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Microstructure and High Temperature Deformation Behavior of Cast 310S Alloy

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Abstract—High temperature deformation behavior of cast 310S stainless steel has been investigated in this study by performing tensile and compression tests at temperatures from 900 to 1200°C. Rectangular ingots of which the dimensions were 350×350×100 in millimeter were cast using vacuum induction melting. Phase equilibrium was calculated using the FactSage®, thermodynamic software and database. Thermal expansion coefficient was also measured on the ingot in the temperature range from room temperature to 1200°C. Tensile strength of cast 310S stainless steel was 9 MPa at 1200°C, which is a little higher than that of a wrought 310S. With temperature decreased, tensile strength increased rapidly and reached up to 72 MPa at 900°C. Elongation also increased with temperature decreased. Microstructure observation revealed that σ phase was precipitated along the grain boundary and within the matrix over 1200°C, which is detrimental to high temperature elongation.

Keywords—Stainless steel, STS 310S, high temperature deformation, microstructure, mechanical properties.

I. Introduction

STAINLESS steels are iron-base alloys that contain a minimum of approximately 11% Cr, the amount needed to prevent the formation of rust in unpolluted atmosphere. Few stainless steels contain more than 30% Cr or less than 50% Fe. They achieve their stainless characteristics through the formation of an invisible and adherent chromium rich oxide surface film [1].

Austenitic stainless steels are commonly used to continuous and intermittent high temperature services [2], [3]. However, the use or heat treatment of these steels in the 450~850°C promotes intense chromium carbide precipitation in the grain boundaries [4]. When heated for small periods and low temperatures in this temperature range the steel becomes sensitized and susceptible to intergranular corrosion attack, due to chromium depletion near the grain boundaries [5].

High chromium austenitic stainless steels are also susceptible to sigma phase precipitation during prolonged aging at high temperatures [6], [7]. Intergranular chromium cardies increase the creep resistance, but decrease ductility, low temperature toughness and corrosion resistance. Sigma phase produces the same effects on duplex stainless steels [8], and also increase the hardness [9]. Previous works has shown that sigma phase precipitation can be the cause of failure of austenitic stainless steels used at high temperatures. However, previous works were most focused on the wrought austenitic stainless steels and investigations on the cast ones are very rare so far.

Cast stainless steels are widely used for their corrosion resistance in aqueous media at or near room temperature and for service in hot gases and liquids at elevated temperatures. In general, the cast and wrought stainless steels possesses equivalent resistance to corrosive media, and they are frequently used in conjunction with each other. Important differences do exist; however, some cast stainless steels and their wrought counterparts. One significant difference is in the microstructure of cast austenitic stainless steels. There is usually a small amount of ferrite present in austenitic stainless steel castings, in contrast to the single phase austenitic structure of the wrought alloys. Cast stainless steels are most often specified on the basis of composition [1].

As is well known, castings are classified as heat resistant if they are capable of sustained operation while exposed continuously or intermittently, to operating temperatures that result in metal temperatures in excess of 650°C. Cast steels for this type of service include Fe-Cr, Fe-Cr-Ni, or Fe-Ni-Cr alloys. In applications of heat-resistant alloys, considerations include resistance to corrosion at elevated temperature, resistance to warping, cracking, or thermal fatigue, and creep strength. Commercial applications of heat resistant castings include metal treatment furnaces, gas turbines, aircraft engines, military equipment, oil refinery furnaces, cement mill equipment, power plant equipment, steel mill equipment, turbochargers, and equipment used in manufacturing glass and synthetic rubbers.

In the present study, high temperature deformation behavior of as cast 310S stainless steel has been studied by performing tensile and compression tests at temperatures ranging from 900 to 1200°C and the microstructure evolution was also observed.

II. Experimental Procedures

The material used in this study was 310S stainless steel ingot produced by vacuum induction melting, of which the chemical compositions are 25% Cr, 20% Ni, 1.5% Si, 2% Mn, and 0.1% C in weight percent. Appearance of the ingot was shown in Fig. 1, and the dimensions were 350mm in width, 350mm in height, and 100mm in thichness. On the ingot, coefficient of thermal expansion (CTE) and dilatation behavior were measured at

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temperatures from room temperature to 1200°C with heating rate of 2°C/min using NETZSCH DIL402C.

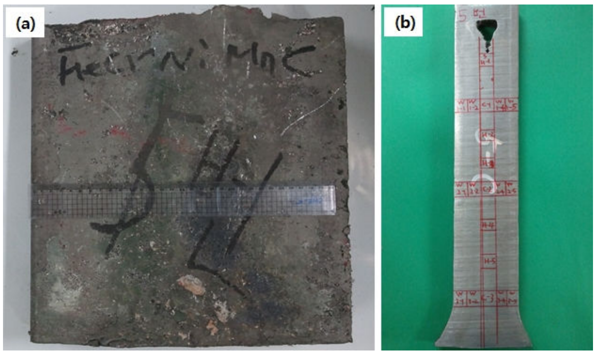

Fig. 1 Appearance of the 310S stainless steel ingot (a) and its cross-section (b) used in this study

High temperature tensile and compression tests were carried out in a vacuum using the Gleeble at temperatures ranging from 900 to 1200°C under the strain rate of 5×10^{-4}/s^{-1}. Cylindrical compressive specimens with a diameter of 8mm and a height of 12mm were prepared by electro-discharge machining. Tensile specimens with a gage length of 6mm and a diameter of 6mm were also prepared and the appearance is given in Fig. 2, together with that of a compressive specimen. Specimens were heated by induction coils at a heating rate of 5°C/min and soaked for 300 sec at test temperature before the tests were started. Athremo-couple was spot welded on each specimen before tests. The true stress-true strain curves were obtained from the load-displacement test. In order to investigate the microstructural evolution during the deformation, the specimens were quenched from the test temperature immediately after deformation using liquid nitrogen.

Fig. 2 Appearance of tensile (a) and compressive (b) specimen used in this study

The microstructure before and after deformation were observed by optical microscopy using an etchant consisting of HNO_3, HCl, and Glycerin.

III. Results and Discussion

Fig. 3 shows the results of dilatation and CTE measurement, in which CTE of as-cast 310S stainless steel appeared to increase with temperature increased and reached up to 17.3×10^{-6}/K^{-1}at 1200°C. Dilatation curve in Fig. 3 shows monotonically increasing curve without any inflection points.

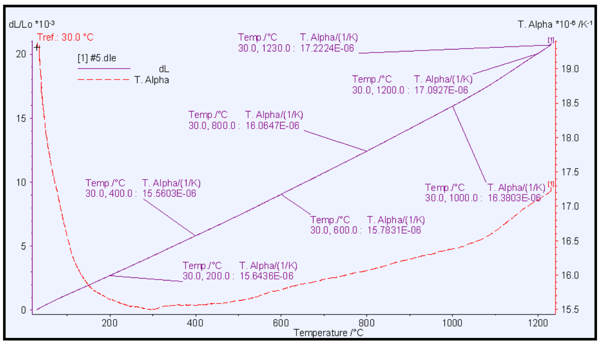

Fig. 3 Dilatation and CTE measured on as-cast 310S stainless steel ingot at temperatures ranging from room temperature to 1200°C

Fig. 4 is the results obtained from thermodynamic calculation using FactSage® and showing stable phases and their weight fractions of 310S stainless steel. It is apparent that most stable phase is austenite precipitating from 1350°C and $M_{23}C_6$ type carbide of which the amount of 2% can be formed at a low temperature. Interestingly, about 18% of ferrite can also be formed at 500°C and a little amount of sigma phase precipitation is expected at around 650°C.

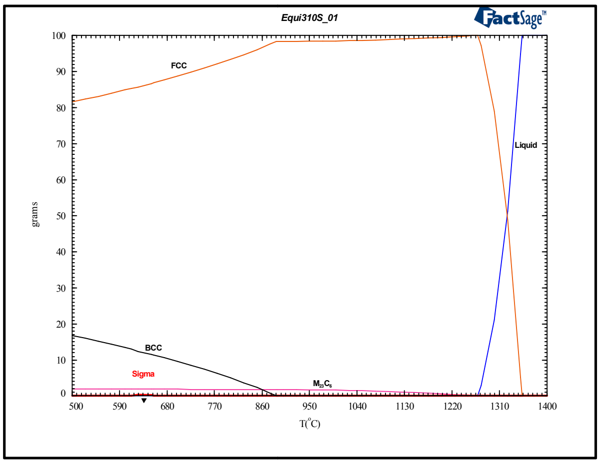

Fig. 4 Calculated phase equilibrium showing stable phases and their weight fractions of 310S stainless steel

As-cast microstructures of 310S stainless steel ingot were given in Fig. 5. In the optical micrograph as in Fig. 5 (a), typical feature of single phase with large grain size and without severe precipitations can be observed, while the SEM image in Fig. 5 (b) shows serrated grain boundaries [10] and sigma phase and carbides precipitated in the vicinity of grain boundaries. Along the grain boundaries, fragmented $M_{23}C_6$ type carbides were precipitated and the thickness was measured as about 0.2μm and the length was about 0.5μm.

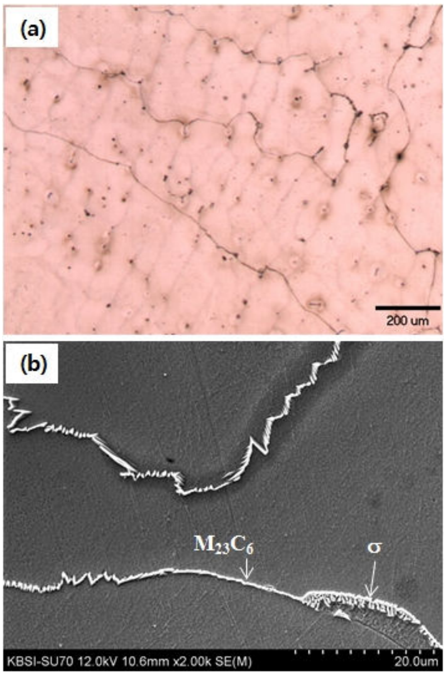

Fig. 5 Optical micrograph (a) and SEM image (b) showing typical microstructure of as-cast 310S stainless steel

Fig. 6 shows appearances of specimens after tensile tests at various temperatures, in which fracture surfaces of specimens, with very poor reduction of area, tested at higher temperatures, were easily observed. At relatively lower temperatures as given in Figs. 6 (c) and (d), evidence of plastic deformation was apparent.

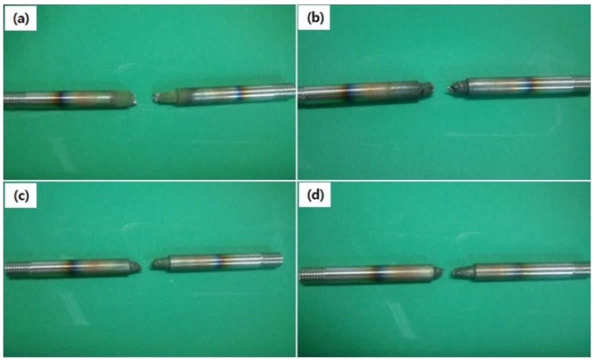

Fig. 6 Appearances of specimens after tensile tests conducted at temperatures of 1200°C (a), 1100°C (b), 1000°C (c), and 900°C (d), respectively

True stress-true strain curves obtained from a series of tensile tests at temperatures ranging from 900 to 1200°C were summarized in Fig. 7. It is very interesting to note that the elongation of as-cast 310S stainless steel decreases with temperature increased. Yield strength of as-cast 310S stainless steel dramatically increased with temperature and reached up to 72 MPa at temperature of 900°C. Abnormal decrease of elongation with increasing temperature is presumably associated with incipient melting in the vicinity of grain boundaries at high temperatures. Microstructure observation results given in Fig. 8 support this conjecture. As shown in Fig. 8 (a), any evidence for plastic deformation could not be observed. Incipient melting [11] can cause early separation of specimen as shown in Fig. 6 (a). Results of hardness test conducted on the specimens after tensile tests were given in Fig. 9, which also supports the presumable incipient melting at high temperatures of 1200°C and 1100°C. Compression test results, showing very similar trend to tensile tests, are summarized in Table I together with the results of tensile tests.

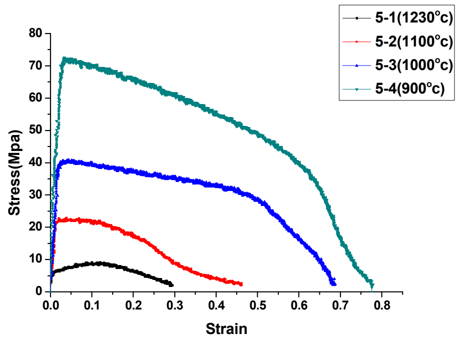

Fig. 7 True stress-true strain curves obtained from tensile tests conducted on as-cast 310S stainless steel at various temperatures

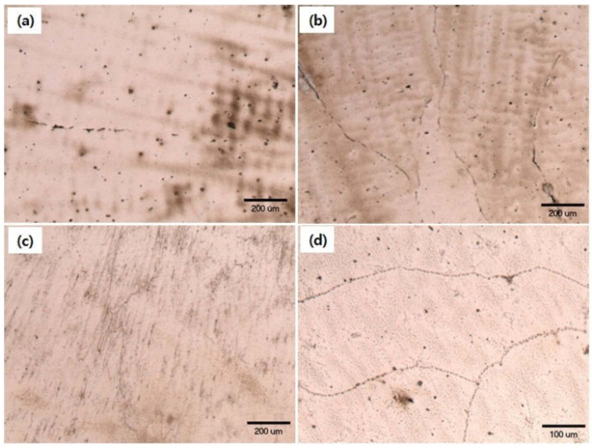

Fig. 8 Microstructure observed after tensile tests conducted at temperatures of 1200°C (a), 1100°C (b), 1000°C (c), and 900°C (d), respectively

TABLE II
MECHANICAL PROPERTIES OF AS-CAST 310S STAINLESS STEEL

Tension	900°C	1000°C	1100°C	1200°C
YS (MPa)	70.3	39.4	21.5	6.3
UTS (MPa)	70.4	40.9	22.8	9.2
Elongation (%)	77.6	68.6	46.2	29.3
Compression	900°C	1000°C	1100°C	1200°C
YS (MPa)	31.4	40.0	17.0	5.78
Peak Stress (MPa)	105.9	63.7	27.9	11.6

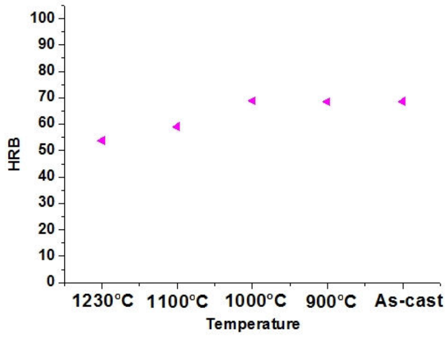

Fig. 9 Hardness of specimens deformed by tensile tests at various temperatures

IV. Conclusions

In this study, high temperature deformation behavior of as cast 310S stainless steel has been studied by performing tensile and compression tests at temperatures ranging from 900 to 1200°C and the microstructure evolution was also observed. Stable phases and their weight fractions of 310S stainless steel were calculated from thermodynamic calculation using FactSage®. $M_{23}C_6$ type carbide is expected to precipitate in the amount of 2%. Coefficient of thermal expansion of as-cast 310S stainless steel appeared to increase with temperature increased and reached up to $17.3\times10^{-6}/K^{-1}$ at 1200°C. Elongation of as-cast 310S stainless steel decreased with temperature increased and the yield strength dramatically increased with temperature and reached up to 72 MPa at temperature of 900°C.

Acknowledgment

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