03 Sep 2020

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Recommended Citation

S. Ganguly et al., "A Modified Johnson-Cook Model Incorporating the Effect of Grain Size on Flow Stress," *Proceedings of the AISTech 2020 (2020, Cleveland, OH)*, pp. 1614-1621, Association for Iron & Steel Technology (AIST), Sep 2020.
The definitive version is available at https://doi.org/10.33313/380/174

DOI 10.33313/380/174

A Modified Johnson-Cook Model Incorporating the Effect of Grain Size on Flow Stress

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ABSTRACT

The mechanical properties of steel are influenced by grain size, which can change through mechanisms such as nucleation and growth at elevated temperatures. However, the classic Johnson-Cook model that is widely used in hot deformation simulations does not consider the effect of grain size on flow stress. In this study, the Johnson-Cook model was modified to incorporate the effects of austenite grain size on flow stress. A finite element model was employed to characterize the effects of grain size on the flow stress for different steel grades over a range of temperatures (900ºC to 1300ºC). Simulation results show good agreement with experimental observations.

Keywords: Johnson-Cook Model, Thermo-mechanical characterization, Prior-austenitic grain size, Finite-Element model

INTRODUCTION

Finite element analysis is the most widely used numerical methodology for simulating complex manufacturing processes for metals, such as forming, rolling, machining, molding or forging. In order to develop an accurate finite element model, it is essential to accurately describe the material flow behavior using a constitutive model. The Johnson-Cook (JC) plasticity model has been widely used to describe the strain hardening and temperature dependent behavior for metals undergoing large deformation [1]. The JC model is a phenomenological constitutive model that is derived by fitting experimental data using regression analysis or other curve fitting methods. The JC model assumes isotropic behavior and is reasonably accurate for most metallic alloys but is not very accurate in describing strain hardening behavior. In comparison, physics-based models utilize complex mathematical theories based on thermodynamics and kinetics to derive the flow stress-based equations. Other phenomenological models include the Arrhenius constitutive model [2] used for metals that takes in account the activation energy for deformation, the Durrenberger model [3], which predicts the flow stress as a function of a long range internal stress component and a thermally activated stress component and the Zerrili-Armstrong model [4] which relates the flow stress to the dislocation density. However, none of the models account for the effect of grain size on flow stress. Although grain size does not change significantly at room temperature for metals, it can change at elevated temperatures and the plastic deformation can have an effect on it [5].

In order to accurately model material behavior, it is essential to include the effect of grain size evolution as well. The classic Hall Petch equation [6] has shown that the coarsening of grains results in loss of material strength [7]. There have been some phenomenological models that have accounted for grain size. The KLH model [8] introduced the effect of grain size on yield stress. The recently proposed the Molinari–Ravichandran model simulates a flow stress as a function of the intrinsic resistance of the material, temperature, strain rate as well as grain size. However, most of these models only incorporate the effect of grain size at room temperature. Hence these models are not suitable to be used to simulate manufacturing process at elevated temperatures.

In this work a modified version of the JC model was introduced that includes the effect of grain size evolution at high temperatures. The aim of the study was to determine the evolution of grain size in steel grades at elevated temperatures. In addition, the dependence of strength of the material from grain size was also obtained using experimental techniques. Finally, a new material model was developed based on the classical JC equation that modified to include the effect of grain size on flow stress.

EXPERIMENTAL PROCEDURE

JC strength model

In this work, the isotropic thermomechanical behavior of steel was modeled using the Johnson-Cook (JC) strength model [1], which constitutive equation is given in Eq.1. An explanation of different JC parameters can be found in [9], [10]:

$$\sigma = (A + B\varepsilon^n)(1 + C \ln \dot{\varepsilon}^*)(1 - T^{*m}) \tag{1}$$

An MTS load frame was modified to performed hot tensile tests on AISI/SAE 15V38, ASTM A572, ASTM A690 and AISI/SAE 1018 grade steels. Details of this experiment were described in [11]. The stress-strain data was further processed to calibrate the material JC parameters. This calibration was done by global optimization methods using a Genetic Algorithm approach, as detailed explained in [12].

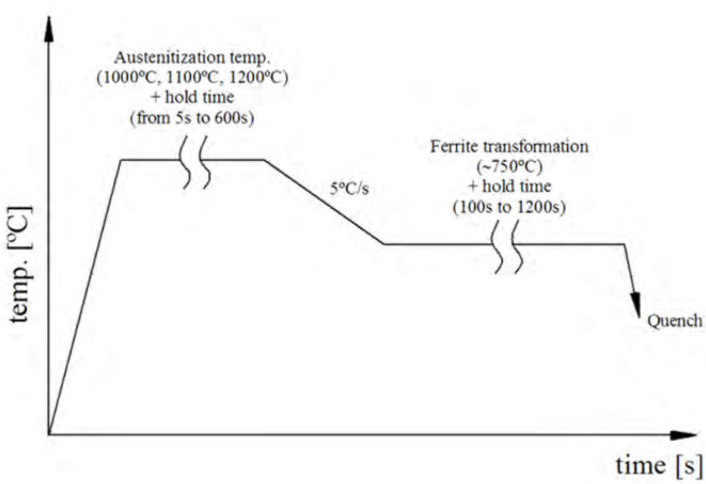
Grain growth model

The normal grain growth model relates the effect of temperature on grain size as given by the general grain growth law [13], as follows:

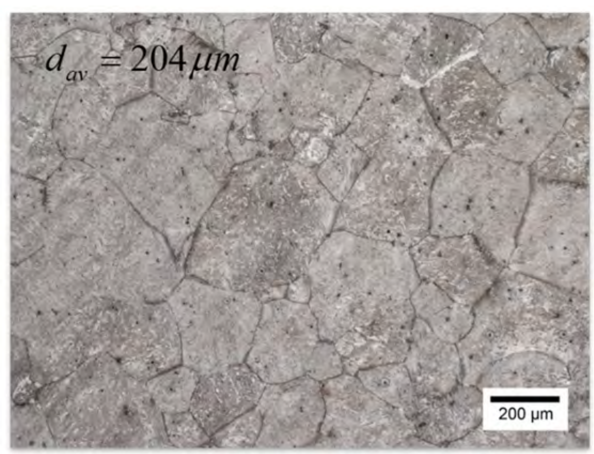
$$d^{n_G} = d_0^{n_G} + A_G \exp\left(-\frac{Q_G}{\mathrm{R}T}\right) t \tag{2}$$

where: d and d_0 are the final and initial grain diameters, , A_G and n_G are material parameters, Q_G is the activation energy of grain growth, R is the gas constant, T is absolute temperature and t is the time.

The effect of temperature and time on grain size was measured using an experiment that involved heating a cylindrical steel sample above the austenization temperature, and then holding it for time intervals ranging from 5 s to 600 s. Thereafter the sample was cooled below 750 ºC for a short time to allow some ferrite to form along the austenite grain boundaries and then freeze the grain size by quenching in water, as shown in Figure 1a. After that, sample was cut and prepared metallographycally. The prior austenitic grain size was measured using an optical microscope for each temperature and time combination (Figure 1b), and then the experimental data was used to obtain the grain growth parameters in Eq.2.



(a)



(b)

Figure 1. (a) Steps during grain size measurement, and (b) metallographic observation of the prior austenitic grain size in A572 steel grade, after austenitization at 1100 ºC per 600 s.

Measurement of flow stress
Another set of experiments were conducted to measure the effect of grain size on flow stress. In this test, cylindrical samples (0.5" diameter × 0.5" long) were subjected to compression using a MTS frame with induction heating. The sample was heated and soaked at 1200ºC for 60s using an induction coil. Then, the temperature was decreased to the desired test temperature (1200ºC, 1100ºC or 1000ºC), and held for different times before compression testing. Boron nitride compression plates were used to isolate the induction heated sample from the MTS system. Figure 2b shows an example of this test for the case of a holding times of 120 s. Compression test was performed at a constant 1 s^{-1} strain rate and 15% deformation (to avoid fracture of boron nitride plates).

After compression tests, the stress-strain data was used to evaluate the effect of the grain size on the flow stress, σ using the Eq3

The effect of grain diameter on the flow stress can be expressed in the form of the following additional terms in the modified JC (JCM) model:

$$\sigma = (A + B\varepsilon^{n})(d/dref)^{-n_d}(1 + C\ln\dot{\varepsilon}^{*})(1 - \dot{T}^{\mathrm{m}}) \tag{3}$$

where: all parameters are the same of the previous JC model (Eq.1) while extra term (second bracket) was added to account for the effect of the grain size. In this model, d and d_{ref} are the actual and the reference grain sizes., In this study, the maximum experimentally measured grain size was used for d_{ref} and grain size exponent (n_d) was measured independantly for each material.

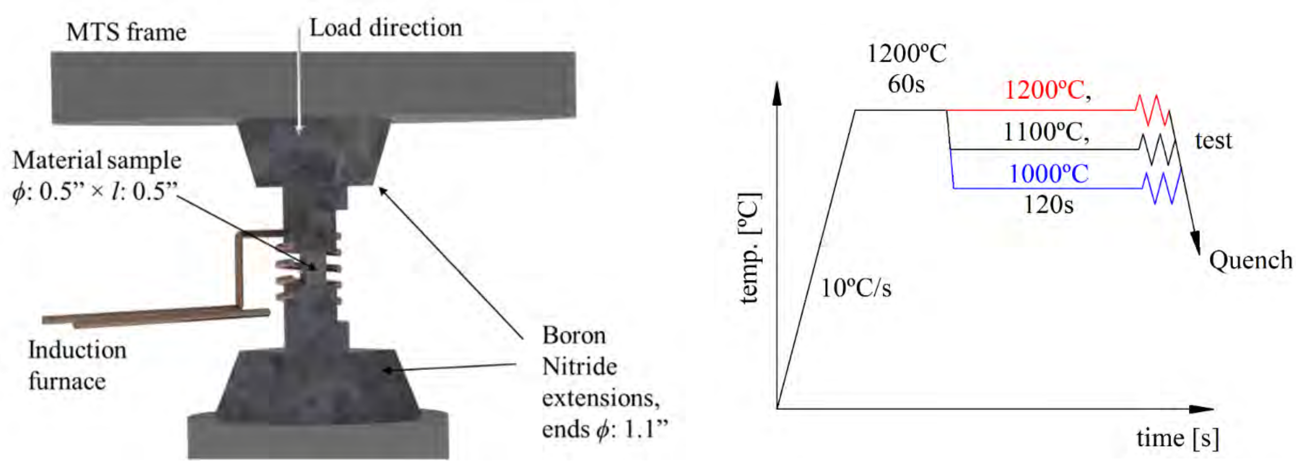


Figure 2. Compression test: (a) schematic view of the system, and (b) steps during flow stress measurement.

Finite element model
The JCM model (Eq.3) was used to represent the material behavior for the various steel grades in the three-dimensional finite element model. The JC model is extremely effective in describing materials undergoing large plastic deformation at high temperatures. The JCM model used in this work is more accurate in that it accounts for the change in grain size that affects the flow stress. This effect is highly pronounced at elevated temperatures where the grain growth is large.

Commercial code Abaqus 6.13 [14] was used to conduct the finite element simulation. A coupled thermal displacement analysis type in Abaqus explicit module was used to determine the finite element stiffness matrix. The JCM material model was coded in a user defined subroutine VUMAT [14] to update the flow stress varying with the strain. A rectangular shaped sample of size (100 mm × 100 mm × 400 mm) was created and meshed with three dimensional thermally coupled brick elements. The bottom surface of the sample was fixed while deformation was applied along the top surface as shown in Figure 3. The steel samples were compressed for 5% strain within 10 s and then allowed to relax for 10 min at 1200 ºC. The flow stress and grain size were recorded with the progress of time during the simulation.

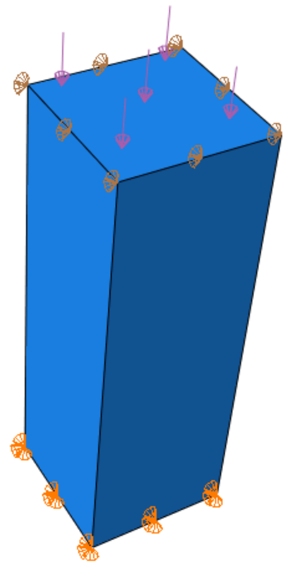


Figure 3. Boundary conditions applied to finite element model of rectangular sample used to simulate compression and relaxation.

RESULTS AND DISCUSSION

JC Strength Model Parameters

The Johnson-Cook (JC) material parameters were determined for the studied material and they are shown in Table 1. Notice that ε_{ref} was including as a material parameter, as discussed by Schwer [15].

Table 1. Calibrated Johnson-Cook parameters for studied steel grades.

Steel grade	*A* (MPa)	*B* (MPa)	*C*	*n*	*m*	$\dot{\varepsilon}_{ref}$
A690	14.4	107.49	0.2494	0.38	0.68	0.0399
A572	10.8	86.38	0.24	0.37	0.69	0.0163
1018	8.9	84.2	0.28	0.4	0.75	0.0291
15V38	16.94	45.91	0.62	0.55	0.64	0.0299

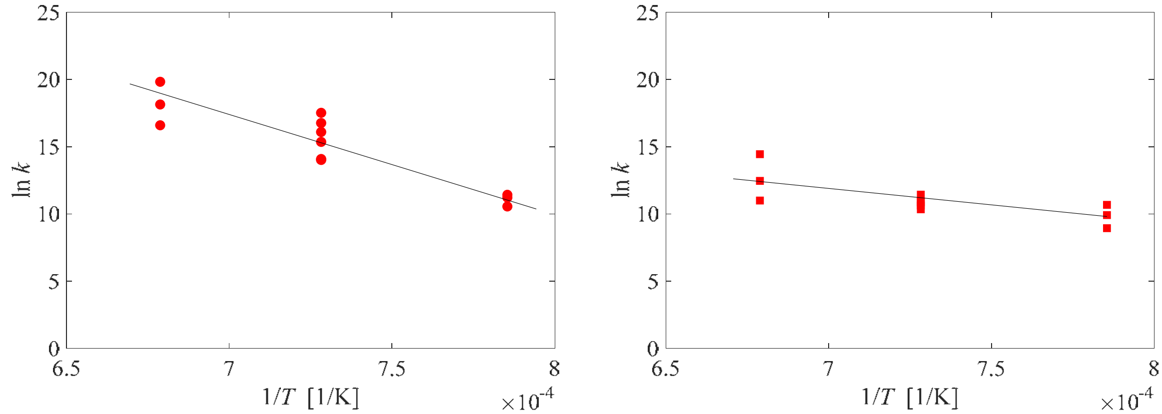
Grain Size Evolution

Using the grain size data obtained for varying holding times, the grain diameter versus time relationships were determined for different steels studied at a temperature of 1100 ºC. Similar plots were also obtained using experiments conducted at 1000 ºC and 1200 ºC. The grain growth Eq. 2 was written in the following format:

$$\ln k = lnA_G - \left(\frac{Q_G}{RT}\right) \tag{4}$$

where: $k = (d^{n_G} - d_0^{n_G})/t$.

Hence, it is possible to obtain the range of values for constants A_G and n_G by plotting ln k versus $1/T$ as depicted in Figure 4. The intercept of the line along the ordinate axis provides the A_G parameter, while the slope of the line provides the Q_G parameter. A genetic algorithm is then was used to narrow down the results to realistic output. Using this process, the grain growth parameters were determined for the steel grades A690, A572, 1018 and 15V38, as shown in Table 2.



(a)   (b)

Figure 4. Grain growth parameter plot for (a) A572 steel and (b) A690 steel.

Table 2. Grain growth parameters for the studied steel grades.

Steel grade	n_G	Q_G (J/mol)	A_G
A690	4.092	645,200	1.34E30
A572	4.39	559,900	8.33E27
1018	2.58	169,400	6.91E9
15V38	5.006	956,900	1.09E44

Flow stress evolution

The compression tests carried out after holding the steel grades for times varying from 30 s to 300 s provided the stress-strain plots shown in Figure 5 for the different steels studied.

An average flow stress was calculated using the flow curves and further utilized to plot the average flow stress versus grain size, as shown in Figure 6. A line joining the data points allows us to determine the JCM parameter n_d using the slope. As mentioned before, the reference grain size d_{ref} was taken as the maximum grain size measured experimentally. In this manner the JCM parameters were determined using this experimental procedure, which are listed in Table 3. All the material parameters (Table 1, Table 2, and Table 3) were further utilized in developing the numerical material model for the steel grades.

Numerical analysis

To start the simulations, the initial grain size of all steel grades was assumed to be 20 µm. The sample was then compressed up to 5% strain and thereafter left to relax. The loss in stress during the relaxation stage was recorded as the stress relaxation. It is observed from the simulations that the steel grade 1018 has largest grain growth whereas A690 steel grade has the lowest. 15V38 steel grade shows grain diameter increases 18.3 times, while A572 steel grade shows an increase of 14.5 times.

The numerical result agrees with the experimental data collection of grain size for the respective steel grades. Correspondingly it is also observed that considerably larger loss of flow stress is obtained for 1018 steel grade in comparison to the other steel grades. Figure 7 shows the drop in flow stress with time for steel grades A690, 1018, 15V38 and A572. Results have been compared with classical JC model. In the case of steel grade A690 the loss of flow stress is 18% while in the case of steel grade 1018 the loss is 27% (Table 4). Steel grades A 572 and 15V38 also show stress relaxation lower than steel grade 1018. Hence the new material model shows that the finer the grain size increases the strength of the material.

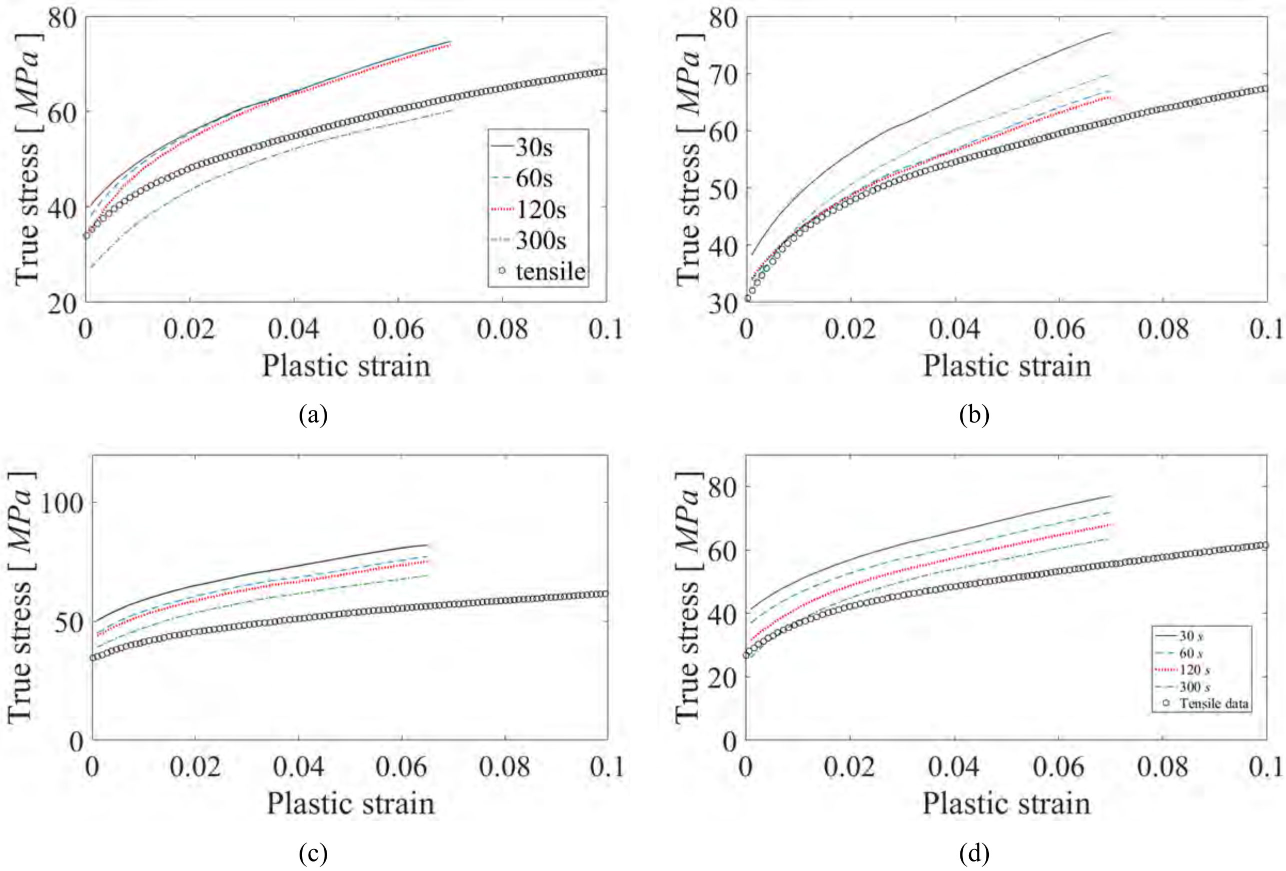


Figure 5. Stress strain curves after compression tests at 1100 ºC and $1s^{-1}$: (a) A69, (b) A572, (c) 15V38, and (d) 1018 steel grades.

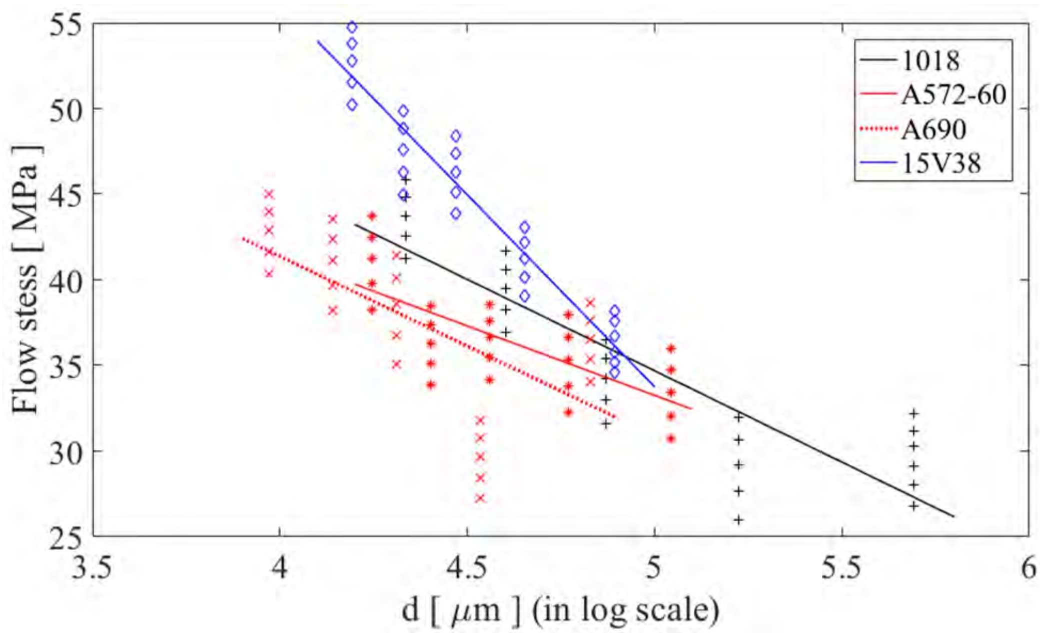
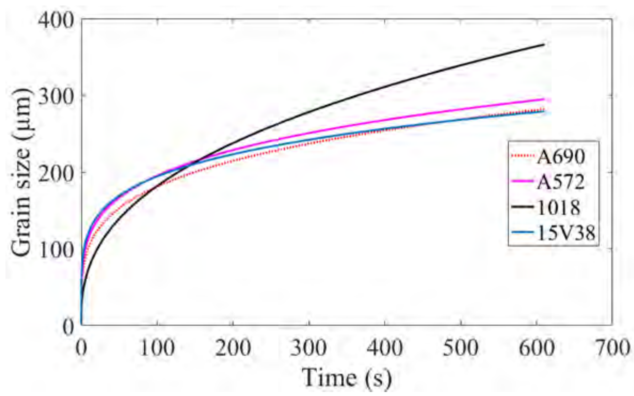


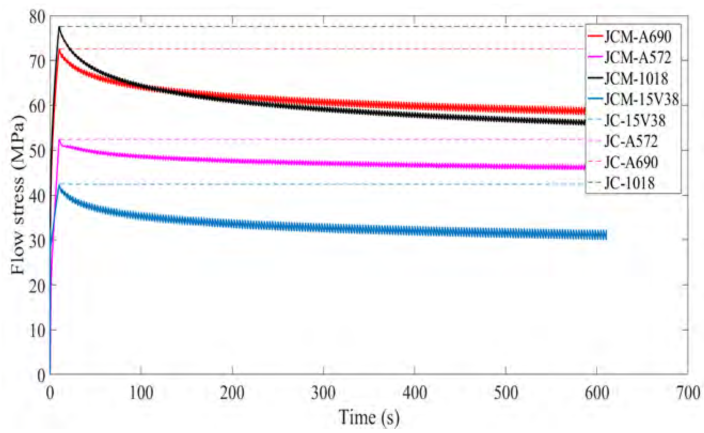
Figure 6. The maximum flow stress with varying grain size for the studied steel grades

Table 3. Modified JC model grain size parameter.

	1018	A572	A690	15V38
n_d	0.2391	0.1443	0.2430	0.4958
d_{ref} [µm]	501	322	125	133



(a)



(b)

Figure 7. Comparison of varying steel grades: (a) evolution of grain size with time and (b) change in flow stress with time for modified JC model and classical JC model.

Table 4. Comparison of stress relaxation for varying steel grades.

	Stress relaxation %
A690	18
A572	10.8
1018	27
15V38	24.2

CONCLUSIONS

In this study a modified version of the classical JC model has been introduced that accounts for the influence of grain size evolution on flow stress. This model is expected to be highly useful in simulating manufacturing processes at very high temperatures, such as forming, rolling etc. A novel experimental methodology has been used to study the evolution of grain size, as well as its effect on grain size at elevated temperatures in four different varieties of steel. The experimental study showed that all the steel grades showed significant grain size increase between temperatures of 1100 ºC and 1300 ºC. The study also showed a substantial decrease in flow stress with increasing grain size. The modified JC model was implemented using a user subroutine in commercial code Abaqus and compression test simulations were conducted to validate the effect of grain size on flow stress. The study showed that the modified JC model predicted the influence of grain size evolution on flow stress accurately. This model can be used in the future to simulate manufacturing processes involving the steel grades studied to obtain more realistic flow stress and mass flow influenced by grain size variations in comparison to the classical JC model.

ACKNOWLEDGEMENTS

This work was supported by the Peaslee Steel Manufacturing Research Center (PSMRC) at Missouri University of Science and Technology.

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