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High temperature tensile deformation behavior of Grade 92 steel

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HIGHLIGHTS

- This study reports the results of the high temperature tensile deformation tests of Grade 92 steel.
- The study analyzed the tensile data obtained at different temperatures and strain rates.
- Elevated temperature tensile flow mechanism explained with the threshold stress approach.

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ABSTRACT

Candidate structural materials for advanced reactors need to have superior high temperature strength and creep-rupture properties among other characteristics. The ferritic–martensitic Grade 92 steel (Fe–9Cr–2W–0.5Mo, wt.%) is considered such a candidate structural material. Tensile tests were performed at temperatures of 600, 650 and 700 °C in the strain rate range of 10^{-5}–10^{-3} s^{-1}. After analyzing the tensile results using the Bird–Mukherjee–Dorn (BMD) equation, a stress exponent of about 9.5 and an activation energy of about 646 kJ/mol were obtained. In the light of high values of the stress exponent and activation energy, the threshold stress concept was used to elucidate the operating high temperature deformation mechanism. As a result of this modification, the true activation energy and stress exponent of the high temperature deformation in Grade 92 steel were found to be about 245 kJ/mol and 5, respectively. Thus, the dominant high temperature deformation mechanism was identified as the high temperature climb of edge dislocations and the appropriate constitutive equation was developed.

1. Introduction

Gen-IV nuclear reactors are designed to operate at higher temperatures and for longer time periods [1]. Hence, the candidate structural materials for such applications are required to have properties that enable them to perform satisfactorily under harsh reactor conditions [2]. There are many ferritic–martensitic (F–M) steels such as Grade 91, Grade 92 and HT9, which have attracted considerable interest. Interestingly, the development of these alloys was first spearheaded for their use in the structural applications of fossil-fuel-fired power plants.

Grade 92 steel is considered a modified version of the Grade 91 steel [3]. The nominal chemical composition of this steel is Fe–9Cr–0.5Mo–1.8W–VNb (in wt.%), and is similar in composition to NF616 steel [4]. Grade 92 steel is a promising F–M steel. This steel, in general, possesses excellent properties [3–5]. For instance, it has high creep and tensile strength, low thermal expansion coefficient and high thermal conductivity [5,6]. The following microstructural features exert influence on the high temperature deformation properties of these materials: fine, uniformly dispersed carbides and/or carbonitrides which pin the grain boundaries and lead to the obstruction of the dislocation movement [7]; the dislocation density within the martensitic laths (characterized by the narrow mesh of substructures); and solid solution strengthening of the matrix by elements such as W and other alloying elements [3–7]. In Grade 92 steel, the fine/stable carbides and carbonitrides are formed due to the presence of strong carbide/carbonitride formers like Nb and V [4–6].

The mechanical properties of F–M steels such as Grade 92 have been investigated for better understanding of its applicability [1,4,8–21]. However, more attention was devoted to understanding the creep properties of these alloys rather than the tensile flow properties. This explains the lack of published literature on the flow properties of Grade 92 steel and elucidation of the high

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Table 1
The chemical composition of the as received Grade 92 steel.

Element	Composition (wt.%)
C	0.09
Mn	0.42
Si	0.34
P	0.015
S	0.001
Cr	8.68
Mo	0.55
V	0.19
N	0.045
Ni	0.12
Al	0.02
Nb	0.079
W	1.66
B	0.003
Fe	Bal.

temperature deformation mechanisms [8–11]. Hence, the focus of the present study was on understanding the high temperature tensile deformation behavior of Grade 92 steel. In this work, the tensile flow behavior of Grade 92 steel is analyzed at different temperatures (600–700 °C) and strain rates (10^{-5} to $10^{-3}\,s^{-1}$). Furthermore, the dominant high temperature deformation mechanism was identified using the Bird–Mukherjee–Dorn equation with the help of threshold stress compensation.

2. Experimental procedure

The Grade 92 steel used in this study was procured from the Tianjin Tiangang Weiye Steel Co., China. The steel was received in the form of cylindrical bars with a diameter of 14 mm. The as-received alloy was in F92 condition in accordance with the ASTM A182 standard. According to the standard, the material was normalized at a temperature between 1040 and 1080 °C. Then, tempering was conducted at a temperature between 730 and 800 °C. The nominal composition of the as received alloy is included in Table 1.

The tensile specimens were prepared with a gage length of 25.4 mm and a gage diameter of 6.4 mm. An Instron universal tester (model No. 5982) was used to carry out the tensile tests. The test temperatures were maintained within ±3 °C of the set point in a three-zone furnace (model No. SF-16 2230) and the soaking time was kept at 50 min.

Standard metallographic procedures were followed in this work to reveal the relevant microstructure. After grinding, polishing was performed down to 3, 1 and 0.5 μm finish using water-based polycrystalline diamond suspensions. Afterwards, etching was completed using the Marble etchant consisting of 50 ml hydrochloric acid, 10 g of copper sulfate and 50 ml of distilled water. Next, an OLYMPUS PMG3 optical microscope was employed for examining the microstructure of the Grade 92 steel.

TEM samples (disks with 3 mm diameter) were punched out from 60 μm thick foils and subsequently jet polished using a Fischione twin-jet polisher. Jet polishing was conducted in a low temperature environment using a dry ice bath (around −40 °C) using a solution of 20 vol.% nitric acid and 80 vol.% methanol. Finally, TEM imaging was conducted using a JEOL JEM-2010 TEM microscope operated at an accelerating voltage of 200 kV.

3. Results and discussion

3.1. Microstructural characteristics

The microstructure of the as-received Grade 92 steel shows a normalized/tempered martensitic microstructure as shown in Fig. 1. Fig. 1a shows an optical micrograph of the overall tempered martensitic structure of the as received alloy. The lath microstructure of the Grade 92 alloy is evident in the TEM image presented in Fig. 1b. During tempering, particles such as the chromium-rich precipitates ($M_{23}C_6$) precipitated on the prior austenite grain boundaries (PAGB), lath boundaries and within the lath microstructure [3,12]. Other precipitates were also reported in Grade 92 steel such as the fine-MX precipitates. The stability of these strengthening precipitates at high temperatures was found to be instrumental in enhancing the elevated temperature creep strength in Grade 92 steel [12,13].

3.2. Tensile properties of Grade 92 steel at elevated temperatures

Fig. 2 shows a representative engineering stress–strain curve for the as-received Grade 92 steel at room temperature and a strain rate of $10^{-3}\,s^{-1}$. The yield strength (YS) and ultimate tensile strength (UTS) were estimated to be 1063 and 1385 MPa, respectively. The tested alloy exhibited an elongation to fracture (ductility) of about 19%.

Grade 92 steel specimens were tested at different temperatures of 600, 650 and 700 °C. For each temperature, different strain rates of 1×10^{-3}, 3×10^{-4}, 1×10^{-4}, 3×10^{-5} and $1\times10^{-5}\,s^{-1}$ were employed. The highest YS and UTS were obtained at the highest strain rate and the lowest temperature ($10^{-3}\,s^{-1}$ and 600 °C, respectively) among the test conditions. The strength of the Grade 92 steel decreased with decreasing strain rate for all test temperatures. Also, the strength dropped with increasing test temperatures. Therefore, the minimum strength was associated with the lowest strain rate and the highest temperature ($10^{-5}\,s^{-1}$ and 700 °C, respectively) as shown in Fig. 3a–c. Clearly, the strength

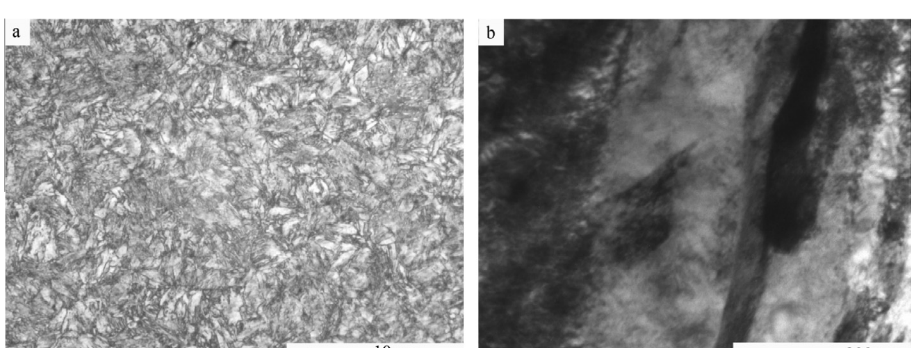

Fig. 1. The microstructure of the as-received Grade 92 steel: (a) an optical micrograph shows the normalized and tempered microstructure, and (b) a bright field TEM image showing the lath microstructure.