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Effect of temperature and strain rate on the compressive deformation behavior of 42CrMo steel

*Y.C. Lin**, *Ming-Song Chen*, *Jue Zhong*

School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China

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ABSTRACT

In order to perform numerical simulation of forging and establish the hot formation processing parameters for 42CrMo steel, the compressive deformation behaviors of 42CrMo steel were investigated at the temperatures from 850 °C to 1150 °C and strain rates from $0.01\,s^{-1}$ to $50\,s^{-1}$ on Gleeble-1500 thermo-simulation machine. It was found that the flow stress of 42CrMo steel is evidently affected by both deformation temperature and strain rate, i.e., the flow stress decreases with the increase of deformation temperature and the decrease of strain rate, which can be represented by a Zener–Hollomon parameter in an exponent-type equation. For the relatively high temperature and low-strain rate, a typical flow stress curve is composed of four stages: stage I (work hardening stage), stage II (transition stage), stage III (softening stage) and stage IV (steady stage). While for the relatively low temperature and high-strain rate, stage III (softening stage) and stage IV (steady stage) are not very obvious. The flow stress constitutive equations of hot deformation for 42CrMo steel were developed. The predicted flow stress curves by the developed constitutive equations well agree with the experimental results, which confirmed that the proposed deformation constitutive equations can give an accurate and precise estimate of the flow stress for 42CrMo steel, and can be used for the analysis problem of metal-forming processes.

1. Introduction

The understanding of metals and alloys behavior at hot deformation condition has a great importance for designers of metal-forming processes (hot rolling, forging and extrusion) because of its effective role on metal flow pattern as well as the kinetics of metallurgical transformation (Lee et al., 2007; Eghbali and Abdollah-Zadeh, 2006; Mulyadi et al., 2006). Meanwhile, the constitutive relation is one of the most important factors for the analysis problem of metal-forming process. Therefore, a number of research groups have attempted to develop constitutive equations of materials from the experimentally measured data to describe the hot deformation behavior (Sheng and Shivpuri, 2006; Thomas et al., 2006; Takuda et al., 1998; Zhan et al., 2006; Lee and Lin, 1997).

42CrMo (American grade: AISI 4140) is one of the representative medium carbon and low-alloy steel. Due to its good balance of strength, toughness and wear resistance, 42CrMo high-strength steel is widely used for many general purpose parts including automotive crankshaft, rams, spindles, crow bars, ring gears, etc. 42CrMo steel contains chromium and molybdenum as alloying elements and may be heat treated over a wide range to give the combined advantages of proper hardness, strength and ductility. In conditions where localized hardness may be required, this steel is readily flame or induction hardened. In the past, many investigations have been carried out on the behavior of 42CrMo steel. Holzapfel

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* *Corresponding author*. Tel.: +86 731 8877915.
E-mail address: yclin@mail.csu.edu.cn (Y.C. Lin).

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Nomenclature

A	material constant (s^{-1})
Q	activation energy of hot deformation (kJ/mol)
R	universal gas constant (8.31 J/(mol K))
T	absolute temperature (K)
Z	Zener–Hollomon parameter
n	material constant

Greek symbols

α	material constant (MPa^{-1})
β	material constant (MPa^{-1})
$\dot{\varepsilon}$	strain rate (s^{-1})
σ	flow stress (MPa)

et al. (1998) studied the residual stress relaxation in 42CrMo steel due to quasistatic and cyclic loading at higher temperatures. Celik and Karadeniz (1995) investigated the influence of plasma nitriding on the fatigue behavior of AISI 4140 low-alloy steel under varying process conditions of temperature, time, heat treatment before ion nitriding and gas mixture. Sarioglu (2001) studied the stress corrosion cracking behavior of low-alloy steel 42CrMo in 33% sodium hydroxide solution at 80 °C under freely corroding conditions, and found that the crack growth behavior and fracture mode were sensitive to the presence of inclusions and to the microstructure of the steel. Totik et al. (2002) carried out a comparative study of the hot workability by hot torsion test of 42CrMo steel. Kim and Yoo (2002) established the quantitative relationships between the flow stress and the volume fraction of dynamic recrystallization (DRX) as a function of processing variables such as strain rate, temperature, and strain for AISI type 4140 medium carbon steel, by means of torsion tests.

Despite large amount of efforts invested into the behaviors of 42CrMo steel, the hot compressive deformation behavior of 42CrMo steel need to be further investigated to perform numerical simulation of forging and establish the hot formation process parameters for 42CrMo steel. The objective of the present work is to investigate the effects of deformation temperatures and strain rates on the hot deformation characteristics of 42CrMo steel by hot compression tests. Flow stress data are analyzed in terms of strain rate and temperature sensitivities. The constitutive equations describing the dependence of the flow stress on strain, strain rate and temperature are developed and verified.

2. Experiments

Table 1 – The main chemical composition of 42CrMo steel (mass fraction,%)

Element	wt.%
C	0.38–0.45
Si	0.17–0.37
Mn	0.50–0.80
Cr	0.90–1.20
Mo	0.15–0.25
P	≤0.04
S	≤0.04
Cu	≤0.30

The material used in this investigation was the commercial 42CrMo high-strength steel, and its chemical composition (wt.%) is given in Table 1. Cylindrical specimens were machined with a diameter of 10 mm and a height of 12 mm. In order to minimize the frictions between the specimens and die during hot deformation, the flat ends of the specimen were recessed to a depth of 0.1 mm deep to entrap the lubricant of graphite mixed with machine oil. The hot compression tests were performed on Gleeble-1500 thermo-simulation machine in the temperature range of 850–1150 °C and strain rate of 0.01–50 s^{-1}. To measure the temperature during the heating of the specimen, a thermocouple was attached to the surface of the specimen. Each sample was heated to deformation temperature at a rate of 10 °C s^{-1} by thermo-coupled feedback-controlled AC current, and held for 5 min at isothermal conditions before compression tests, in order to obtain the heat balance. The reduction of height is 60% at the end of the compression tests. The load-displacement data were recorded automatically by the computer control system of the thermal simulator.

3. Results and discussion

3.1. *True stress and true strain*

True stress–true strain curves of 42CrMo steel can be easily transformed from the load-displacement data recorded by the thermal simulator during hot compression test. Fig. 1 shows the typical true stress–strain curves obtained from hot compression tests of 42CrMo steel.

From the experimental results (shown in Fig. 1), it can be found that, at relatively high temperatures and low-strain rate, a typical flow stress curve is composed of four stages (Sheng and Shivpuri, 2006; Smallman and Bishop, 2002): stage I (work hardening stage), stage II (transition stage), stage III (softening stage) and stage IV (steady stage). This is a combination effect of work hardening, which is primarily caused by second order pyramidal slip system dislocation motion, and thermally activated softening. In the initial stage of the deformation, i.e., stage I (work hardening stage), hardening rate is higher than the softening rate and thus the stress rises steeply at microstrain deformation then increases at a decreased rate, followed by stage II (transition stage). In transition stage, the competition between the work hardening and the softening phenomenon induced by dynamic recovery, as well as the dynamic recrystallization (DRX), takes place. Also, the flow stress still increases, but the increase rate continuously decreases. Then, stage III (softening stage): the dislocations are annihilated in large numbers through the migration of a high angle boundary and the stress drops steeply, which is related with dynamic recrystallization, dynamic precipitation, etc. Finally, stage IV (steady stage): the stress becomes steady when a new balance between softening and hardening is obtained. While, for the relatively low temperature and high-strain rate, stage III (softening stage) and stage IV (steady stage) are less and less obvious,