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Effects of strain rate on the hot deformation behavior and dynamic recrystallization in China low activation martensitic steel

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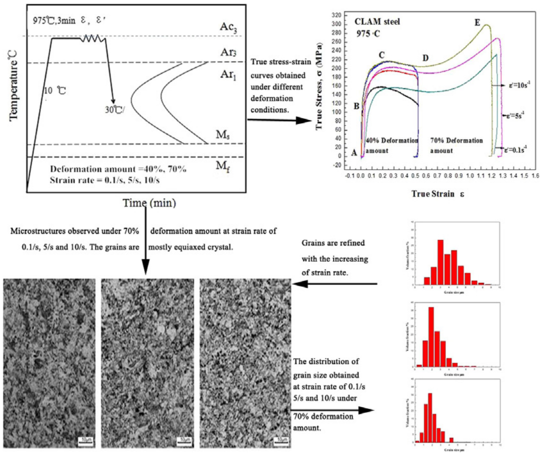
HIGHLIGHTS

- Average grain sizes of 1.8 μm are observed at strain rate of 10 s^{-1}.
- Peak stress value increased, but strain decreased with increasing of strain rate.
- A catenuliform recrystallized occurred at a strain rate of 5 s^{-1}.
- DRX effect improved with increasing of deformation amounts.

GRAPHICAL ABSTRACT



True stress-strain curves obtained under different deformation conditions.

Microstructures observed under 70% deformation amount at strain rate of 0.1/s, 5/s and 10/s. The grains are mostly equiaxed crystal.

Grains are refined with the increasing of strain rate.

The distribution of grain size obtained at strain rate of 0.1/s 5/s and 10/s under 70% deformation amount.

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ABSTRACT

To investigate the effects of strain rate on dynamic recrystallization (DRX) behavior on China low activation martensitic steel, hot uniaxial compression tests with strain rates ranging from 0.1 s^{-1} to 10 s^{-1} and deformations amounts of 40% and 70% where conducted. The true stress–true strain curves were analyzed for the occurrence of DRX under the different strain rates and compressive deformation amounts. The steel microstructures were examined and linked to the observed stress-strain diagrams to study DRX. Results show that DRX was responsible for refining the grain structure over a wide range of strain rates under 70% deformation. However, significant DRX occurred only at the relatively low strain rate of 0.1 s^{-1} under 40% deformation. The original elongated microstructure of the rolled plate from which the specimens were taken was replaced by dynamic recrystallization grains. At 70% deformation, the average grain size was 4.2 μm at a strain rate of 0.1 s^{-1}, 2.5 μm at a strain rate of 5 s^{-1}, 1.8 μm at a strain rate of 10 s^{-1}. In conclusion, with increasing strain rate, the recrystallized grain size decreased and the peak stress increased.

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1. Introduction

The demand for energy across the world continues to grow at an astounding rate. Energy production from fossil fuel and fission nuclear reactors produces continuing concerns about pollution and waste management. Nuclear fusion energy generation has the potential to produce abundant useable energy with minimum pollution and maximum economic efficiency to successfully solve the energy problem. Development of materials and structure to contain a sustained fusion reaction is the key to practically achieving a fusion power system [1]. Currently, the reduced activation ferritic/martensitic (RAFM) steels are being widely studied as the basis for fusion equipment development around the world. RAFM steels have low residual radioactivity, good resistance to void swelling, good thermal stress resistance and relatively mature material fabrication technologies [2–5]. China low activation martensitic (CLAM) steel is a type of RAFM steel owing independent intellectual property rights to China. It is chosen as the candidate structural material for series fusion reactors and the ITER liquid LiPb Test Blanket Module of China. Presently, researches on the properties of CLAM steel mainly include composition optimization, smelting and processing preparation, physical properties, mechanical properties, radiation performance, liquid metal corrosion and welding performance [2–5]. Nonetheless, besides the properties mentioned above, further study is required on the hot-workability of CLAM steel for practical applications.

With the development of modern deformation theory, studies on thermoplastic forming processes have not only been confined to the flow behaviors but include focusing on microstructure evolution during hot deformation [6–13]. Microstructures undergo a series of changes, such as dynamic recovery (DRV), dynamic recrystallization (DRX) and deformation induced transformation, and grain growth and phase transition during cooling [6,14–17]. The flow stress of a metal alloy under hot forming strongly determines the evolution of microstructure [18]. Hot deformation processing is an indispensable technology for many practical applications of high strength steel. Microstructure and properties of 700 MPa grade high–strength-low-alloy steel during different temperature-deformation conditions studied by Chen [19,20] demonstrated that the microstructure transformation of deformed austenite is quite different under different processing conditions. With increasing deformation, the microstructure becomes less equiaxed and more lath-shaped, and with decreasing heating rate, the microstructure becomes more uniform and equiaxed. The occurrence of DRX during thermo-mechanical processing in a heat-resistant martensitic stainless steel was observed by Zeng [21]. Results show that DRX occurs readily at lower strain rates and higher deformation temperatures. So far, the flow behaviors of different alloys, especially aluminum alloys [14,15,17] and magnesium alloys have been widely investigated at high temperature. In recent work, the hot deformation characteristics of martensitic steels were studied [22–27], including the development of constitutive equations, the study of predominant softening processes under different deformation conditions and the corresponding microstructure evolution. There has also been considerable research on the DRX behavior during deformation of RAFM [28,29]. However, little similar research has been conducted on CLAM steel. Hu etc. [30,31] described the low cycle fatigue behavior of CLAM steel by controlling total strain amplitude from 0.14% to 1.8% with a constant strain rate of $2.4 \times 10^{-3}\,s^{-1}$ at 823 K. Results revealed that microstructure and precipitate distribution of CLAM steel gradually changed during continuous cyclic deformation. Tempered martensitic laths decomposed into sub-grains. The size and quantity of carbonitride precipitates decreased with the increasing total strain amplitude. But in that situation, the strain and strain rate are quite small and significantly different than the situation in thermoplastic molding process. Wang [32] reported the flow behaviors of CLAM steel under the strain rate from $0.001\,s^{-1}$ to $5\,s^{-1}$ at temperatures from 850 °C to 1050 °C. Results showed that the flow stress decreased with increasing deformation temperature and as strain rate increased the flow stress increased. However, there is no metallographic evidence and relevant analysis mentioned.

In this paper, thermostatic compression near the Ac_3 temperature was conducted with different strains and strain rates on CLAM steel. The effects of strain and strain rate on flow stress and microstructure during hot deformation were studied by true stress–true strain curve and microstructure characterizations. Combining stress-strain curves and microstructure investigation, the DRX behaviors of CLAM steel during a range of hot deformation conditions are discussed. Hot deformation behavior provides a theoretical basis for the development of extrusion, rolling, torsion, fatigue and thermal applications. Study of hot deformation characteristics can also improve the microstructure, microstructural evolution, and mechanical and physical properties of metallic materials and can improve understanding of the hardening and softening behaviors and stress response of materials during deformation.

2. Material and methods

2.1. Experimental materials

The thermo-mechanical compression tests were performed on cylindrical specimens produced from 33 mm thick, hot-rolled CLAM steel plate. The specimens were cut from the plate using wire EDM with the longitudinal axis of the cylinders perpendicular to the plate rolling direction. The specimens were 8 mm in diameter and 12 mm tall with a surface roughness of 3.2. After cutting, the specimens were polished and then washed with dilute hydrochloric acid to remove surface oxides and irregularities and therefore reduce the traction stress from friction between the specimen end surfaces and the compression test fixture. The CLAM steel microstructure prior to compression testing is shown in Fig. 1 and consists of a typical lath martensite. The CLAM steel chemical composition and mechanical properties are shown in Tables 1 and 2, respectively.

2.2. Thermo-mechanical compression tests

Thermostatic compression testing was carried out using a Fuji Electronic Industries Thermecmastor-Z thermo-mechanical simulator. Prior to testing, a thermocouple, used to monitor and control

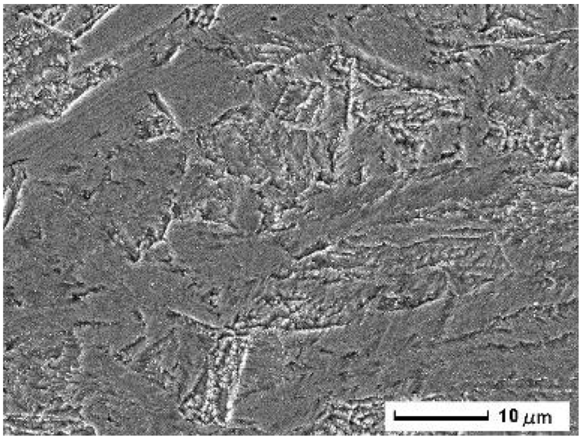

Fig. 1. Photomicrograph of CLAM steel microstructure prior to hot compressive deformation processing.