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Effect of borides on hot deformation behavior and microstructure evolution of powder metallurgy high borated stainless steel

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ABSTRACT

To investigate borides effect on the hot deformation behavior and microstructure evolution of powder metallurgy high borated stainless steel, hot compression tests at the temperatures of 950– 1150 °C and the strain rates of 0.01– 10 s^{-1} were performed. Flow stress curves indicated that borides increased the material's stress level at low temperature but the strength was sacrificed at temperatures above 1100 °C. A hyperbolic-sine equation was used to characterize the dependence of the flow stress on the deformation temperature and strain rate. The hot deformation activation energy and stress exponent were determined to be 355 kJ/mol and 3.2, respectively. The main factors leading to activation energy and stress exponent of studied steel lower than those of commercial 304 stainless steel were discussed. Processing maps at the strains of 0.1, 0.3, 0.5, and 0.7 showed that flow instability mainly concentrated at 950– 1150 °C and strain rate higher than 0.6 s^{-1}. Results of microstructure illustrated that dynamic recrystallization was fully completed at both high temperature-low strain rate and low temperature-high strain rate. In the instability region cracks were generated in addition to cavities. Interestingly, borides maintained a preferential orientation resulting from particle rotation during compression.
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1. Introduction

Boron has been extensively used in the nuclear industry due to its capacity to absorb thermal neutron [1,2]. Among boron-containing neutron shielding materials, high borated stainless steel (modified austenitic stainless steel containing 0.2– 2.25% B) is attractive for additional both excellent mechanical and anti-corrosion properties. However, the low solubility of boron in stainless steel induces a large amount of orthorhombic Cr-rich M_2B to be generated during the solidification process [2–5]. The considerable differences in mechanical and corrosion properties with austenite matrix make boride evidently affect the performances of steel [6–10]. In consideration of the fact that powder metallurgy (P/M) products contain finer, less elongated and more uniformly distributed borides compared with those formed through ingot metallurgy [2,11–13], P/M technology obviously improves the performances of borated stainless steel. Thus this method is commonly used to fabricate high borated stainless steel used as structural material.

The incompatibility between ductile matrix and hard borides as well as the low melting point of austenite/boride eutectic makes hot forming operations of borated stainless steel complex [7,14]. Previous work on as-cast borated stainless steel containing 0.56% boron has revealed that boride particles promote the generation of cavities and cracks [15], which could lead to failure during hot working. Consequently, hot deformation of casting products should be performed carefully within a controlled processing window. It has been demonstrated that the deformability of casting products can be improved by refining boride particles, promoting them spherical and homogeneous distribution through increasing crystallization rate and further high temperature annealing [13]. It is therefore natural to suppose that compared with the ingot metallurgy, P/M technology could improve the hot workability of borated stainless steel. However, the difference in plastic deformation resulting from boride characteristics (including particle size, quantity, shape, and distribution) should not be neglected.

Unfortunately, up to now, there is little information available in literature on the hot deformation behavior of P/M high borated stainless steel. Therefore, the purpose of this study is to characterize the hot deformation behavior of P/M high borated stainless steel using the constitutive equation and processing maps as well as to reveal microstructure characteristics during hot deformation. Additionally, the effect of boron and boride on the hot deformation behavior and microstructure evolution is studied.

2. Material and Methods

ASTM A887-89 UNS S30467 high borated stainless steel (modified 304 stainless steel with 1.75– 2.25% boron) was utilized in this study. The chemical composition is given in Table 1. Dense steel was fabricated

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Table 1
Chemical composition (wt%) of studied high borated stainless steel.

B	C	Si	Mn	Cr	Ni	Fe
2.10	0.02	0.53	1.63	19.3	14.10	Balance

by hot pressing sintering at 1150 °C for 60 min under 30 MPa [2]. The cylindrical specimens with the diameter of 8.0 mm and height of 12.0 mm were machined from sintered bulk. Hot compression tests were conducted on a Gleeble-3500 thermal/mechanical simulator. The compression tests were performed at temperatures of 950, 1000, 1050, 1100, and 1150 °C and strain rates of 0.01, 0.1, 1, and 10 s^{-1}, respectively. Prior to the compression deformation, all specimens were fast heated to 1150 °C at a heating rate of 10 °C/s and soaked for 3 min, and then cooled to test temperature at the rate of 10 °C/s. All specimens were compressed to 50% of the original height followed by water quenching. For metallographic observations, the specimens were polished to 0.5 μm diamond finish and etched by the Marble's reagent. Specimens for electron backscatter diffraction were prepared by standard mechanical polishing with 0.5 μm diamond finish, followed by electrochemical polishing in a solution of 6 ml perchloric acid, 34 ml *n*-butyl alcohol and 60 ml methyl alcohol. Microstructure examinations were performed on a scanning electron microscope (SEM) with electron backscatter diffraction (EBSD). Energy dispersive spectrometer (EDS) was applied to measure the chemical compositions of austenite matrix and boride particle.

3. Results

3.1. Flow Curves

The true stress-true strain curves of hot pressing sintered (HPed) high borated stainless steel obtained at different compression conditions are illustrated in Fig. 1. These flow curves exhibit typical dynamic recrystallization (DRX) flow curves with a single stress peak followed by a gradual fall towards a steady state stress. The initial rapid rise in stress is in context with the work hardening caused by dislocation interaction and multiplication and the generation of poorly developed subgrain boundaries [16]. The flow stress level decreases with the increase of temperature and increases with the increase of strain rate. It is apparent that the peak strain can be retarded by either increasing the strain rate or by reducing the deformation temperature. Moreover, it is noteworthy that the strengthening effect of boride particles depends on the temperature in comparison with flow curves of commercial 304 stainless steel [17,18]. Borides strengthen steel in low temperature, while those particles sacrifice the strength when the temperature higher than 1100 °C. This observation is in agreement with studies on as-cast borated stainless steel and is attributed to borides broke and/or rotated, cavities generation, and solid solution softening by boron [15].

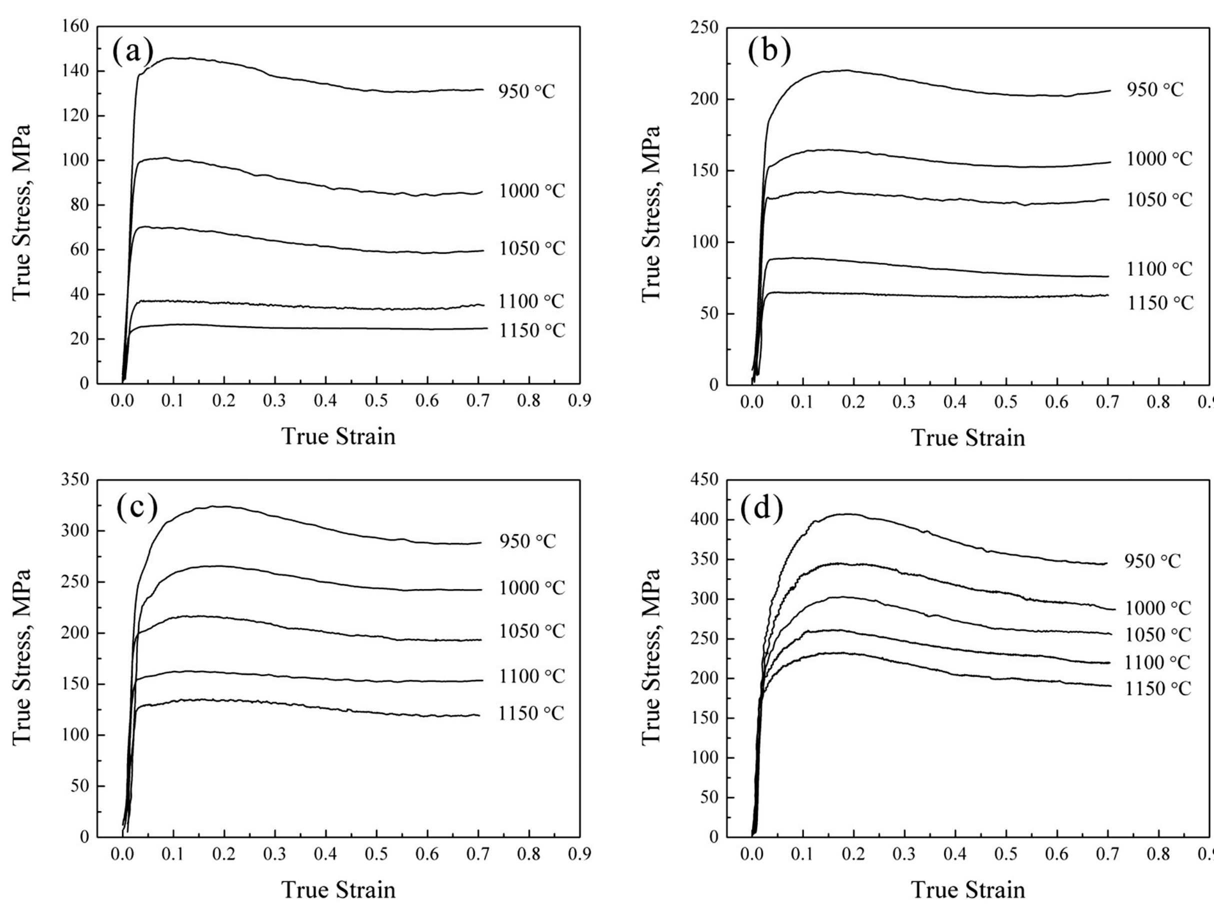

Fig. 1. Flow curves obtained at different deformation conditions: (a) 0.01 s^{-1}; (b) 0.1 s^{-1}; (c) 1 s^{-1} and (d) 10 s^{-1}. (TIF format, 174.0 mm × 129.3 mm, 500 dpi, 2 columns fitting image).

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