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Effects of temperature and strain rate on the tensile behaviors of SIMP steel in static lead bismuth eutectic

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HIGHLIGHTS

- The tensile behaviors of SIMP steel in LBE are investigated for the first time.
- The SIMP is susceptible to LME at different strain rates and temperatures.
- The total elongation is reduced greatly.
- The ductility trough is wider under SSRT.
- The tensile specimens rupture in brittle manner without obvious necking.

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ABSTRACT

In order to assess the susceptibility of candidate structural materials to liquid metal embrittlement, this work investigated the tensile behaviors of ferritic-martensitic steel in static lead bismuth eutectic (LBE). The tensile tests were carried out in static lead bismuth eutectic under different temperatures and strain rates. Pronounced liquid metal embrittlement phenomenon is observed between 200 °C and 450 °C. Total elongation is reduced greatly due to the liquid metal embrittlement in LBE environment. The range of ductility trough is larger under slow strain rate tensile (SSRT) test.

1. Introduction

The concept of Accelerator Driven Sub-critical (ADS) system [1–3] was proposed in 1990s to transmute the nuclear waste. The strategic objective of ADS is to transmute (burn up) long-lived minor actinide in order to reduce the amount and the radiotoxicity of high radio-toxicity level nuclear waste, and to close the fuel cycle including minor actinides [3]. In ADS, the neutrons are produced to transmute the long-lived elements into short-lived elements [4,5]. Over the sodium alloy used in sodium cooled fast reactor, the lead and lead alloy, especially the lead-bismuth eutectic (LBE), are considered as the primary candidate for coolant and/or spallation target of ADS.

Many candidate structural materials suffer from serious corrosion from LBE at elevated temperatures. However, low melting point (126 °C) of LBE enables ADS to operate in the lower temperature range than pure lead. These lower operating temperatures, in the range of 250–550 °C, may be low enough to reduce the corrosion susceptibility making it possible to use commercially available high strength, creep resistant steels [6]. In addition, the currently envisaged approach to mitigating liquid metal corrosion relies on combining lower operating temperatures with a precise control of the concentration of dissolved oxygen in the heavy liquid metal, as it has been shown that the formation of oxides scales on the steel surface minimizes the undesirable steel dissolution [7].

Apart from the corrosion issues, the challenge of liquid metal embrittlement (LME) is mostly in fulfilling preconditions. The

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phenomenon of LME is the drastic reduction in strength and ductility of original ductile solid metal in contact with special low melting point liquid metal directly [8–11].

9% Cr ferritic-martensitic steels, which are considered as the structural materials for ADS, are prone to the LME effects. The mechanical properties of steels deteriorate when stressed in liquid metal environment [12–14]. Literature [10,15] shows that the total elongation, strength, fracture energy, creep-rupture, ductility, fatigue life of structural materials are deteriorated by LBE. The elongation at room temperature after pre-exposure to LBE also degrades [16]. Some premature failure of structure material will occur without necking [17]. So, it is necessary to avoid the possible LME phenomenon for the long-term safe operation of ADS.

LME phenomenon is pronounced especially in the range of 300–550 °C according to literature [6], coinciding with the operation temperature range of experimental ADS system. The susceptibility of structural materials to LME is unacceptable for ADS long-term safe operation criterion. So, it is important to investigate the LME phenomenon in order to ensure the compatibility of structural materials with LBE.

By now, a large number of investigations on LME have been carried out. Although much experimental data is available, the mechanism of LBE embrittlement effects on martensitic steel is not yet clear [18]. The reason is that the embrittlement phenomenon is complicated. The LME phenomenon depends on many parameters [6,19], including temperature, composition, microstructure, strain rate, hardness, stress concentration and surface state. Nicaise et al. [20] considered LME as the decrease of surface energy by wetting. Others attributed it to the dynamic strain aging (DSA) or liquid metal environment assisted crack (EAC) nucleation and branching [8,21], stress assisting liquid metal to dissolve and transport solid metal atoms, complex oxidation reaction, etc. [8–11,13,22].

The aim of this experiment is to assess the susceptibility of SIMP steel to LME in a range of simulated operating conditions. The tensile behaviors of SIMP steel in static LBE are investigated at different temperatures. The total elongation as a function of temperature was measured to find the ductility trough. The LME likely occurs under slow strain rate tensile (SSRT) conditions [18,19,23,24]. Long et al. [25] reported that the T91 steel tempered at low temperature demonstrated more pronounced susceptibility at SSRT. So, the tensile tests were performed under different strain rates to investigate the possible LME phenomenon.

Previous studies [5,19] show that ferritic-martensitic steels are more prone to LME than austenitic steel 316L. The elongation degrades greatly when tensile tests were carried out at the temperature interval of 300–550 °C, i.e., the ductility trough [6,19,24]. The candidate ADS structural materials, such as T91, will serve in irradiation environment and be subject to irradiative damages, such as swelling, creep, hardening and embrittlement. Previous tests [23,26] show that after irradiation or tempering at low temperatures, the steels with higher hardness are more susceptibility to LME.

A previous study used T91 tempered at low temperatures and mentioned the difficulties in handling radioactive materials and the lack of irradiated specimens [25]. Literature [20,25,27] shows that T91 is sensitive to LME phenomenon after tempering at 500 °C in LBE and lead. In this experiment, SIMP steel was tempered at 500 °C to obtain high hardness. It is possible for SIMP steel to be more prone to LME phenomenon than T91 because of the higher carbon and other alloying element contents.

Table 1
Chemical composition of the experimental SIMP steel (wt%).

C	Cr	W	Mn	Si	V	Nb	Ta
0.2	10.7	1.2	0.5	1.4	0.2	0.01	0.1

2. Experimental procedure

2.1. Materials and specimens

The steel employed in this research is the newly developed SIMP steel. The chemical composition of the experimental steel is shown in Table 1. The SIMP steel was normalized at 1050 °C for 30 min, and then tempered at 500 °C for 90 min.

The original microstructure of SIMP steel is the tempered martensite. The average size of primary austenite grains is approximately 20 μm. The lath microstructure of the SIMP steel is shown in Fig. 1. Ref. [28] gives a detailed analysis of carbide precipitation in this type of steels.

The cylindrical tensile specimens with gauge length of 25 mm and diameter of 4 mm were machined. The dimension of the tensile specimens is shown in Fig. 2. The native oxide film on the gauge of the tensile specimens was removed by grinding using abrasive paper of 2000 # prior to tensile tests. The purpose of removing the

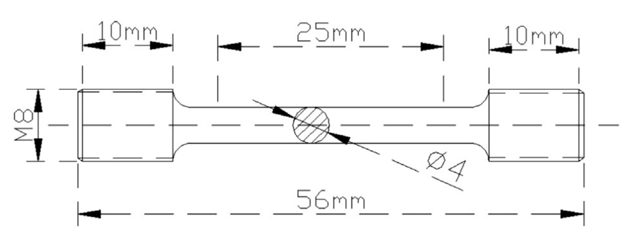

Fig. 2. Specimen for tensile tests.

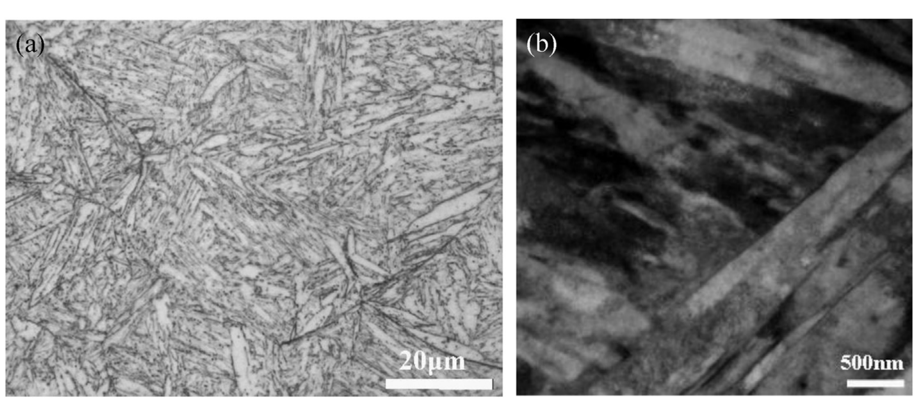

Fig. 1. Microstructure of SIMP. (a) Optical; (b) TEM.