under the uncorrected stress- strain curve, ρ is the density, C_p the specific heat and 0.95 is the fraction of mechanical work transformed into heat with the remaining fraction going to microstructural changes. Adiabatic heat calculated from the experimental data reveals that the temperature at the center at a strain rate of $0.25s^{-1}$ and deformation temperature of $1200^{\circ}C$ is $8.24^{\circ}C$ at $0.25s^{-1}$ and $14.6^{\circ}C$ at $2s^{-1}$. From the simulation results, the adiabatic heat generated due to hot compression at strain rates of $0.25s^{-1}$ and $2s^{-1}$ at a deformation temperature of $1200^{\circ}C$ is $\sim 8.4^{\circ}C$ and $\sim 19.4^{\circ}C$. It is also observed that the temperature distribution along the sample after a strain of 1 is not uniform at $0.25s^{-1}$ whereas it is significantly uniform at high strain ($2s^{-1}$). This temperature distribution reveals that the Arrhenius model predicts reasonably well the adiabatic heat generated during the deformation at low strain rates where as in case of high strain rate, the difference in experimental and simulated is significantly higher.

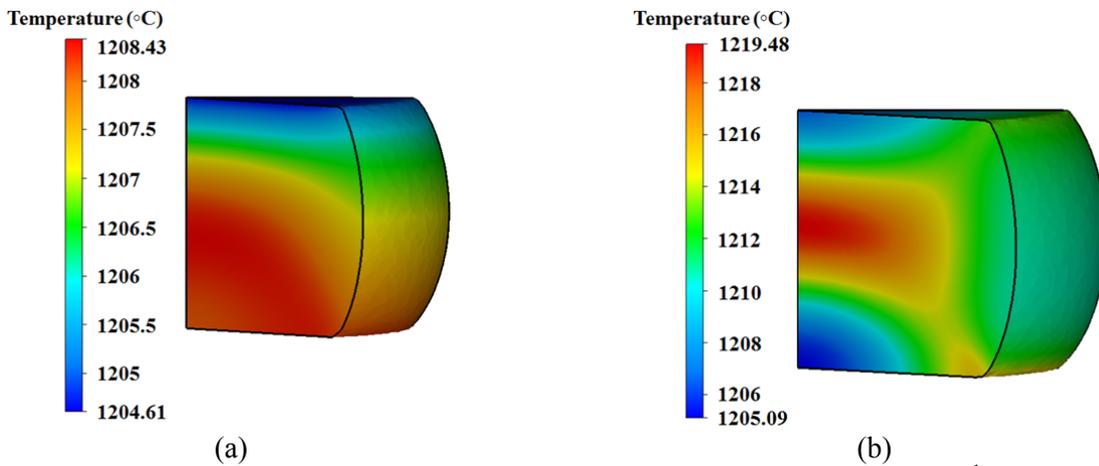


Fig. 6: Simulated temperature distribution map of 42CrMo at a strain rate of (a) $0.25s^{-1}$ and (b) $2s^{-1}$ at a deformation temperature of $1200^{\circ}C$.

To verify the accuracy this model further, force versus time analysis was compared. Fig. 7 shows the force versus time plot of predicted and experimental data. From the plots, it was found that at lower strain rates, Fig. 7(a), the difference in predicted and experimental values is $\sim 4\%$ whereas at higher strain rate, Fig. 7(b), the difference comes down to $\sim 1\%$. The indifference in the force reading between the experimental and predicted result is mainly due to the effect of friction during hot compression. It is well known fact that friction plays a major role in stress strain plots during hot compression [11]. From the experimental values it was calculated that the friction effect was more at higher strain rates as compared to lower strain rates, which is completely taken into the account by the Arrhenius Model.

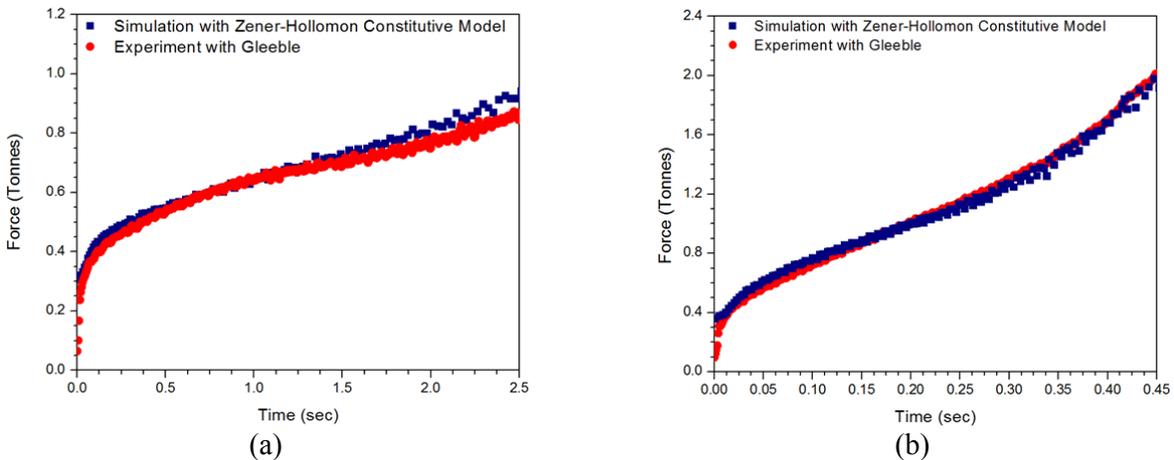


Fig. 7: Force versus time plot of experimental and predicted at strain rate (a) 0.25s^{-1} and (b) 2s^{-1} at a deformation temperature of 1200°C .

Conclusions:

1. Hot compression of as-cast 42CrMo alloy reveals that at low strain rates, dynamic recrystallization occurs, whereas at low strain rate recovery occurs.
2. Arrhenius model significantly predicts the flow curves. It is not only able to predict softening of flow stress due to dynamic recrystallization but takes into account the frictional effect at the end of deformation.
3. Simulation results reveal that the model is able to predict the adiabatic heating during deformation at a slow strain rate, but not there is large variation in the values at higher strain rates. It can significantly predict the force with the time at both strain rates.

Acknowledgements

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