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Influence of non-metal inclusions on mechanical properties of CLAM steel

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ABSTRACT

The effect of the size and distribution of non-metal inclusions on mechanical properties of the China low activation martensitic steel (CLAM) was investigated. The tensile and Charpy V-notch impact tests showed that electroslag remelting improved the tensile properties and reduced the ductile brittle transition temperature (DBTT). Inclusion detection of CLAM by optical microscopy and scanning electron microscope showed that both the dimensions and quantities of the alumina inclusions decreased and their distributions became more uniform after remelting. The better refinement and distribution uniformity of alumina inclusions were considered as the main possible reasons for the improvement of the mechanical properties of CLAM steel after remelting.

1. Introduction

With good irradiation swelling resistance, thermo-physical and thermo-mechanical properties, the reduced activation ferritic/martensitic steels (RAFMs) have been considered as the primary candidate structural materials for application in fusion systems [1]. Researchers in Japan, Europe, USA and Russia are actively doing research on the RAFMs including the development of JLF-1 and F82H alloy, EUROFER97 alloy, ORNL 9Cr2WVTa alloy and RUSFER-EK-181 alloy in the past 30 years and some great achievements have been made [2].

The China low activation martensitic steel (CLAM) based on the nominal compositions of 9Cr–1.5W–0.2V–0.15Ta is being developed in the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) under wide collaboration with many other institutes and universities in domestic and overseas [3,4]. The elements Nb and Mo which can cause long term activation under neutron irradiation are replaced by W, V and Ta compared to the common martensitic steels. The Ta content is set to 0.15% to improve the properties at high temperature. The impurity elements, such as O, N, S and Nb, etc., are reduced to a level as low as possible. The R&D activities mainly cover composition design, smelting of the steel, impurity control, property test, welding techniques, e.g. hot isostatic pressing (HIP) joining, tritium permeation barrier coating, compatibility study with liquid metal LiPb, irradiation experiments and activation analysis, etc. [5–8]. Current tests results show that CLAM steel has good properties and it has been considered as the primary candidate structural material for the FDS series liquid metal LiPb blanket designs [9–12].

Non-metallic inclusions in steel normally have a negative contribution to the mechanical properties of steel, since they can initiate ductile and brittle facture. Among various types of non-metallic inclusions, oxide, and sulphide inclusions have been thought to be harmful for common steels [13]. In this paper, the effect of non-metallic inclusions on tensile and impact properties of CLAM steel was investigated.

2. Experimental procedure

The CLAM steel (HEAT 0603A) was melted in a vacuum induction smelting furnace. In order to study the influence of non-metal inclusions on mechanical properties, 40 kg HEAT 0603A were remelted by electro-slag remelting (ESR) process at argon atmosphere named as HEAT 0603B. Their chemical compositions are shown in Table 1. Both heats were hot-forged at 1423 K and then rolled into 12 mm thick plate. The heat treatment was quenching at 980 °C for 30 min and then cooled by air or water and tempering at 760 °C for 90 min and then cooled by air.

The microstructure of CLAM steel after the heat treatment consists of a mixture of lath–martensite phase and well-tempered martensite phase, and there was no δ ferrite [6]. For determining whether there was remaining austenite, the X-ray diffraction (XRD) examination for HEAT 0603A was carried out.

The specimens taken from the 12 mm plate in parallel with rolling direction were used for tensile tests under temperatures ranging from room temperature (RT) to 873 K. Round-bar tensile specimens with gauge of Φ5 mm × 25 mm for HEAT 0603A and Φ4 mm × 20 mm for HEAT 0603B were tested, according to ISO

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Table 1
Chemical compositions of HEATs 0603A and 0603B in wt%.

	Cr	W	C	Mn	V	Ta	O	N	P	S	Al	Fe
HEAT 0603A	9.23	1.37	0.15	0.43	0.20	0.15	0.0017	0.00585	0.0032	0.0042	0.027	Bal.
HEAT 0603B	9.09	1.39	0.155	0.38	0.185	0.046	0.00685	0.00638	0.0030	0.00274	0.0035	Bal.

783:1989 "Metallic materials-Tensile testing at elevated temperature". The 0.2% proof strength was measured as yield strength.

The specimens fabricated from the 12 mm plate were used for the Charpy impact tests. Full size V-notched Charpy specimens (10 mm × 10 mm × 55 mm, V-notch: 45° × 2 mm (depth) × 0.25 mm (root radius)) were machined in parallel (*L*) and perpendicular (*T*) to the plate rolling direction. Specimens were tested at temperatures ranging from 81 K to 313 K to obtain a ductile–brittle transition behavior by with a pendulum type impact tester, according to ISO 148:1983 "Metallic materials-Charpy".

The average grain size estimation and non-metallic inclusion analysis were carried out by scanning electron microscopy (SEM) and optical microscopy (OM) observations. The distribution of precipitates was observed in SEM to determine the prior austenite grain size after etching in an alcohol solution of picric acid and muriatic acid. The samples for average grain size estimation were etched using a solution of HNO_3–C_2H_5OH.

3. Results and analysis

3.1. Tensile properties

The tensile specimens were tested from RT to 873 K. The results are shown in Fig. 1. It can be seen that the yield strength (YS) of HEAT 0603B is higher than that of HEAT 0603A, and the ultimate tensile strength (UTS) of HEAT 0603A is similar to HEAT 0603B at all tested temperatures. For HEAT 0603A, the UTS is 700 MPa and the YS is 560 MPa at RT, while they are 365 MPa and 278 MPa at 873 K, respectively. The differences in UTS and YS for HEATs 0603A and 0603B are 20 MPa and 20 MPa at RT, and 10 MPa and 50 MPa at 873 K, respectively. At RT, the UTS of HEAT 0603B is higher than that of HEAT 0603B by 20 MPa; when the temperature is up to 573 K, the UTS shows no difference; and at 873 K, the UTS of HEAT 0603A is higher than that of HEAT 0603B by 10 MPa. The total elongation of HEAT 0603B is about 2% higher than that of HEAT 0603A at all tested temperatures.

3.2. Impact properties

The impact properties of both heats are shown in Fig. 2. The tests were performed in the temperatures ranging from 81 K to 313 K.

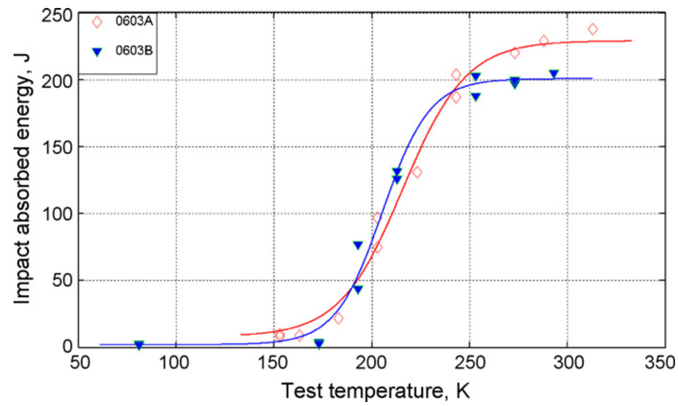

Fig. 2. Charpy impact absorbed energy vs. temperature for HEATs 0603A and 0603B.

Charpy data were fitted with a hyperbolic tangent function to obtain the transition temperature. The ductile brittle transition temperature (DBTT) used here was the temperature corresponding to half of the upper-shelf energy (USE) and lower-shelf energy (LSE) [14]. From Fig. 2, the DBTT of HEAT 0603A is about 215 K, which is 10 K higher than that of HEAT 0603B. The USE and LSE of HEAT 0603A are larger than that of HEAT 0603B. For the HEAT 0603A, the USE is 229 J and the LSE is 8 J. The differences in USE and LSE for HEATs 0603A and 0603B are 29 J and 6 J, respectively.

3.3. Microstructure observation

Fig. 3 shows the XRD diagram for the 12 mm HEAT 0603A plate. There was only a single phase in the CLAM steel after heat treatment. It can be concluded that the microstructure of the CLAM steel after the heat treatment is full martensite phase.

The SEM observations of the HEATs 0603A and 0603B are shown in Fig. 4. In these images, since the precipitates exhibit a strong bright contrast, the prior austenitic grain boundaries can be seen. The prior austenite grain size of HEAT 0603A is smaller than that of HEAT 0603B. The precipitates are mainly $M_{23}C_6$ type carbides with the similar dimensions and quantities for two heats.

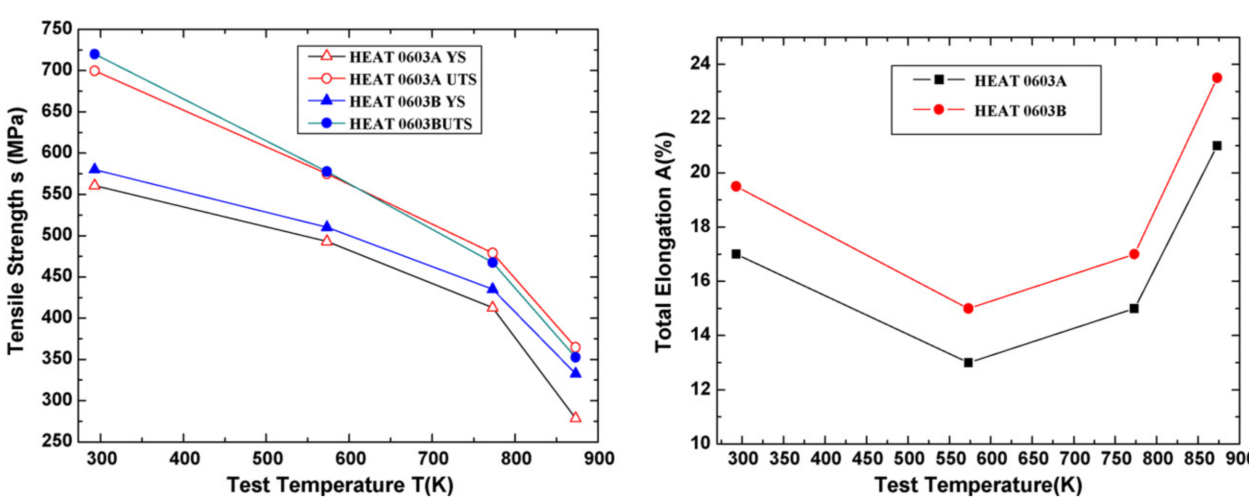

Fig. 1. The UTS, YS and total elongation of HEATs 0603A and 0603B.