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Constitutive modeling for investigating the effects of friction on rheological behavior during hot deformation

W.Q. Li, Q.X. Ma *

[a] Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China
[b] Key Laboratory for Advanced Materials and Processing Technology of Ministry Education, Tsinghua University, Beijing 100084, China

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ABSTRACT

In order to establish rheological relationship and improve the accuracy of numerical simulations, a mathematical method has been developed to determine flow stress at the hot deformation condition. The proposed constitutive model not only considers work softening behavior induced by dynamic recovery and dynamic recrystallization, but also takes into account the influence of friction. To verify the model, hot compressions experiments under the different conditions of lubrication styles, strain rates and temperatures have been carried out. The calculated stress–strain curves are in good agreement with the experimental results, which confirms the validity of the proposed model.

1. Introduction

The understanding of metal constitutive behavior under the conditions of hot deformation is of great importance to the analysis of numerical simulation and the design of metal forming processes owing to its effective role on the metal flow pattern as well as the kinetics of metallurgical transformation [1–2]. Therefore, many investigations have been carried out to determine metal constitutive behavior at hot deformation condition [3–8]. Sellars [3] has taken advantage of Avrami-type equation to consider the effect of dynamic recrystallization, and developed an exponential function for evaluating flow stress at hot working conditions. Based on the Arrhenius-type hyperbolic-sine relationship, Rao et al. [4] have developed a constitutive equation which can describe strain-hardening, dynamic recovery and dynamic recrystallization at higher strains. Combining the hyperbolic-sine equation with Avrami-type equation, Kowalski et al. [5] have developed a constitutive equation by means of hot compression tests. Serajzadeh and Taheri [6] have developed a mathematical model taking into account work softening due to dynamic phase transformations as well as the effect of temperature to determine flow stress at hot deformation condition. McQueen and Ryan [7] have derived constitutive equations for hot working of large strain and high strain rate successfully which combines the stress dependence through the hyperbolic sine for strain rate and the Arrhenius function for temperature with activation energy. Liu et al. [8] have put forward a new flow stress model characterizing dynamic recrystallization for magnesium alloy based on the idea that the flow stress is regarded as the function of the peak stress and the strain. Furthermore, many studies on constitutive behavior have also been investigated against various metal materials [9–21].

It is commonly understood that the value of flow stress σ of constitutive behavior can be expressed with the function of strain ε, temperature T as well as strain rate $\dot{\varepsilon}$, whilst many constitutive models have been established with considering the influence of strain ε, temperature T and strain rate $\dot{\varepsilon}$ by means of the upsetting test at the different isothermal conditions [22–24]. However, the flow stress suffers from the influence of friction which exists between die/specimen. Moreover, regarding to the previous investigations of constitutive models, they have not considered the influence of friction. If constitutive models established with these stress–strain data including the influence of friction were directly applied to metal plastic simulation, they would cause the iterative application of friction, which leads to the serious deformation non-uniformity and the error magnification of mechanics behavior. This phenomenon has attracted great attention, and many friction corrections of constitutive model have been done [25–28]; however, the valid research is very scarce. In the present study, a new constitutive model taking into account the role of friction was established based on the dislocation model developed by Bergstorm [29]. Hot compression experiments have been carried out to check the reliability of the model.

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* Corresponding author at: Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China.
E-mail address: maqxdme@mail.tsinghua.edu.cn (Q.X. Ma).

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2. Material constitutive behavior and softening mechanisms

According to the compressed deformation of carbon steel, it is obvious that the flow stress is influenced by strain, temperature and strain-rate. Low temperature and high strain rate will increase the flow stress, whilst high temperature and low strain rate will decrease the flow stress owing to much longer time for energy accumulation and higher mobility at boundaries for the nucleation and growth of dynamically recrystallized grains, and dislocation annihilation.

Combined the effects of work hardening and thermally activated softening mechanisms, the flow stress can be divided into four stages of I (Work hardening stage), II (Transition stage), III (Softening stage) and IV (Steady stage) as shown in Fig. 1 via analyzing the compressed deformation of carbon steel [30]. In the Stage I, work hardening (WH) and dynamic recovery (DRV) play a dominant role in the increase of the flow stress. The rate of WH is much higher than that of softening behavior induced by DRV. Therefore, the flow stress rises steeply with the strain's augment in this stage. And there is no dynamic recrystallization (DRX) happening in this stage. In the Stage II, the behavior of DRX takes place. However, the amount of softening behavior induced by DRV and DRX can't offset the amount of WH behavior, so the flow stress still keeps increasing; yet the increasing amplitude decreases gradually with the augment of strain. The amount of softening behavior induced by DRV and DRX reaches the amount of WH behavior at the point of peak strain ε_p, after which softening behavior playing a dominant role leads to the descending of the flow stress as the Stage III. In the Stage IV, the flow stress becomes steady owing to reaching the balance state between softening and hardening behaviors. The whole true stress–strain curve of the above four stages is shown as Curve B in Fig. 1. For some experimental conditions or some metals/alloys, the flow stress continuously increases as Curve A in Fig. 1 owing to that softening behavior induced by DRV and DRX can't offset WH behavior in the whole process of plastic deformation.

However, it is known that the flow stress is not only influenced by strain, temperature and strain-rate, but also influenced by friction. Friction arouses more serious WH, and thus leads to the increase of the flow stress as Curve C and Curve D in Fig. 1 [31]. With the influence of friction, the new equilibrium of WH, DRV and DRX is reconstructed. Therefore, it is extremely necessary to study the effect of friction on stress and establish a new constitutive model considering the effect of friction.

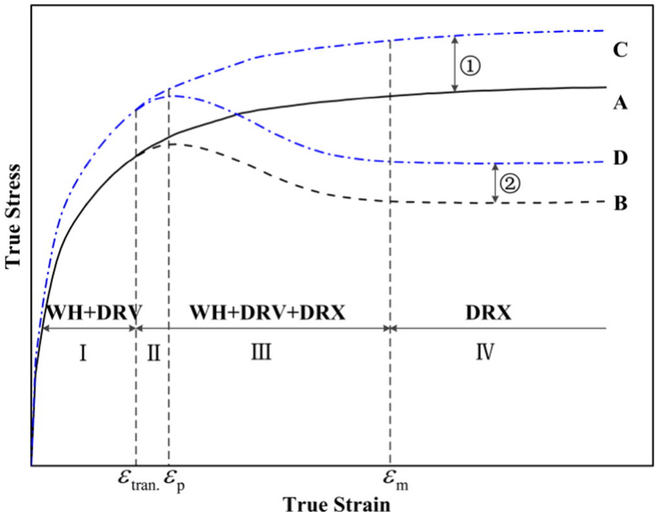

Fig. 1. True stress–strain curves for typical carbon steel. ① and ② are work hardening incurred by friction.

3. Experiment and results

3.1. Experiments

In order to establish constitutive equation accurately and demonstrate the universality of the constructed model, metal material of 30Cr2Ni4MoV, which is widely applied to ultra-super-critical turbine rotor owing to its excellent mechanical properties [32], was employed in this study.

The entire cylinder specimens made with both the diameter and the height of 10 mm were tested with Gleeble-1500D by the method of cylinder upsetting test, a conventional friction test used to evaluate interfacial friction [33–34]. The cylinder upsetting tests shown in Fig. 2 were carried out under the conditions of three strain rates of 1, 0.1, 0.01 s^{-1} and four different temperatures of 900, 1000, 1100, and 1200 °C. For the sake of unifying the experimental condition of interfacial friction and investigating the effects of interfacial friction on flow stress, three lubrication styles of graphite sheet lubrication, Tantalum sheet lubrication and dry friction (no lubrication) were set at both of the top and end interfaces between the dies and the specimen. The whole upsetting tests were carried out at the orthogonal experimental conditions of three strain rates, four test temperatures, and three lubrication styles as shown in Table 1. It is unrealistic to show all the graphs in the paper, so the following contents only show the graphs at strain rate of 0.01 s^{-1}.

After carried out the hot compression test of all the specimens with reduction in height of 50% at the orthogonal experimental conditions, minimum radius R_I, maximum radius R_M, and height H after the deformation can be measured. However, it is unpractical to measure the minimum radius R_I under the conditions owing to both of the interfaces of the specimens after the deformation under the conditions of dry friction suffering destruction. Therefore, with the profile approximation of the barreled specimens with the circle arc, top radius can be determined by the following equation [35]:

$$R_I = \sqrt{3H_0R_0^2/H - 2R_M^2}. \tag{1}$$

3.2. Flow stress behavior with the influence of friction

After the cylinder upsetting tests were implemented at the orthogonal experimental conditions of temperatures, strain rates as well as lubrication styles, the true stress–strain curves of 30Cr2Ni4MoV under the different conditions can also be obtained as depicted in Fig. 3.

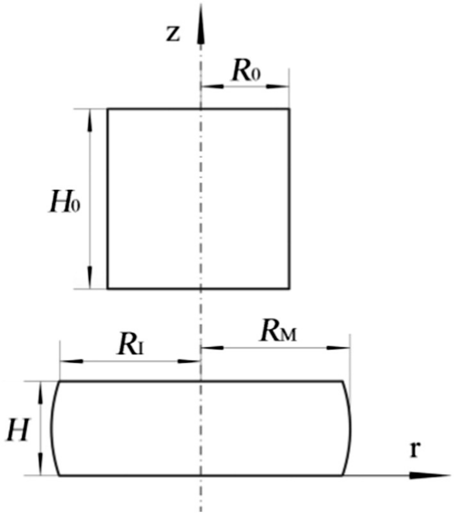

Fig. 2. Schematic of cylinder upsetting test, R_0 and H_0: original radius and height of cylinder. R_I, R_M, and H: minimum radius, maximum radius, and height after deformation, respectively.