High-temperature Softening of ASTM Gr.92 Steel for a SFR Fuel Cladding

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1. Introduction

Ferritic/martensitic (F/M) steels are widely used as structural materials in various types of nuclear reactor facilities. The main advantages of the steels are their high resistance to void swelling, low irradiation creep rates, and relatively low radioactivation after neutron irradiation. The steels have higher thermal conductivities and lower expansion coefficients than austenite stainless steels [1,2]. Nowadays, the F/M steels are currently being considered as candidate materials for cladding and duct applications in a Gen-IV SFR fuel. Since the operation condition in the design of Gen-IV SFR would be envisioned to be harsh from the viewpoints of temperature (≥600°C) and irradiation dose (≥200 dpa) [3], the primary emphasis is on the fuel cladding materials, i.e. high-Cr F/M steels.

However, the well-known disadvantages of the F/M steels are their low long-term creep strength at high temperatures and their inclination to low-temperature irradiation embrittlement [4]. A softening behavior of the steels is also observed during tensile tests and it is characterized by low maximal homogeneous elongation compared to the fracture elongation [5]. The softening behaviors of ASTM Gr.92 steel during the uniaxial tension has been study in this study. Tensile tests have been carried out at 650°C, a typical operating temperature of cladding for the Gen-IV SFR fuel, in order to analyze the influence of the softening behaviors of the ASTM Gr.92.

2. Experimental Procedure

The ingot of ASTM Gr.92 steel, as shown in Table 1, was melted by a vacuum induction melting (VIM) method and hot-rolled to a 15mm thickness at 1150°C. After the hot-rolling, specimens were austenitized at 1050°C for 1 hour, and then were tempered at 750°C for 1 hour. All the specimens were cooled in the air at room temperature after the austenitization and tempering treatments.

Table 1 Chemical composition of ASTM Gr.92 steel in wt.%

C	Si	Mn	Ni	Cr	Mo	W
0.1	0.454	0.440	0.494	9.00	0.467	1.60
V	Nb	N	B	P	S	Fe
0.202	0.072	0.042	0.0039	0.020	0.009	Bal.

Tensile tests were performed in air at 650°C with a universal tensile test machine, which was equipped with a cylindrical furnace. Tests were conducted on smooth sheet specimens with 25.4 mm gage length, machined in parallel to the rolling direction. The test temperatures were controlled by 3 attached thermocouples along the gage length of the specimen, in order to guarantee a precious better than ±2°C. The tensile tests were carried out at 4 different strain rates such as 3.33×10^{-3} s^{-1}, 3.33×10^{-4} s^{-1}, 3.33×10^{-5} s^{-1} and 3.33×10^{-6} s^{-1}. And six tensile tests with a strain rate of 3.33×10^{-4} s^{-1} were interrupted before the fracture at different levels of strains (1%, 2%, 7.5%, 10.5%, 15% and 22%) in order to investigate the influence of mechanisms responsible for the softening behaviors at 650°C.

The microstructures and fractographs after the tensile tests were characterized by using TEM (transmission electron microscope), SEM (scanning electron microscope) and OM (optical microscope). For the interrupted specimens, the macroscopic neckings were observed by a profilometric measurement.

3. Results and Discussion

3.1 Strain rates

Fig. 1 shows the engineering stress-strain curves of ASTM Gr.92 steel for the 4 different strain rates at 650°C. At this temperature, a short work hardening step was observed, followed by a long stable softening stage. The softening stage is characterized by a drop of stress, reaching 60 MPa for a strain rate of 3.33×10^{-6} s^{-1}. A higher softening induced a change in slope and led to fracture.

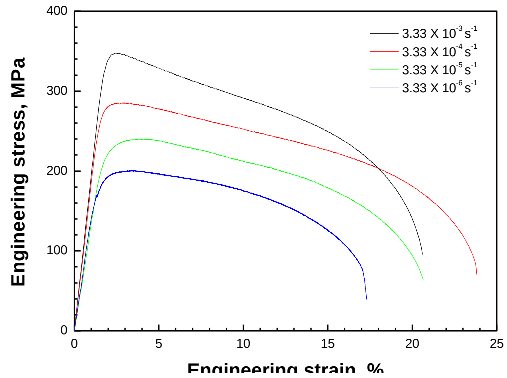

Fig. 1 Engineering stress-strain curves of ASTM Gr.92 steel at 650°C

When the strain rate decreased from 3.33x10^{-3} s^{-1} to 3.33x10^{-6} s^{-1}, the viscoplasticity of the steel caused a decrease in the tensile stress but an increase in the uniform elongation except for a 3.33x10^{-6} s^{-1}strain rate. Fracture elongation was reduced as a decrease of strain rate from 3.33x10^{-4} s^{-1} to 3.33x10^{-6} s^{-1}. And softening slope increased when the strain rate decreased.

3.2 Necking

To observe the beginning of macroscopic necking, the interrupting tensile tests before fracture were carried out for the different strain values under the 3.33x10^{-4} s^{-1} strain rate at 650°C. The engineering strain-strain curves are revealed in Fig. 2. The six curves are almost superimposed with the curve corresponding to the fractured test (0). Specimen 1, 2, 3 and 4 did not show any macroscopic mechanical instability but specimen 5 and 6 showed the macroscopic necking. To verify this result, a profilometric measurement along the gage length of the specimens showed the necking appeared clearly for specimen 5 and 6. These interrupted tests could be categorized using the different stages.

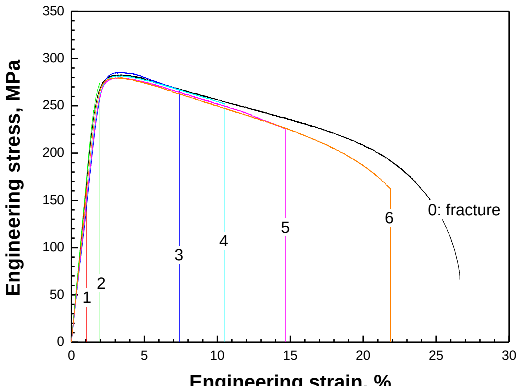

Fig. 2 Engineering stress-strain curves at 3.33x10^{-4} s^{-1} of ASTM Gr.92 steel at 650°C

The initiation of the macroscopic necking was confirmed using the hypothesis of constant volume during the plastic deformation. By neglecting elastic strains, this hypothesis leads to a linear relationship between axial and transversal strains. For specimen 1, 2, 3 and 4, their strains were homogeneous along their gage length. For specimen 5 and 6, however, the strains were not homogeneous and corresponded to the onset of macroscopic necking. The macroscopic neckings were observed at a much higher elongation than the uniform elongation point. Although the mechanical instability of the steel was started from the uniform elongation point, no strain inhomogeneity was detected at the strain region less than 10.5 %.

4. Conclusions

A series of tensile tests at different strain rates and strains were carried out at 650°C on ASTM Gr.92. From this study, the existence of a softening stage was verified as a typical characteristic of the steel at high temperature. The first softening stage was observed after the maximal homogeneous elongation, characterized by a constant decreasing load, which depends on the strain rate.

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