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The deformation behavior in isothermal compression of 300M ultrahigh-strength steel

J. Luo*, M.Q. Li, Y.G. Liu, H.M. Sun

School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, PR China

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ABSTRACT

The flow stress, the apparent activation energy for deformation and the growth behavior of austenite grains in isothermal compression of 300M steel are investigated at the deformation temperatures ranging from 850 °C to 1250 °C, the strain rates ranging from $0.1\,s^{-1}$ to $25.0\,s^{-1}$, and the height reductions ranging from 30% to 70%. Through the analysis of flow curves and microstructure, it is confirmed that dynamic recovery is the dominant softening mechanism at a deformation temperature of 900 °C. At a deformation temperature of 1100 °C, the process of dynamic recrystallization has completed and the austenite grain growth is in progress in isothermal compression of 300M steel. Coarse macro-grains in isothermal compression of 300M steel are observed at the deformation temperatures above 1140 °C. The apparent activation energy for deformation of 300M steel is in the range of 332 ± 61 to $397 \pm 31\,kJ\,mol^{-1}$. The processing maps of 300M steel at a series of strains are constructed based on the dynamic materials model (DMM). The results show that the unstable region in instability maps decreases with an increase in strain. At a strain of 0.7, the unstable region occurs at the deformation temperatures ranging from 900 °C to 1140 °C and the strain rates ranging from $0.1\,s^{-1}$ to $2.1\,s^{-1}$. And the processing maps exhibit the peak efficiency of power dissipation of 0.86 occurring at the deformation temperatures ranging from 1100 °C to 1140 °C and the strain rates ranging from $0.1\,s^{-1}$ to $0.16\,s^{-1}$, which is correspondent to the optimal deformation condition of 300M steel.

1. Introduction

300M steel as a commercial low-alloy ultrahigh-strength (UHS) steel was widely used in aircraft landing gear because of excellent combination of high strength and fracture toughness. The mechanical properties of this medium-carbon steel were modified by adding the alloying elements of 1.6% silicon and 0.1% vanadium in 4340 steel. The presence of high silicon concentration in 300M steel encourages retention of ductile high-carbon austenite, rather than the formation of brittle interlath cementite films which have a detrimental effect on both ductility and toughness [1]. Vanadium serves to restrict austenite grain growth during the austenitizing heat treatment, usually carried out at a temperature not high enough to completely dissolve particles of vanadium carbides [2]. The alloy modification, together with vacuum arc remelting (VAR) gives 300M steel a higher yield and tensile strength of 1615 MPa and 1963 MPa in the quenched and low-temperature tempered conditions.

For 300M steel, the austenite grain coarsening occurs easily at high deformation temperature or after holding at a given temperature for long time due to strongly microstructural sensitivity and overheating sensitivity. Moreover, the austenite grains at high deformation temperature have a significant effect on the phase transformation characteristics during the cooling stage and microstructural features at ambient temperature. In other words, the austenite grain size at high deformation temperature will affect significantly the mechanical properties of 300M steel at ambient temperature. It is well known that the yield strength of the metal varies reciprocally with the grain size. The relation between them is described mathematically by the Hall–Petch equation:

$$\sigma_y = \sigma_0 + k_y d^{-1/2} \quad (1)$$

where σ_y is the yield strength (MPa), σ_0 is the start stress for dislocation movement or the resistance of the lattice for dislocation motion (MPa), k_y is the strengthening coefficient ($MPa\,mm^{1/2}$), and d is the average grain size (μm).

Therefore, the austenite grain coarsening occurring in hot forging of 300M steel has a detrimental effect on plasticity, strength and toughness, which is a non-negligible problem that hinders the development of high performance and complex component of 300M steel. So it is necessary to investigate the growth behavior of austenite grains and deformation mechanisms in hot forging

* Corresponding author. Tel.: +86 29 88460465.
E-mail addresses: luojiao@nwpu.edu.cn, schjiaozi@163.com (J. Luo).

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process so as to improve the strength/toughness combination in medium-carbon low-alloy steels.

In the past several decades, a number of research groups have paid attention to the growth behavior of austenite grains of 300M in different heat treatment conditions. For instance, Zhang et al. [3] investigated the austenite recrystallization mechanism in the heating process of 300M steel, and pointed out that 300M steel being fabricated by vacuum induction melting and vacuum arc remelting had higher purity and strongly overheating sensitivity, in which the growth tendency of austenite grains increased and it would result in the occurrence of coarse grains as adopting unsuitable forging method [4]. In terms of the experimental results, two heat treatment processes of 300M steel were suggested so as to eliminate the coarse grains as follows [5]: (1) austenitising in the temperature range of 970–980 °C and air-cooling and (2) tempering at 700 °C for 60 min and air-cooling, then rapidly heating to 930 °C with holding time of 60 min, and finally air-cooling. Zhang et al. [6] acquired the conclusions that the austenite grain size increased with an increase in heating temperature and holding time in the heating process of 300M steel. Moreover, considerable research has been carried out to enhance the fracture toughness and stress corrosion cracking (SCC) of 300M steel [7–13]. These studies lay a foundation for understanding the growth behavior of austenite grains, optimizing the heat treatment conditions and improving the strength/toughness combination.

The objective of present research is to study the flow stress, the growth behavior of austenite grains and the deformation mechanisms in isothermal compression of 300M steel. The processing maps are adopted to analyze the high temperature deformation behavior. This study will be beneficial for designing hot working schedules so as to optimize intrinsic workability, control microstructural evolution and avoid the occurrence of coarse macro-grains.

2. Experimental

2.1. Experimental material

As-received bar stock of 300M steel is 22.0 mm in diameter. The chemical composition (wt%) of 300M steel used in this investigation is as follows: 0.39 C, 1.61 Si, 1.82 Ni, 0.69 Mn, 0.91 Cr, 0.42 Mo, 0.07 V, 0.06 Cu, 0.0012 S, 0.0089 P and the bal. Fe. The A_{c1} temperature and A_{c3} temperature of as-received 300M steel are 748 °C and 802 °C, respectively. The morphology of austenite grains in as-received 300M steel is shown in Fig. 1. It is seen from Fig. 1 that the prior austenite grains of 300M steel are equiaxed with an average grain size of about 26.30 μm.

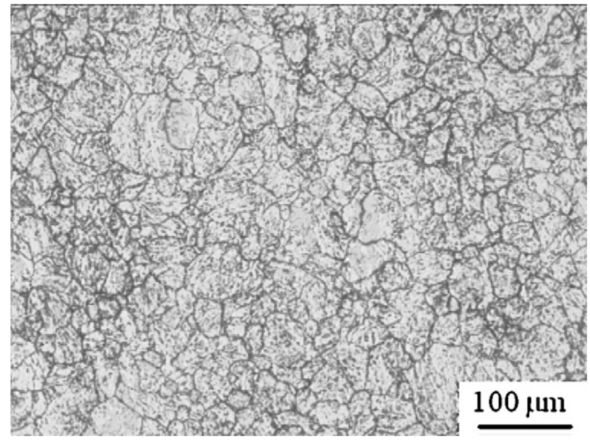

Fig. 1. The morphology of austenite grains in the as-received 300M steel.

2.2. Experimental procedures

Cylindrical compression specimens have 8.0 mm in diameter and 12.0 mm in height. A series of isothermal compressions were conducted on a Gleeble-3500 simulator at the deformation temperatures of 850 °C, 900 °C, 950 °C, 1000 °C, 1050 °C, 1100 °C, 1120 °C, 1140 °C, 1160 °C, 1180 °C, 1200 °C and 1250 °C, the strain rates of 0.1 s^{-1}, 1.0 s^{-1}, 10.0 s^{-1} and 25.0 s^{-1}, and the height reductions of 30%, 40%, 50%, 60% and 70%. The specimens were heated and held for 5 min at the deformation temperature to establish a uniform temperature in the specimens. The flow stress–strain curves were recorded automatically in isothermal compression. After the compression, the specimens were rapidly quenched in water. And the specimens were axially sectioned and prepared using standard metallographic techniques. The saturated aqueous picric acid solution with a few drops of detergent was used to reveal the prior austenite grain boundaries, and polished surfaces were etched in this aqueous solution for about 30 min at room temperature. Three measurement points and six visual fields of one point in the different deformation regions were observed. The austenite grain size was measured at an OLYMPUS PMG3 microscope with the quantitative metallography image analysis software SISC IAS V8.0 and the austenite grain size was calculated by the average of eighteen visual fields.

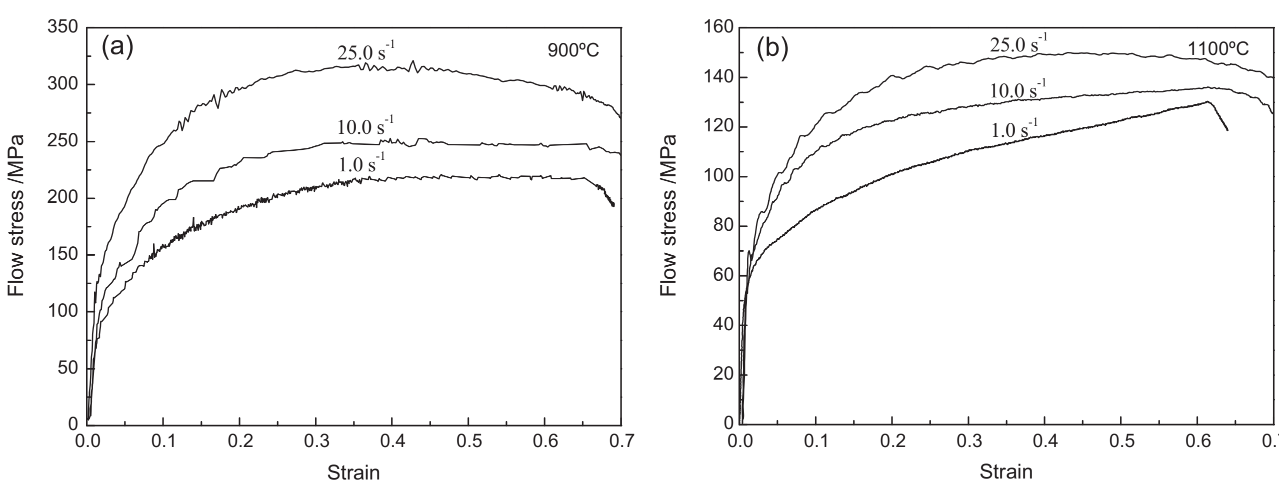

Fig. 2. Selected flow stress–strain curves in isothermal compression of 300M steel.