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Influence of Sc addition on tensile, creep and impact properties of RAFM steel

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1. Introduction

Research programs for the development of low activation materials began in the mid-1980s. This is based on the US Nuclear Regulatory Commission Guidelines (10CFR part 61) developed to reduce long-lived radioactive isotopes, which allows nuclear reactor waste to be disposed of by shallow land burial when removed from service. The development of reduced-activation materials is also a key issue in nuclear fusion systems, as the structural components can became radioactive due to a nuclear transmutation caused by exposure to high-energy neutron irradiation. Reduced-activation ferritic-martensitic (RAFM) steel has been developed in leading countries for nuclear fusion technology [1], and is now being considered as a primary candidate material for the test blanket module (TBM) in the international thermonuclear experiment reactor (ITER).

The mechanical properties of RAFM steel are strongly affected by alloying elements. Increase of W or Ta contents, for example, is known to enhance the strength of RAFM steel, but has a detrimental effects on impact resistance and ductility [2,3]. The latter is assumed to be caused by formation of W or Ta-base carbides which are brittle in nature. As an effort to develop new RAFM steel for helium-cooled ceramic reflector (HCCR) TBM applications, we have designed RAFM steels with various alloy compositions and evaluated their mechanical properties. In the alloy design, we includes scandium (Sc), which is soluble in Fe matrix up to 0.06 wt.% and also induces relatively short-lived transmutation nuclides, expecting that addition of small amounts of Sc leads to solid-solution hardening with forming undesirable precipitates. The present paper reports the influence of Sc addition on mechanical properties of RAFM steel.

2. Methods and Results

2.1 Experimental procedures

A total of seventy-three alloys in three different batches were designed, where the amounts of alloying elements vary systematically in (8~10)Cr-based RAFM steel. Rectangular-shaped ingots were produced by a vacuum induction melting (VIM) method, and were hot rolled at 1150°C to 16 mm-thick plates. The hot-rolled plates were normalized at either 1050°C or 980°C, and then tempered at 760°C for various time durations.

Plate-type sub-size tensile specimens with a gage dimension of 2.5 mm in thickness, 6.25 mm in width and 25 mm in length (ASTM E8) were machined from the tempered plates, and an uniaxial tensile test was performed at 25°C at an initial strain rate of 10^{-3} s^{-1}. A creep rupture test was conducted at 550 °C under an applied stress of 240 MPa, using a rod-type specimen with a gage dimension of 6 mm in diameter and 28 mm in length. A ductile-brittle transition temperature (DBTT) of the tempered plates was determined by a Charpy impact test, for which a full-size notched bar was used according to the ASTM E23.

2.2 Results and Discussion

The yield strength (YS) and total elongation (TE) of the program alloys determined at room temperature are shown in Fig. 1.

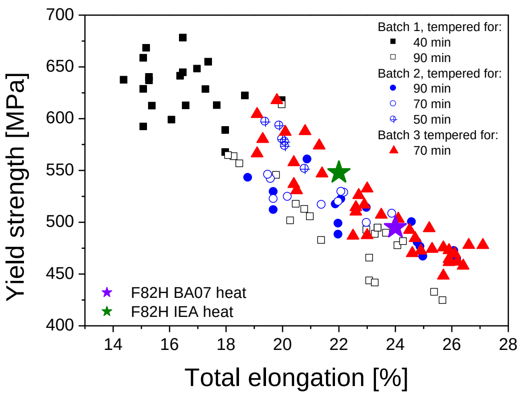

Fig. 1. The room-temperature tensile properties of seventy-three RAFM steels investigated in the current study.

The YS and TE exhibit a clear trade-off, which is mainly due to the extents of tempering but is partly due to effects of alloying elements. The program alloys in the batch 1 tempered at 760°C for either 40 min. or 90 min. show a wide range of the YS-TE properties: the alloys tempered for 40 min. show high strength and low ductility, while lower strength and high ductility are observed for those for 90 min. The program alloys in batch 2, which were tempered for 50 min., 70 min. or 90 min. exhibit relatively narrow distribution in the YS-TE space. Alloys in batch 3 tempered only for 70 min. still show a broad range of the YS-TE properties, which is mainly caused by addition of Sc.

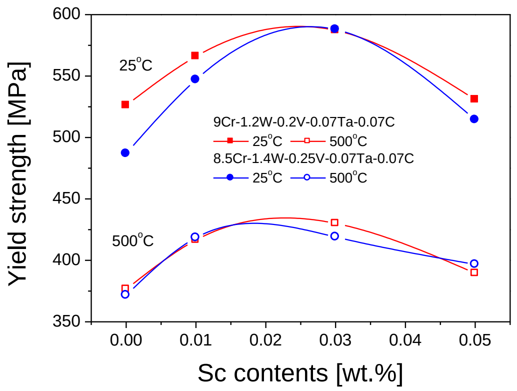

Fig. 2. Effects of Sc addition on the yield strengths of the program alloys at 25°C and 500°C.

Shown in Fig. 2 are the effects of Sc addition on the yield strength of 9Cr-1.2W-0.2V-0.07Ta-0.07C and 8.5Cr-1.4W-0.25V-0.07Ta-0.07C alloys. It is clear in both alloy systems that increase of Sc contents up to 0.03 wt.% enhances the yield strength at both 25°C and 500°C: the amounts of increase in the yield strength are 60~100 MPa and 50~55 MPa at 25°C and 500°C, respectively. However, further increase of Sc content to 0.05 wt.% reduces the strength at both temperatures.

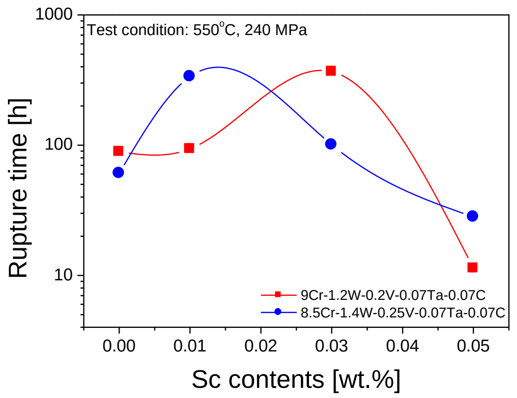

Fig. 3. Effects of Sc addition on the creep-rupture time of the program alloys.

Addition of Sc also improves creep resistance of RAFM steel. The creep-rupture times of the program alloys under 240 MPa at 550°C are plotted against Sc contents in Fig. 3. The creep-rupture time is increased with increasing Sc contents up to 0.01wt.% or 0.03 wt. depending on the alloy systems: the creep-rupture time is increased by ~4 times with an addition of 0.03 wt.% Sc for the 9Cr-1.2W-0.2V-0.07Ta-0.07C alloy system, and is by ~5 times with an addition of 0.01 wt.% Sc for the 8.5Cr-1.4W-0.25V-0.07Ta-0.07C alloy system. With further increase of Sc contents, however, reduces the creep-rupture time significantly, similarly to the trend observed in the tensile tests (Fig. 2).

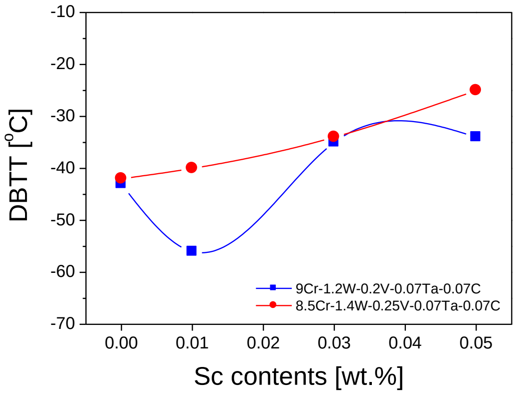

Fig. 4. Effects of Sc addition on the DBTT of the program alloys.

Charpy impact tests reveals that the DBTT of the model alloys are slightly increased with Sc contents. As shown in Fig. 4, Sc-free alloys show DBTT around -42°C and addition of 0.05 wt.%Sc increases the DBTT to -25°C and -34°C for 9Cr-1.2W-0.2V-0.07Ta-0.07C and 8.5Cr-1.4W-0.25V-0.07Ta-0.07C alloy systems, respectively. However, addition of 0.01 wt.% Sc results in a negligible increase or a slight decrease of the DBTT of model alloys.

3. Conclusions

Effects of Sc addition on the mechanical properties of RAFM model alloys were examined, and it is found that addition of 0.01~0.03 wt.% Sc generally enhances the strength and creep resistance of of RAFM model alloys without a significant sacrifice in impact resistance. This suggests a potential of Sc as an alloying element in RAFM steel.

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