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Deformation and Recrystallization Behavior of the Cast Structure in Large Size, High Strength Steel Ingots: Experimentation and Modeling

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Modeling deformation and recrystallization behavior in large size high strength steel ingots

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Abstract

Constitutive modeling of the ingot-breakdown process of large size ingots of high strength steel was carried out through comprehensive thermomechanical processing using Gleeble 3800® thermomechanical simulator, Finite Element Modeling (FEM), optical and Electron Back Scatter Diffraction (EBSD). For this purpose, hot compression testing in the range of 1200ºC to 1050ºC and strain rates of 0.25 s^{-1} to 2 s^{-1} was carried out. The stress-strain curves describing the deformation behavior of the dendritic microstructure of the cast ingot were analyzed in terms of the Arrhenius and Hansel-Spittel models which were implemented in Forge NxT 1.0® FEM software. The results indicated that Arrhenius model was more reliable in predicting microstructure evolution of the as-cast structure during ingot breakdown, particularly the occurrence of dynamic recrystallization (DRX) process which was a vital parameter in estimating the optimum loads for forming of large size components. The accuracy and reliability of both models were compared in terms of correlation coefficient (R) and the average absolute relative error (ARRE).

Keywords: Medium Carbon low alloy steel, As-cast structure, constitutive model, FEM simulations, Arrhenius model, Hansel-Spittel model

1. Introduction

High strength steels, with a microstructure composed of tempered martensite and fine bainite, are generally used as mold and die materials in transport industries [1, 2]. These alloys are generally produced by ingot casting followed by open die forging and heat treatment processes. The major requirement by the end users includes a combination of desired mechanical properties and microstructure in the entire volume of the material. In recent years, even larger dies are required by the industries, which lead to major metallurgical challenges in achieving uniform hardness and microstructure.

The solidification process results in a typical as-cast structure which is characterized by chemical (micro and macrosegregation) as well as microstructural heterogeneities (chill, columnar, and equiaxed zones) [3], the magnitude of which increase with the size of the ingot. In order to break this inhomogeneity in microstructure, ingot breakdown is performed at very high temperatures (~0.75 of melting point "$\boldsymbol{M_P}$") [4]. While this step remains quite crucial in modifying the microstructure, very little quantitative information is available on the response of as-cast structures to thermomechanical processing as compare to extensive data on wrought structures [5]. It is envisaged that the grain structure inhomogeneity would largely affect the mechanical behavior as compared to that of a wrought alloy. Therefore, a comprehensive understanding of the hot deformation behavior of as-cast microstructure is essential, from the viewpoints of process optimization and fundamental understanding.

Material flow characteristics of a hot deformation process like forging consists of strain hardening and softening due to dynamic processes, such as recovery and recrystallization [6]. Constitutive relations are often used to model the forging process in order to describe the plastic flow properties of metals and alloys [2, 7-9]. These equations are then used as inputs for predicting the response of the material under specified loading conditions. Therefore, the developments of accurate constitutive equations are a critical step towards developing integrated material models and reliably simulate microstructural evolution and properties at macroscopic scales applicable for large size components [10-13].

Arrhenius [14, 15] and Hansel-Spittel [16] are two of the most employed phenomenological models for studying the flow behavior during hot deformation of various alloys [2, 5, 8, 17-23]. Both models relate temperature, strain and strain rate to the flow stress of the materials by different constants which are determined through experiments. Despite their widespread applications, very little information is available regarding their suitability for as-cast high strength steels and integration with FEM software for simulating the ingot breakdown process.

In the present work, using a combination of careful experimentation and simulation, the ingot breakdown process of 42CrMo steel is studied and the model which can better predict and model the stress strain curves during the ingot breakdown process is determined. Specifically, both constitutive models are developed using hot compression tests and then incorporated in FEM code Forge NxT 1.0® in order to simulate real time analysis of the process. The simulation results thus generated are further applied to analyze the adiabatic heating and force vs. time analysis. In order to determine the applicability and the validity for a wider range of deformation conditions, FEM simulations are performed using different set of parameters other than those used to develop the models. Likewise, a combination of optical and electron microscopy are used to validate the predictions of the models on the occurrence of the softening processes as suggested by the stress-strain curves.

2. Materials and Methods

The material used for the current investigation was as-cast 42CrMo high strength steel. The detailed composition of the alloy could be as depicted in Table 1. The materials were provided by Finkl Steel, Sorel, Quebec, Canada. Specimens were taken from the columnar region of the ingot and perpendicular to the ingot axis. In order to reveal initial macrostructure, the specimens were etched by 3% Nital solution and then, were observed using an optical microscope (Make: AM Scope; Model: ZM-1TZ). To reveal microstructure through EBSD, the samples were polished mechanically using SiC paper of grit size 2000 and then electropolished at room temperature using a mixture of Perchloric acid and ethanol (1:9 by volume). The electropolishing voltage and time were 25V and 15sec, respectively. The samples were placed in such a way that compression axis was parallel to the incident electron beam. EBSD characterization was performed with FEG-SEM (Make: Carl Zeiss, Germany; Model: Supra 40) using TSL-OIM™ software (version 6.2). Cylindrical specimens were machined with a diameter of 10mm and a height of 15mm. Hot compression tests were performed with Gleeble 3800® thermomechanical simulator at four different temperatures, 1050°C, 1100°C, 1150°C and 1200°C (temperature readings were selected as per the industrial ingot forging using a FLIR® T650sc thermal camera) and four strain rates, $0.25 s^{-1}$, $0.5 s^{-1}$, $1 s^{-1}$ and $2 s^{-1}$. The heating rate was maintained at 2°C s^{-1} till 1260°C where it was maintained for 300 Sec (the optimum holding time for uniform temperature distribution throughout the specimen, confirmed using three sets of thermocouples placed at different positions of the specimens) so as to get homogenous temperature throughout the specimens. The specimens were then cooled to the deformation temperature at the rate of 1°C s^{-1}. The specimens were then compressed to a true strain of 0.8 and water quench immediately to preserve the deformed microstructure. Tantalum sheets of 0.1mm thickness were used between the sample and pure tungsten anvils as the lubricant.

3. Results

3.1. As cast microstructure

Fig. 1 shows the optical micrograph of the as cast material from the columnar region of the ingot, reveals the presence of large sized dendrites due to the fact that specimens were machined from large sized ingot. Fig. 2, shows the EBSD IPF (Inverse Pole Figure) Y-axis map of the microstructure of the as-cast material. The microstructure consists of a very coarse structure with no specific grain boundary.

3.2. Flow Curves

Fig. 3 depicts the flow curves obtained from the hot deformation tests carried out at temperatures of 1200°C (Fig. 3 (a)), 1150°C (Fig. 3 (b)), 1100°C (Fig. 3 (c)) and 1050°C (Fig. 3 (d)) using strain rates of $0.25s^{-1}$,$0.5s^{-1}$, $1s^{-1}$ and $2s^{-1}$. It is observed from the curves that the flow stress increases with increasing strain rate, but decreases with increasing deformation temperature. Analysis of the flow curves indicates that at a deformation temperature of 1200°C and 1150°C and for strain rates of $0.25s^{-1}$ and $0.5s^{-1}$, the curves exhibit flow softening after initial work hardening. A peak stress at a strain value of ~0.26 for 1200°C and at a strain value of ~0.32 for 1150°C could be observed. The flow curves at 1200°C, 1150°C and for the strain rate of $0.25s^{-1}$ and $0.5s^{-1}$ show peak stress followed by a continuous decrease in the flow stress till the maximum strain of 0.8. This behavior is typical of the occurrence of dynamic recrystallization [6, 24, 25].

In contrast, for tests carried out at different temperatures using higher strain rates of 1 s^{-1} and $2s^{-1}$, no peak stress can be seen after initial work hardening but a steady state is attained indicating the absence of dynamic recrystallization [26]. At deformation temperature of 1050°C and strain rates of $1s^{-1}$ and $2s^{-1}$ (Fig. 3d), work hardening can be observed clearly. This is due to the fact that high strain rates indeed provide enough driving force for the dislocation generation, but low temperatures are insufficient to provide necessary dislocation movement for the annihilation to happen. In addition, due to the presence of alloying elements, precipitation can occur at lower temperatures which may further pin down the dislocations [4].

3.3. Constitutive Equations

3.3.1. Arrhenius Equation

The effect of deformation temperature and strain rate on the deformation behavior can be expressed by Zener-Hollomon parameter (Z) [6] as follows:

$$Z = \dot{\varepsilon} \exp(\frac{Q}{RT}) \tag{1}$$

Where, $\dot{\varepsilon}$ = strain rate, T= deformation temperature (K), Q= activation energy for deformation ($kJmol^{-1}$) and R is the universal gas constant ($8.314 Jmol^{-1}K^{-1}$).

Arrhenius-type model [19] is used to describe the relationship between flow stress, deformation temperature and strain rate during high temperature deformation. It is given by,

$$\dot{\epsilon} \;= AF(\sigma)\exp(-\frac{Q}{RT}) \tag{2}$$

Generally, $F(\sigma)$ is in the form of power function or exponential function or hyperbolic sine function as listed below:

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

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

$F(\sigma) = [sinh(\alpha\sigma)]^n$ (for all σ)

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

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**.**

The values of material constants, A, n_1, n, α and β were calculated using regression analysis [1, 4, 7, 22-24]. The calculation of these constants using the regression analysis is shown in Figs. 4 and 5.

After calculating the constants $(\alpha, n, Q \text{ and } A)$ in the above equation, the flow stress can be obtained. The constants were calculated without taking into account the effect of strain. The 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 $(\alpha, n, Q \text{ and } A)$ by:

$$\begin{aligned} \alpha &= B_0 + B_1\varepsilon + B_2\varepsilon + \cdots \ldots \ldots + B_m\varepsilon^m \\ n &= C_0 + C_1\varepsilon + C_2\varepsilon + \cdots \ldots \ldots + C_m\varepsilon^m \\ Q &= D_0 + D_1\varepsilon + D_2\varepsilon + \cdots \ldots \ldots + D_m\varepsilon^m \\ ln\,A &= E_0 + E_1\varepsilon + E_2\varepsilon + \cdots \ldots \ldots + E_m\varepsilon^m \end{aligned} \tag{3}$$

The order (m) of the polynomial varies 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 the results are shown in Fig. 6 (a) - (d).

Using hyperbolic sine function, the constitutive model which relates the flow stress and Zener-Hollomon parameter can be written as [27]:

$$\sigma = \frac{1}{\alpha} \ln \left\{ \left(\frac{Z}{A}\right)^{1/n} + \left[\left(\frac{Z}{A}\right)^{\frac{2}{n}} + 1 \right]^{1/2} \right\} \tag{4}$$

Then, the flow stress values may be predicted with varying temperature, strain and strain rate through Eqs. (1), (2), (3) and (4) and are presented in Fig. 7.

3.3.2. Hansel-Spittel Model

Hansel-Spittel equation [16] (Eq. (5)) has many constants as compared to Arrhenius equation which need to be calculated in order to derive the constitutive model. It is given by:

$$\sigma = A_o e^{m_1 T} \varepsilon^{m_2} \dot{\varepsilon}^{m_3} e^{\frac{m_4}{\varepsilon}} (1+\varepsilon)^{m_5 T} e^{m_6 \varepsilon} \dot{\varepsilon}^{m7} T^{m_8} \tag{5}$$

Where, σ = stress, ε = strain, $\dot{\varepsilon}$ = strain rate, T= deformation temperature, m_1 to m_8 define the material parameters. Usually, constants m_7 and m_8 are taken as zero [20].

In order to calculate the material constants, linear regression analyses were performed using Matlab® and Origin® 2015 software and are provided in Table 2. The constants were then used in the equation for various values of strain, strain rate and temperature in order to find the values of stress.

Fig. 7 shows a comparison between the stress values derived from both models. It can be seen that the Arrhenius model can track the experimental data precisely over the entire deformation temperature range of 1050°C to 1200°C. The model takes into account the softening behavior of the material, which can be observed at high temperatures and low strain rates. The effect of recovery and strain hardening is also significantly predicted by this model. In contrast, the flow stress predicted using the Hansel-Spittel model shows significant differences with the experimental values. Specifically, the prediction of recrystallization occurring in the material, at high temperature and low strain rates cannot be predicted using the Hansel-Spittel model. Instead, the stress-strain plot ends as a flat curve similar to a recovery curve. The model is also not able to predict the material behavior such as work hardening at low temperatures (1050°C) and high strain rates ($2s^{-1}$) and a significant deviation (8 to 13%) can be observed between the experimental and predicted values. Therefore, it can be concluded that Arrhenius model is much better in predicting the hot deformation behavior of the as-cast structure as compared to the Hansel-Spittel model.

4. Simulation

The flow characteristics of 42CrMo steel can be seen through the flow curves generated using hot compression. The dependence of material properties and microstructure changes rely on parameters like strain rate and temperature. However, there are additional factors which also play crucial role in determining the flow behavior, including die temperature, friction between die and work piece, adiabatic heating, heat conduction, etc. In order to study the effect of various process variables on hot compression behavior, FEM was conducted [26]. Numerical simulations consist of various elements which represent the real forming process. Amongst these, the geometrical models of the ingot, dies, material model and a set of boundary and initial conditions are included. In the present simulation model, the developed Hansel-Spittel material model has been implemented in Forge NxT 1.0® and simulations have been performed. The dimensions of the specimen are kept similar to the experimental specimens. The die temperature has been also kept similar to the deformation temperature. The density of the alloy calculated using Thermo-calc® software is 7386.80465 Kg/m^3 and the specific heat is 661.94 J/Kg/°K. Deformation heating is usually generated in any alloy during deformation and is a function of the applied strain rate [4]. This generated heat, usually termed adiabatic heating, results in a temperature increase in the sample thereby reducing the flow stress. The temperature increase is represented by the following equation:

$$\Delta T_{Adiabatic} = \frac{0.95 \int \sigma d\epsilon}{\rho C_p} \tag{6}$$

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 [4].

Adiabatic heating temperature calculated from the experimental data using Eq. (6) reveals that the temperature at the center of the specimen after deformation at 1200°C is 8.24°C at 0.25s^{-1} and 14.5°C at 2s^{-1} as reported elsewhere [28, 29]. From the simulation results, the amount of temperature increase that occurs during hot compression at 1200°C using strain rates of 0.25s^{-1} and 2s^{-1} is ~7°C and ~15°C respectively (Table 3) [28, 29]. In the present paper simulation results of the specimen after deformation at 1150°C at a strain rate of 0.25s^{-1} and 2s^{-1} are presented. Adiabatic heating temperature for deformation temperature of 1150°C as calculated from the experimental data using Eq. (6) reveals that the increase in the temperature at the center of the specimen after deformation is 8.36°C at 0.25s^{-1} and 19.02°C at 2s^{-1}. From the simulation results using Hansel-Spittel model, the amount of temperature increase that occurs during hot compression at 1150°C using strain rates of $0.25s^{-1}$ and $2s^{-1}$ is ~7.98°C and ~17.09°C respectively (Table 3) (Fig. 8 (a) & (b)). It is also observed that the temperature distribution along the sample after strain of 0.8 is not uniform at $0.25s^{-1}$ (Fig. 8 (a)), whereas it is nearly uniform at high strain rate ($2s^{-1}$) (Fig. 8 (b)). This temperature distribution reveals that Hansel-Spittel equation predicts very well the adiabatic heat generated during the deformation of the as-cast 42CrMo alloy at both *low* and *high* strain rates.

Arrhenius model was also implemented in Forge NxT 1.0® software. From the simulation results, the adiabatic heat generated due to hot compression at strain rates of $0.25s^{-1}$, $2s^{-1}$ and at a deformation temperature of 1150°C is ~9.38°C and ~21.7°C (Table 3) (Figs. 9 (a) & (b)). It is also observed that while temperature distribution is not uniform at low strain rate (Fig.9 (a)), it is significantly uniform at high values (Fig.9 (b)). The above findings indicate that the Arrhenius model also predicts relatively well the adiabatic heat generated during deformation for both the strain rates. A difference of about 11% is observed between experimental and simulated values.

Figs. 8 ((c) & (d)) and Figs. 9 ((c) & (d)) show the force versus time plots of the predicted (Hansel-Spittel model (Fig. 8) and Arrhenius model (Fig. 9)) and experimental data at strain rates of $0.25s^{-1}$ (c) and $2s^{-1}$ (d), respectively. From the plots, it can be seen that at lower strain rates, Fig. 8 (c), the difference in predicted (Hansel-Spittel model) and experimental values is ~26%, whereas the difference is ~2% with the Arrhenius equation (Fig. 9 (c)). At higher strain rate (Fig. 8 (d)), the difference between experimental and simulated results using Hansel-Spittel model increases to ~41%, whereas with Arrhenius model the difference is ~5% (Fig. 9 (d)). It is well known that friction plays a major role in determining the behavior of the flow curves during hot compression [30]. The difference in the force between the experimental and predicted results is assumed to be mainly due to the effect of friction during hot compression and can be justified from the experimental values. It is calculated that the friction effect at strain rate of $2s^{-1}$ is 0.395 while it is 0.266 for the strain rate of $0.25s^{-1}$. It is important to note that, the friction effect is completely taken into account by the Arrhenius model but not by the Hansel-Spittel model.

5. Discussion

Stress-strain curve of hot compression tests (Fig. 3 (a-d)) reveals that at low strain rates, dynamic softening mechanisms are activated and result in a stress drop after the peak stress. This is a typical dynamic recrystallization behavior [6] which comprises of four stages due to the effect of work hardening and softening mechanisms as shown in Fig. 10.

Stage I: Work hardening due to Dynamic Recovery, 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).

These stages were well observed in the hot compression tests of the as cast 42CrMo steel and will be explained further.

At high strain rates, e.g. at 1150°C and $1s^{-1}$, the flow curves rise sharply and then attains a steady state. This indicates recovery behavior due to which the flow stress attains a steady state as dislocation generation and annihilation process run concurrently. 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 cast structure and generating a more isotropic and much finer recrystallized microstructure. High temperatures along with dissolution of precipitates provides sufficient driving force for dislocation annihilation and thus softening can be seen as shown in Fig. 3 (strain rate $0.25s^{-1}$, T= 1200°C). The EBSD grain boundary map of the specimen deformed at 1200°C and using strain rate of $0.25s^{-1}$ is shown in Fig.11 (a), which shows that the majority of the grains are nucleated due to dynamic recrystallization (shown with black arrows). Low strain rates promote sufficient time for dislocation annihilation and thus softening can be seen as shown in Fig.3. However, at higher strain rates softening due to dynamic recrystallization is not observed even at high temperatures because the time required for nucleation and growth process to occur was insufficient [6]. This is apparent in Fig.11 (b) where it can be seen that the microstructure is composed of HAGB fraction of 47.6% and few recrystallized grains. Semiatin et al. [31] reported in their research similar trend for transverse as-cast superalloy samples. They observed softening was mainly due to dynamic recrystallization at a strain rate of $0.1s^{-1}$ which is in good agreement with the present research. Similar results have been reported by Hotta et al. [32], who observed that dynamic recrystallization took place at low strain rates (10^{-1} - 10^{-3} s^{-1}) (i.e. low Z values), during hot compression of as cast 9%Ni steel. The authors have concluded that the dynamically recrystallized γ grain size is not dependent on initial γ grain size, but can be controlled only by Z value.

5.1. Applicability of Models with Different Parameters

Generally, constitutive equations are derived in order to observe material behavior for various parameters other than the parameters used for deriving the constants. Using these constants for FEM simulation for different parameters can reveal the material behavior when subjected to various deformation parameters at industrial scales. Adiabatic heating and force calculations are a few which can be derived from the simulations of deformation process and can be used to optimize the parameters as per requirements.

The applicability of both these models for different set of parameters is attempted in this research. Two sets of parameters have been selected, keeping in mind their ranges to be different from the experimental ones. The first set consisted of a strain rate of $0.8s^{-1}$ and a deformation temperature of 1180°C and the second one was selected with a strain rate of $0.05s^{-1}$ and a deformation temperature of 1000°C. The values of the parameters are then entered into the respective equations with similar constants which are used to derive the predicted flow curves. The comparison of experimental and predicted results of both the models is shown in Fig. 12 ((a) & (b)).

It can be noted from the comparison plots that the Arrhenius model provides a very good prediction of experimental conditions in both events as compared to the Hansel-Spittel model. It is interesting to note that the Arrhenius model can anticipate the dynamic crystallization behavior of the as-cast material for both strain rates.

The above comparison indicates that Arrhenius equation is better suited for predicting the stress-strain diagram of as-cast investigated steel during the ingot breakdown process. Using Forge NxT 1.0®, the parameters are then used to simulate, the adiabatic heating and force vs time graph as shown in Fig. 13 ((a) & (b)) for 1000°C, $0.05s^{-1}$ and Fig. 14 ((a) & (b)) for 1180°C, $0.8s^{-1}$. Using Eq. 6, the adiabatic heat generated from the experimental curves is calculated to be 5.3°C and 9.7°C for deformation at 1000°C and 1180°C respectively. Simulation results show that adiabatic heat values are very close to the theoretical calculations for both cases and for both models. The major differences lie in the force vs time calculations where it can be observed that Arrhenius model predictions are much better than the Hansel-Spittel predictions.

Reliable prediction of forging loads for industrial size ingots by the FEM model requires accurate prediction of the flow stress. Therefore, the variability in flow stress values need to be determined. To this end, the correlation coefficient (R) and absolute average error (Δ) were determined for the two steels and are discussed in the following.

The correlation coefficient (R) is expressed as [5]:

$$R = \frac{\sum_{i=1}^{N}(\sigma_E^i - \bar{\sigma}_E)(\sigma_P^i - \bar{\sigma}_P)}{\sqrt{\sum_{i=1}^{N}(\sigma_E^i - \bar{\sigma}_E)^2 \sum_{i=1}^{N}(\sigma_P^i - \bar{\sigma}_P)^2}} \tag{7}$$

The absolute average error (Δ) is expressed as:

$$\Delta = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{\sigma_E^i - \sigma_P^i}{\sigma_E^i}\right| X100 \tag{8}$$

Where, $\sigma_E$is the experimental flow stress and $\sigma_P$is predicted flow stress, which is calculated using the two models.

$\bar{\sigma}_E$ and $\bar{\sigma}_P$ are average values of experimental and predicted flow stress respectively. N is the number of data employed in the investigation.

Fig.15 ((a) & (b)) shows the correlation between experimental flow stresses and predicted ones which are obtained using the Arrhenius model and Hansel-Spittel model, respectively. It can be seen that most of the data points fall fairly close to the regression line and good correlation between experimental and predicted data can be obtained. The

R value of Arrhenius model is 0.978 and that of Hansel-Spittel model is 0.972. Generally, the value of R indicates the strength of a linear relationship between the predicted and the experimental values. However, it is not always that the higher value of R can indicate better results as the tendency of the model is often biased towards higher or lower values. Therefore, for a higher precision in the estimation of the values absolute average error (Δ) is used as an unbiased statistical parameter which can further evaluate the predictability of the models [33].

Fig. 16 shows the Δ values at different strains for the two models. It can be observed that the average absolute error from the Hansel-Spittel model is higher than the ones from Arrhenius model. The absolute average error of the entire process has also been calculated and is found to be 1.76% for the Arrhenius model, whereas it is 3.17% for the Hansel-Spittel model.

Comparison of the results from correlation coefficient and absolute average error reveals that Arrhenius model having higher value of R and a lower value of Δ is more accurate and appropriate to use for the prediction of stress strain curves during the ingot breakdown process of as cast steel ingot. In addition to this, simulation results indicate that Arrhenius model is similar to Hansel-Spittel in modeling adiabatic heating, whereas it is far better in force vs. time modeling than its counterpart.

6. Conclusion

Isothermal compression tests were performed on Gleeble 3800® thermomechanical simulator in order to simulate the ingot breakdown process of the as-cast medium carbon low alloy steel 42CrMo. The influence of strain, strain rate, and temperature on flow behavior was studied and constitutive equations using Hansel-Spittel and Arrhenius equations were developed. The following conclusions can be drawn from the analysis:

1. The Hansel - Spittel model was used to predict high temperature flow stress of as-cast 42CrMo steel. The model lacks the desired precision and reliability in predicting stress strain curves which can be justified by the correlation coefficient (0.972) and the absolute error (3.17%).

2. Using Arrhenius model the effect of strain was considered in order to predict the flow behavior of as-cast 42CrMo steel for various deformation parameters. The influence of strain on material constants (α, n, Q and A) with good correlation and precision could be determined using a sixth order polynomial.
3. The occurrence of dynamic recrystallization during the ingot breakdown process could be demonstrated using EBSD. However, the Hansel - Spittel model fails to predict this while Arrhenius equation clearly does. Therefore, the Arrhenius model would be better suited for the FEM simulation of the process of breakdown of large size ingots.

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