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Mechanism for welding liquation cracking in a boron containing 9% Cr martensitic stainless steel

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ABSTRACT

In the present study, welding thermal simulation was carried out on a boron containing 9% Cr martensitic stainless steel and a liquation cracking tendency was found. The steel fractured intergranularly at 1350 °C with tension strain 0.5%, and a large number of eutectic microstructures were found on the fracture surface. Constitutional liquation of large sized interdendritic Laves phase, which had already existed in as received condition, was responsible for the liquation cracking. Welding provided a non-equilibrium heating process in which the released alloy atoms such as Mo by dissolving Laves phase at rapid heating rates could not diffuse sufficiently in the matrix γ-Fe. Matrix adjacent Laves phase became enriched in Mo, and eutectic reaction occurred between Laves phase and matrix, leading to localized liquation. Liquation cracking occurred by the combination of liquid and tension strain at high temperatures. Moreover, a large number of boron atoms released by dissolving Laves phase might also contribute to the liquation cracking tendency.

1. Introduction

9% Cr martensitic stainless steels are widely used in power plants critical components [1]. Adding a trace amount of boron (about 100 ppm) can effectively enhance service temperature to 620 °C due to the delayed coarsening rate of $M_{23}C_6$ carbides by boron atoms [2,3]. Welding are commonly used in components manufacturing and repairing, and during welding microstructures in heat affected zone (HAZ) transform from as received condition into a non-equilibrium state because of rapid heating and cooling. Therefore, some negative effects are introduced to the performance of weld joints. For decades of years, many researches have put focus on microstructures evolution in HAZ during long term high temperature exposure [4,5]. However, only a limited number of investigations can be found on welding crack of martensitic stainless steels. It is well known that welding crack, especially hot crack, is a big concern in austenite stainless steels and nickel-based alloys [6–9]. Liquation crack, a kind of hot crack, often occurs in HAZ, and there are mainly two mechanisms for its formation. One is that some impurities such as S and P segregating at grain boundaries lead to liquation at relatively low temperatures, and this can be avoided by fine smelting of base metals [10]. The other one is that eutectic reactions may occur between carbides/intermetallic compounds and matrix γ-Fe [9]. Besides, incipient melting of grain boundaries at (or above) solidus temperature can also induce grain boundary liquation [11]. Once grain boundaries are wetted by liquid and tension strain is applied, liquation cracks will form. For martensitic stainless steels, one often finds positive remarks regarding the low susceptibility to liquation cracks, and this may be due to the lower alloy elements concentrations compared to austenite stainless steels and nickel-based alloys and impurities absorption by (δ-Fe) which forms at high temperature [12]. Ziewiec A [13] reported liquation cracks in a Cu containing martensitic stainless steel, and concluded that evaporated Cu from weld pool formed some eutectic microstructures with low melting point, leading to liquation cracks in HAZ. While many other studies [12,14] concluded that martensitic stainless steels have high hot cracking resistance.

The engineering background of the present study is the discovery of micro fissures in welding HAZ of COST FB2 steel, a kind of boron containing 9% Cr martensitic stainless steel developed under the frame of COST 522 program in Europe, mainly used for steam turbine rotors operated at 620 °C [15]. In this case, the weld joint was made by submerged arc welding (SAW). In order to find out the reason for the occurrence of micro fissures in HAZ, hot ductility tests were conducted. Here emphases were placed on the mechanism of micro fissures

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Table 1
Chemical compositions of COST FB2 steel (wt. %).

C	Si	Mn	Cr	Mo	Ni	V	Nb	N	B	Co	Fe
0.13	0.08	0.30	9.30	1.50	0.05	0.20	0.05	0.026	0.01	1.00	Bal.

formation in the steel, rather than on the evaluation of weldability. Conclusions obtained in the study can not only enrich welding metallurgy of 9% Cr martensitic stainless steels, but also provide guidance for improvement of quality standards of similar steels.

2. Experimental materials and procedure

The chemical compositions of COST FB2 steel are listed in Table 1. The as received steel experienced three stages of heat treatment, comprising austenization at 1100 °C for 17 h followed by oil quenching, tempering at 570 °C for 24 h and tempering at 700 °C for 24 h, both followed by air cooling.

Thermal-mechanical simulator Gleeble 3500 was employed to evaluate the hot ductility of COST FB2 steel. Three rod specimens for hot ductility tests were prepared, 10 mm in diameter and 121.5 mm in length. The tests were conducted as follows: heating the specimens to a predefined peak temperature (1150 °C, 1250 °C and 1350 °C) at a rate of 100 °C/s, in line with welding heating rate, then holding at peak temperatures for 0.5 s, meantime a displacement of 0.5 mm was applied at a rate of 1 mm/s, at last cooling down to ambient temperature at a rate of 100 °C/s. Argon atmosphere was maintained to prevent oxidation of fractured surface.

Field emission scanning electron microscope (SEM) was employed to observe fracture appearance, and the chemical compositions of microstructures on fracture surface were analyzed by EDX. During thermal-mechanical simulation, in each specimen there existed a uniform temperature zone about 10 mm in length around thermocouple. Microstructures in longitudinal sections of uniform temperature zones were observed by SEM, following mechanical polishing and electrolytic etching (5 V in oxalic acid for 10 s). In addition, a specimen for transmission electron microscope (TEM) observation was prepared by focused ion beam (FIB) to obtain crystallographic information and more accurate chemical compositions of microstructures of interest.

3. Results

3.1. Microstructure of COST FB2 steel in as received condition

Microstructure of COST FB2 steel in as received condition was characterized by optical microscope (OM) and SEM. It is obvious that in as received condition microstructure of COST FB2 steel is tempered martensite, as shown in Fig. 1. A large number of precipitates (mainly $M_{23}C_6$ type [16]) decorate prior austenite grain boundaries (PAGBs) and martensite lath boundaries, as shown in Fig. 1b.

3.2. Results of hot ductility tests and fracture appearance

In hot ductility tests, necking occurred in the two specimens experiencing peak temperatures 1150 °C and 1250 °C, and the reduction of area was 7.84% and 7.04%, respectively. While in the specimen experiencing peak temperature 1350 °C necking was not observed, implying there was a hot cracking tendency of COST FB2 steel. The fracture appearance was featured with two typical morphologies, one of which was intergranular fracture appearance (Fig. 2a) and the other one was characterized by papillae appearance (Fig. 2b). In Fig. 2a, it was evident that the grain size was about 25 μm, while in Fig. 2b grains could hardly be distinguished. It is noteworthy that papillae appearance in Fig. 2b strongly suggested liquation occurrence in this region during the hot ductility test.

In the magnified image of Fig. 2b, some network microstructures can be observed, as shown in Fig. 3a. Most of these morphologically distinguished microstructures were micron sized and located along PAGBs, as arrows indicate in Fig. 3a. EDX results in Fig. 3b show that these microstructures were enriched in Mo, Cr and V.

3.3. Microstructures in specimens experiencing different peak temperatures

On the longitudinal section of specimens experiencing peak temperature 1350 °C, some lamellar/network microstructures surrounding prior austenite grains, similar to microstructures shown in Fig. 3a, were observed, as shown in Fig. 4a. All these microstructures stretched along PAGBs and the tips in circles suggested liquid flowing at high temperatures. Based on the morphology information mentioned above, a conclusion could be obtained that the network/lamellar microstructures were eutectic reaction products at high temperatures. Note that there was only one eutectic constituent that could be observed in Fig. 4a, probably because the other one was etched by electrolytic etching during specimen preparation. Chemical compositions of the remained constituent in Fig. 4a were identical to those of microstructures on fracture surface (Fig. 3b). Besides, in some particular regions, micro fissures accompanying eutectic microstructures could be observed, as shown in Fig. 4b. Micro fissures were the results of combination of liquid existence and 0.5% strain application at 1350 °C. A healing effect of micro fissures by liquid backfilling could also be seen, as the arrow indicated in Fig. 4b.

Fig. 5a shows that in the specimen experiencing peak temperature 1250 °C, some clusters of eutectic microstructures were observed instead of those appearing at 1350 °C. The size of each eutectic microstructure was about 2 μm and characterized by some isolated particles surrounding network eutectic constituent, as shown in Fig. 5b. The chemical compositions of eutectic constituents were in line with those of eutectic microstructures in Fig. 4a.

In specimens experiencing peak temperature 1150 °C, clusters of particle phases could be observed instead of eutectic microstructures, as shown in Fig. 6a. The size of each particle phase was about 2 μm, and concentrations of elements in particle phases were similar to those of

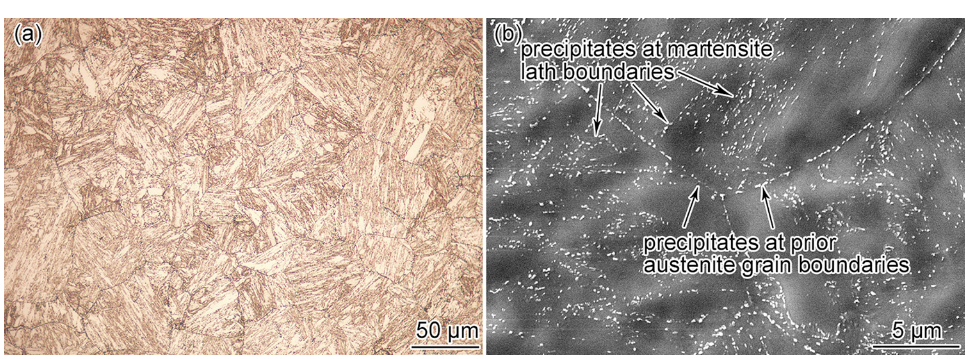

Fig. 1. Microstructure of COST FB2 steel in as received condition observed by (a) OM and (b) SEM.