Journal of Nuclear Materials 386–388 (2009) 931–934

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Nitrogen segregation and blister formation of 316LN austenitic steel during electron beam welding tests for ITER gravity supports

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ABSTRACT

316LN has been widely applied in the design of ITER components, such as shield blanket and gravity supports, due to its excellent corrosion resistance and high strength. The behavior of nitrogen in this steel during welding is important for the mechanical properties of the components. In this study, a focused 150 kv high voltage electron beam with 300 mA beam current has been used to weld 316LN steel under vacuum condition. The microstructure and composition of the welding area were observed and analyzed. The influence of welding on the shock resistance and tensile strength at both room temperature and low temperature were examined. It was found that the mechanical properties are strongly related to the defects formed in the welding process.

1. Introduction

316LN austenitic stainless steel has been widely applied in nuclear fusion devices, such as ITER [1], EAST and KASTAR [2], and chemical reactors, due to its excellent corrosion and fatigue resistance, high strength and low creep rate [3,4]. In ITER, the use of this material for most of the structural components, including vacuum vessel, shied blanket, cooling pipes and magnet supports system is being considered. The gravity supports are one of the key components to support the toroidal field (TF) coils of ITER. These components endure several large forces, such as dead weight (more than 100 MN), electromagnetic forces (normal operation, disruptions and vertical displacement events (VDE), thermal load (cooling of the coils from room temperature to 4 K) and seismic loads (in accident). Therefore, high strength of the support material is required. 316LN with high nitrogen content (preferably 0.12–0.22 wt%) has been recommended as one of the candidate steels for the support system [5], since the strength of 316LN increases with nitrogen content [6]. Based on the ITER design report, the maximum displacement of the TF coils is estimated up to 32 mm in radial direction during cool down, as shown in Fig. 1. In order to satisfy this requirement, each supports has been designed with 21 flexible plates welded to its upper and lower flanges, which makes displacement along the radial direction possible. Based on the structure analysis, the bending stress is very high in the flexible plate-flange junction zone. Therefore, welding technology plays a key role in manufacturing the support, especially for the structure safety. Needless to say, for welding the 316LN flexible plates to the two ends flanges, tungsten inert gas (TIG) welding would cause huge deformation due to large heat affects zones (HAZ), whereas laser beam could be focused to a small area, but welding depth would be limited [7]. Electron beam welding is the best choice for this structure, because it can not only be focused to a very small area, so that the deformation can be controlled to very small level, but also weld thick components. On the other hand, it is still suspected that the behavior of nitrogen, especially for high nitrogen content 316LN, may affect the welding property. Some research results show that the nitrogen can segregate or even react with other elements, such as chromium, and form a brittle phase [8]. Meanwhile, the formation of defects such as nitrogen gas voids may seriously affect the mechanical property of the components. The mechanism of nitrates precipitation has been investigated [9]. However, from the structure safety point of view, there is still a lack of data on 316LN components welding, which is essential for ITER construction, since all the supports will be operated under complex load conditions, including not only the dead weight, but also electromagnetic force and thermal loading.

In this report, the microstructure of electron beam welded 316LN and its effect on mechanical properties have been investigated.

2. Experimental

Thirty millimeters thick type 316LN austenitic stainless steel plate, with the composition shown in Table 1, was used for the present experiment. The plates was cut into 100 × 100 mm squares that, after polishing, ultrasonic cleaning and drying, where put into the vacuum chamber (generally at 10^{-3} Pa) for electron beam welding, as shown in Fig. 2. The electron beam energy is

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doi:10.1016/j.jnucmat.2008.12.242

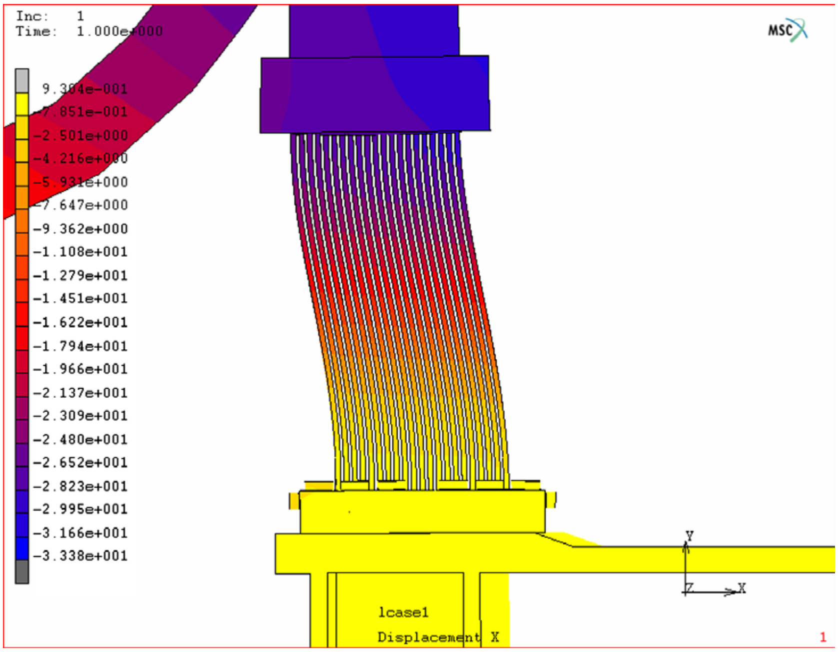

Fig. 1. Displacement of the TF support by FEM analysis during TF coil cool down from room temperature to 4 K.

Table 1
Composition of 316LN material.

Element	wt%
C	0.03
Mn	1.6
Si	0.5
P	0.022
S	0.011
Cr	17.3
Ni	12.3
Mo	2.3
Nb	0.01
Cu	0.15
Co	0.045
N	0.17
Ti	0.11
Ta	0.01
B	0.002

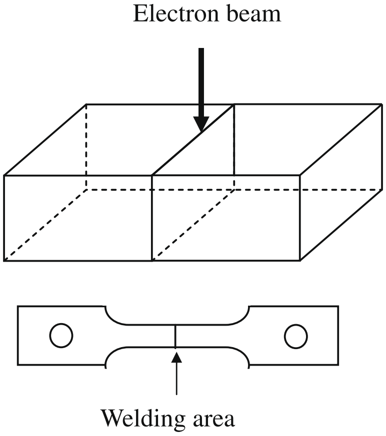

Fig. 2. Schematic illustration of the EB welding of the 316LN sample and the tensile test specimen.

150 kev, and the current can be adjusted from 150 to 300 mA, depending on the welding speed. After welding, the sample was cut, to check the welding result. Specimens for hardness testing were well polished, then a HVS-1000 digital microhardness tester was used to measure the hardness at the welding surface, 1/4 welding depth, 1/2 welding depth and at the rear-side. All the values are the average of 5 specimens. Tensile strength specimens from 1/2 depth of welding area were tested with a WDW-B50 multifunction material tester. During the low temperature strength measurement, the specimens were put into the liquid nitrogen cooled chamber for 30 min to keep the temperature uniform. Specimens for microstructure observation were well polished and acid treated on the surface. Optical spectrometer and scanning electron microscopy (SEM) were used to observe the phase condition and microstructure. Shock resistance was measured by Charpy work to test the resistance from 77 K to room temperature.

3. Results and discussion

The cross-section of the welded sample is shown in Fig. 3. No obvious welding boundary could be seen (Fig. 3(A)). After treatment by acid solution, a zone about 5 mm wide along the electron beam welding path could be seen, indicating that the HAZ area is around 2–3 mm on each side of weld. Optical microscopy observation shows that the grains become coarse in the welding area (Fig. 3(B)). Further observation by SEM, shows that micrometer level voids appeared in the 1/2 depth welding area, in contrast to no obvious defects in the base material, as shown in Fig. 3(C). For the surface area (Fig. 3(D)), the voids and defects are obviously fewer than in the deep area. Because all of the welding experiment is performed in vacuum condition, the possibility of gas bubbles from the environment during re-solidification of the material is very low. On the other hand, there is a high possibility that these voids or defects came from nitrogen segregation and migration from the matrix material in the electron beam melting (heating), re-solidification (cooling) process. Generally, it is easy to pump out the gas bubbles at the surface during welding. On the contrary, because the re-solidification rate is high at the surface during cooling down, nitrogen bubbles segregated from the base material may be trapped in the inner area and difficult to pump out, so that voids form in this area after complete cooling down. However, if the content of nitrogen

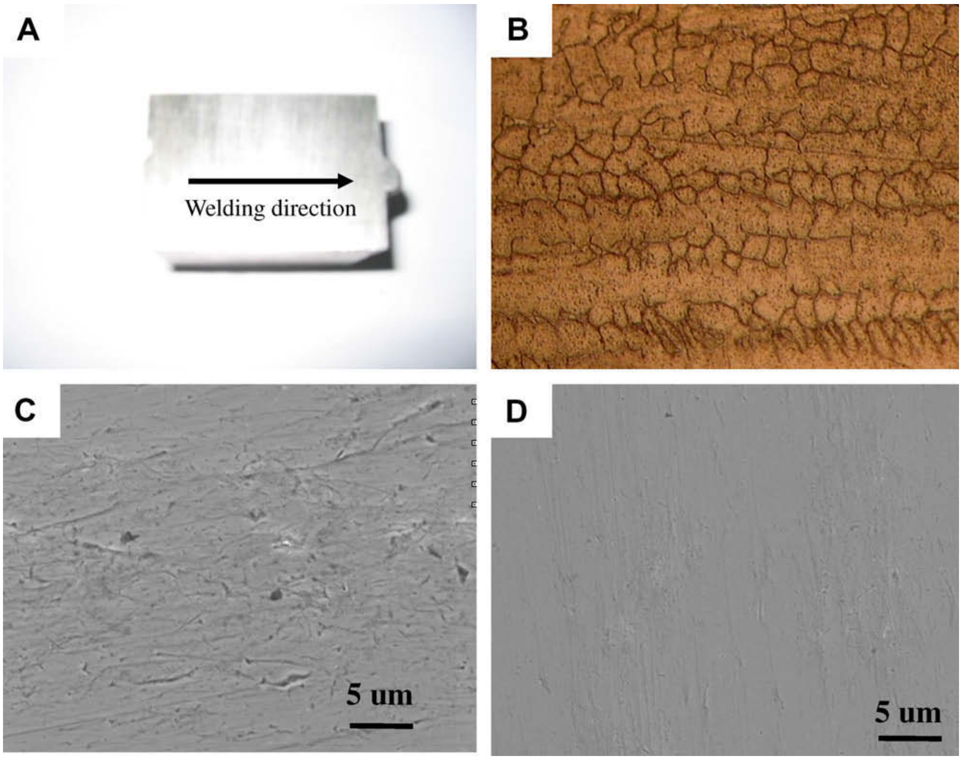

Fig. 3. Photographs of the welded specimens. (A) Cross-section along welding path; (B) optical microscopy observation; (C), SEM observation of 1/2 depth and (D) surface area along welded path.

in the steel is low enough, no obvious voids or defects can be seen [10,11], which confirms again that the voids is due to nitrogen segregation.

Fig. 4 shows the hardness of the welded sample across the welding area. The average hardness is reduced by about 20% in the welded area due to the defects and the reduction of the nitrogen solution in the matrix. In the 1/2 depth area, the average hardness is much lower than that of the surface area, which correspond to the relatively high density of voids and defects as shown in Fig. 3(C), hence, the hardness decreased. It seems that the HAZ area in the welding surface area is much wider than that observed in the inside area and rear-side. This can be explained by the heat distribution in the material during welding. The same phenomena has been observed by Onozuka et al. [10].

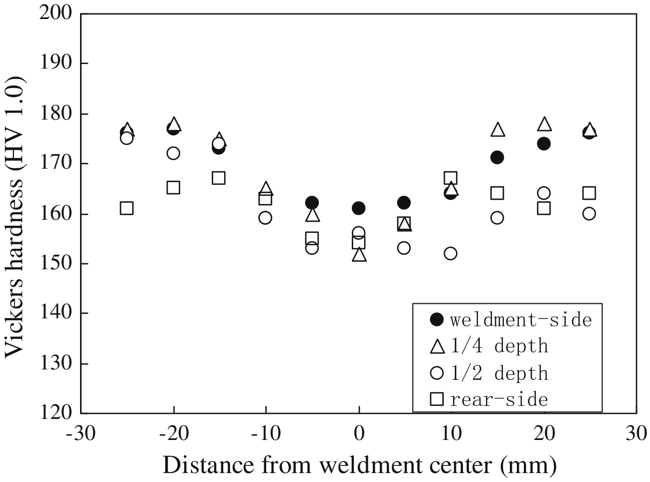

Fig. 4. Vickers hardness of the welded samples.

Fig. 5 shows the load-displacement curves of the welded samples under tension. Under the same condition, the welded samples show the same characteristic as the base material, however, the ultimate strength is quite different. For all the welded specimens, the average tensile strength was about 520 MPa, while that of the base material was 600 MPa, as shown in Fig. 6, a decrease of about 13% of the strength. During test at 77 K, the ultimate strength for specimens and base material were 1100 MPa and 1330 MPa, respectively, a decrease of about 17%. It is well known that the content of nitrogen plays an important role in the strength of 316LN material, especially at lower temperature. After welding,

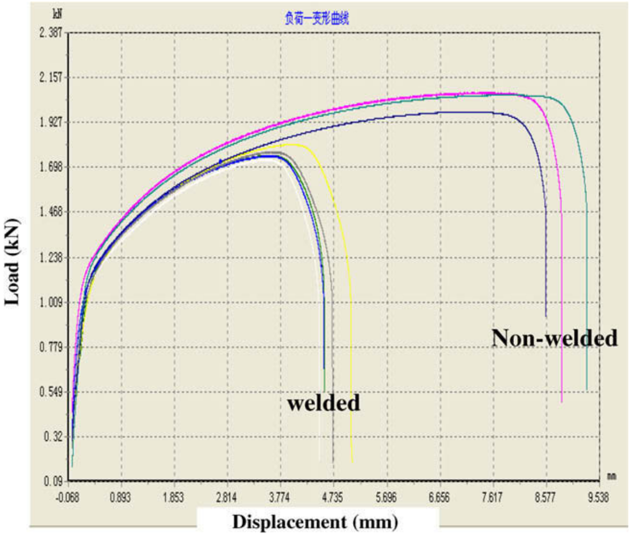

Fig. 5. Load–displacement curves of welded and non-welded 316LN samples tested at room temperature.

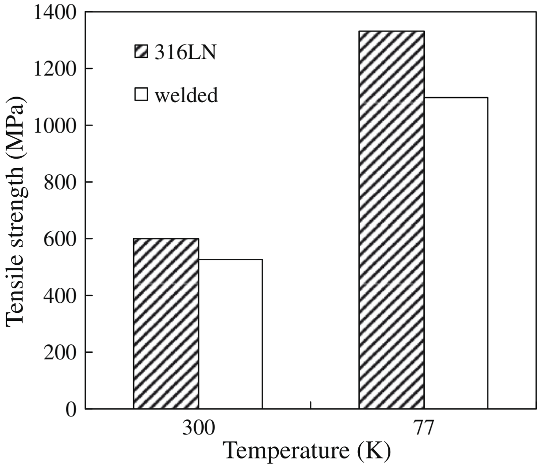

Fig. 6. Ultimate strength of welded and non-welded specimen tested at 77 and 300 K.

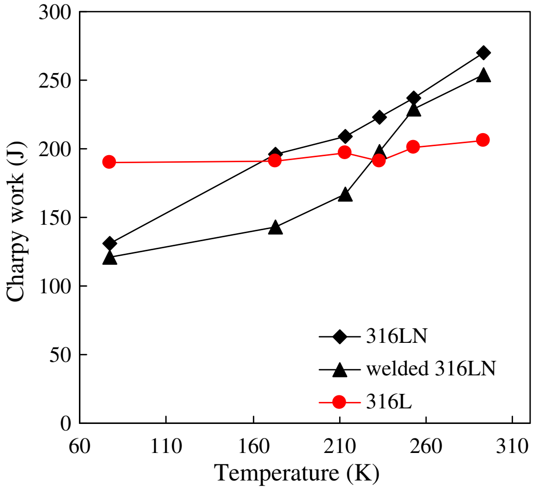

Fig. 7. Charpy work of samples from 77 K to 300 K.

the nitrogen segregates to form voids and nitrates precipitation forms a new phase more or less in the welding area, which may cause strength reduction. Thus, nitrogen segregation combined with defects formation in the welding area should contribute to the strength reduction of 316LN material. It is well known that the higher the nitrogen content, the higher the strength of 316LN austenitic stainless steel. On the other hand, in higher nitrogen 316LN, nitrogen may be segregated much more easily from base material than that in lower nitrogen 316LN when temperature is increased, i.e. by welding. Nitrogen segregation has been clearly observed in the present study. However, if the nitrogen content is low enough, i.e. 0.06–0.08 wt% [11], no such phenomena could be seen. Therefore, an optimum nitrogen content between 0.1 and 0.2 wt% exist, in which the strength is acceptable but there is no obvious nitrogen segregation, which is important for welding. Details of this need further experimental investigation.

The average Charpy work of the welded 316LN is lower than that of the base material at all the examined temperature, as shown in Fig. 7. It indicates that electron beam welding could influence the toughness of the welded components.

4. Conclusions

Electron beam welding of high nitrogen content 316LN has been researched. Defects and small voids due to nitrogen segregation and migration from base material have been observed, which obviously reduced the strength and shock resistance of the material. Therefore, it is suggested that choosing relatively lower nitrogen content 316LN material would be better for gravity support manufacturing.

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