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A physically-based constitutive model for SA508-III steel: Modeling and experimental verification

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ABSTRACT

Due to its good toughness and high weldability, SA508-III steel has been widely used in the components manufacturing of reactor pressure vessels (RPV) and steam generators (SG). In this study, the hot deformation behaviors of SA508-III steel are investigated by isothermal hot compression tests with forming temperature of (950–1250)°C and strain rate of (0.001–0.1)s^{-1}, and the corresponding flow stress curves are obtained. According to the experimental results, quantitative analysis of work hardening and dynamic softening behaviors is presented. The critical stress and critical strain for initiation of dynamic recrystallization are calculated by setting the second derivative of the third order polynomial. Based on the classical stress–dislocation relation and the kinetics of dynamic recrystallization, a two-stage constitutive model is developed to predict the flow stress of SA508-III steel. Comparisons between the predicted and measured flow stress indicate that the established physically-based constitutive model can accurately characterize the hot deformations for the steel. Furthermore, a successful numerical simulation of the industrial upsetting process is carried out by implementing the developed constitutive model into a commercial software, which evidences that the physically-based constitutive model is practical and promising to promote industrial forging process for nuclear components.

1. Introduction

Knowledge of the high-temperature deformation behavior of metals and alloys is very important for the numerical modeling of many industrial processes. Prerequisite for a successful modeling of hot working processes by means of numerical techniques, such as finite element and finite difference methods, one of the most important items is a precise establishment of the constitutive equations which describe the dependence of the flow stress on strain, strain rate and temperature. Therefore, an accurate constitutive equation for the work-hardening and softening behavior is essential. Meanwhile, the understanding of flow behavior of metals and alloys at high temperature is of great importance for designers for hot forming process, such as hot forging, rolling and extrusion. In the last two decades, considerable investigations have been attempted to develop constitutive equations of materials from the experimentally measured data to describe the hot deformation behavior [1–5].

RPV and SG are the key components of nuclear power equipment which dominate the lifespan of nuclear power plants. At present, ASME SA508-III steel has been extensively used as the materials of RPV and SG due to its high strength and toughness to prevent failure under severe working conditions [6]. As a key equipment of the ultra-super-critical generator set, the RPV and SG should have good mechanical properties through hot forging. In the past, many investigations have been carried out on the behavior of SA508-III steel. Kim et al. investigated the failure behaviors of the weld heat-affected zones, strain aging and fatigue crack propagation under certain experiment conditions [7]. At the same time, a new heat treatment process was developed to improve the toughness for SA508-III steel by Kim et al. [8]. Lee et al. studied the relationship of the composition, structure and mechanical properties for the steel [9]. Liu et al. studied the fracture toughness of SA508-III steel in the temperature range from room temperature to 320 °C using the *J*-integral method [10]. Based on the literature reviewed above, it is found that the previous studies mainly focus on the service performance of SA508-III steel. However, there are only few reports on the properties of SA508-III steel during hot forming process. Therefore, in order to study the workability and to optimize the hot forging processing parameters, it is highly necessary to investigate the

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Table 1
The chemical composition of SA508-3 forging billet (wt%).

C	Si	Mn	Cr	Mo	Ni	Cu	S	P
0.18	0.17	1.4	0.14	0.51	0.79	0.04	0.003	0.005
V	Al	N	Co	As	Sn	O	H	Sb
0.005	0.022	0.008	0.0008	0.004	0.0042	0.006	0.0003	0.00005

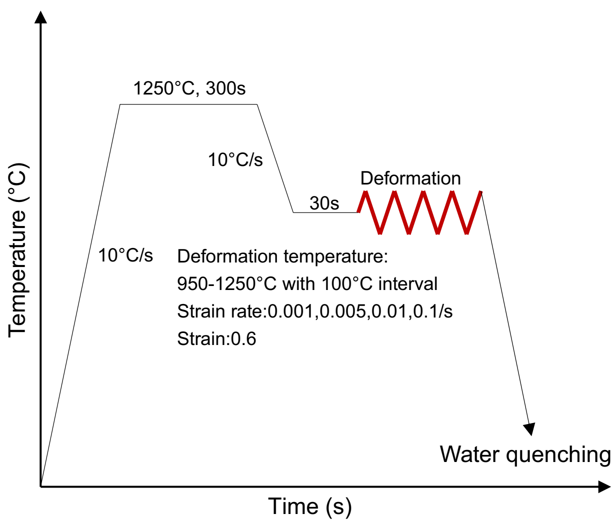

Fig. 1. Schematic representation of hot deformation process used in the experiments.

effects of different thermomechanical parameters on the flow behaviors for this steel.

This paper mainly focuses on the high-temperature deformation behavior of the steel during hot compression at the temperatures from 950 °C to 1250 °C and strain rates from 0.001 s^{-1} to 0.1 s^{-1} using Gleeble-3500 thermo-mechanical simulator. Based on the experimental results, the flow stress constitutive equations are established by introducing the classical stress–dislocation relation and the kinematical recrystallization theory. Then through secondary development of the subroutine, the developed flow stress model is integrated into commercial software DEFORM3D. To verify the validity and effectiveness of the developed program, firstly the isothermal compression tests are simulated to predict the loading force under experimental conditions, and then a three-dimensional hot forging process in the industrial production environment is performed to compare the loading force obtained by the numerical simulation by using the developed constitutive model.

2. Experimental procedures

In this investigation, the chemical compositions (wt%) of the commercial SA508-III steel are summarized in Table 1. Cylindrical specimens were machined with a diameter of 10 mm and a height of 15 mm. The hot compression tests were carried out on a Gleeble-3500 thermo-mechanical simulator according to the schedule illustrated in Fig. 1. The specimens were heated to 1250 °C at

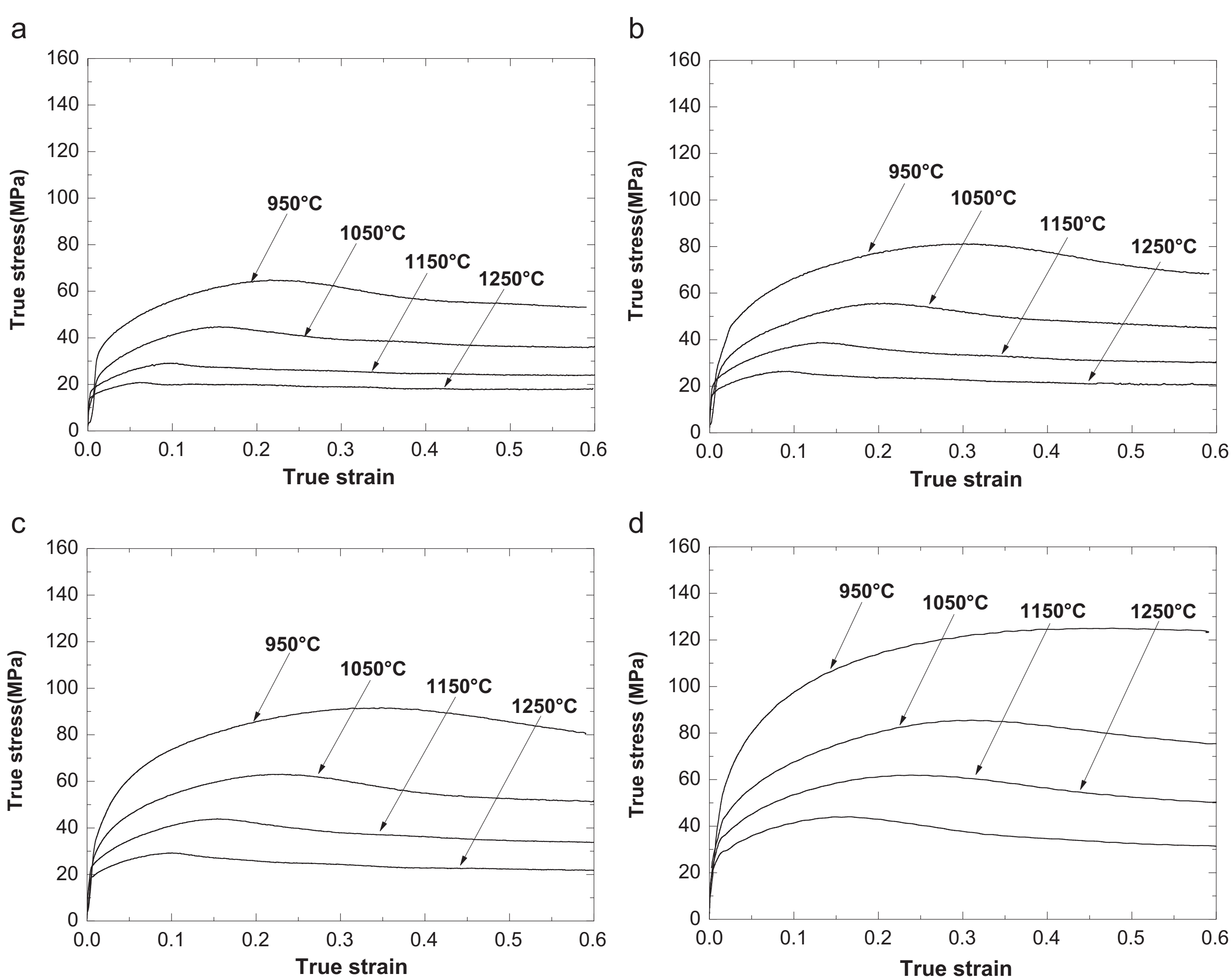

Fig. 2. Flow stress–strain curves of the SA508-III steel in different temperatures at the same strain rates (a) 0.001 s^{-1}, (b) 0.005 s^{-1}, (c) 0.01 s^{-1} and (d) 0.1 s^{-1}.