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Microstructure and Hot Deformation Behavior of Fe-20Cr-5Al Alloy

Jung-Ho Moon, Tae Kwon Ha

Abstract**—**High temperature deformation behavior of cast Fe-20Cr-5Al alloy has been investigated in this study by performing tensile and compression tests at temperatures from 1100 to 1200°C. Rectangular ingots of which the dimensions were 300×300×100 in millimeter were cast using vacuum induction melting. Phase equilibrium was calculated using the FactSage®, thermodynamic software and database. Tensile strength of cast Fe-20Cr-5Al alloy was 4 MPa at 1200°C. With temperature decreased, tensile strength increased rapidly and reached up to 13 MPa at 1100°C. Elongation also increased from 18 to 80% with temperature decreased from 1200°C to 1100°C. Microstructure observation revealed that $M_{23}C_6$ carbide was precipitated along the grain boundary and within the matrix.

Keywords**—**Fe-20Cr-5Al alloy, high temperature deformation, aging treatment, 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].

Stainless steel is used for a variety of automobile components by virtue of its excellent corrosion resistance, heat resistance and good appearance. The automotive use of stainless steel began with decorative trims and the like taking advantage of the good appearance of the material, but it is now used for many functional components as well. Its use for exhaust system components, among others, has increased remarkably, accounting for more than a half of all the stainless steel use for an automobile [2].

An automotive exhaust system consists of the following seven components from the engine side: an exhaust manifold, a font pipe, a flexible pipe, a catalytic converter, a center pipe, a main muffler, an a tail end pipe, as illustrated in Fig. 1. Some models are equipped with more than one catalytic converters and a sub-muffler. The service temperature and required characteristics of each exhaust system component are in a great variety, so a proper material should be used as each component.

J. Moon is with the Department of Electronics Engineering, Gangneung-Wonju National University, 120 Gangneung-daehangno, Gangneung, Gangwon 210-702, South Korea.

T. K. Ha is with the Department of Advanced Metal and Materials Engineering, Gangneung-Wonju National University, 120 Gangneung-daehangno, Gangneung, Gangwon 210-702, South Korea (phone: 82-10-2367-1989; e-mail: tkha@gwnu.ac.kr).

An exhaust gas purifying system called a catalytic converter is installed for mitigating the air pollution caused by automobile exhaust gas. It converts, among the pollutants in the exhaust gas, hydrocarbons and carbon monoxide into carbon dioxide and water, and nitrogen oxides (NO_x) into nitrogen and oxygen. The converter consists of a catalyst, a co-catalyst, wash-coat and a catalyst carrier. Since the catalytic converter is mounted immediately below the exhaust manifold or beneath the body floor, it must withstand severe service conditions of high temperature, vibration and the like. Besides a ceramic carrier made of cordierite, a metal carrier made of ferritic stainless steel foils is used as the catalytic carrier. The reason why ferritic stainless steel foils are used is that they have good thermal shock properties and a small heat capacity. A metal catalyst carrier is composed of a honeycomb core of stainless steel foils and an outer shell of a stainless sheet [3].

Since excellent oxidation resistance is required of the foils, ferritic stainless steels of Fe-Cr-Al system such as Fe-20Cr-5Al alloy are used for them. Some steel grades are alloyed with small amounts of rare earth elements (REM) such as Hf, Sc, Y and Ce for enhancing the adhesion of oxide coating films. The trend is that further enhancement of oxidation resistance is required [4].

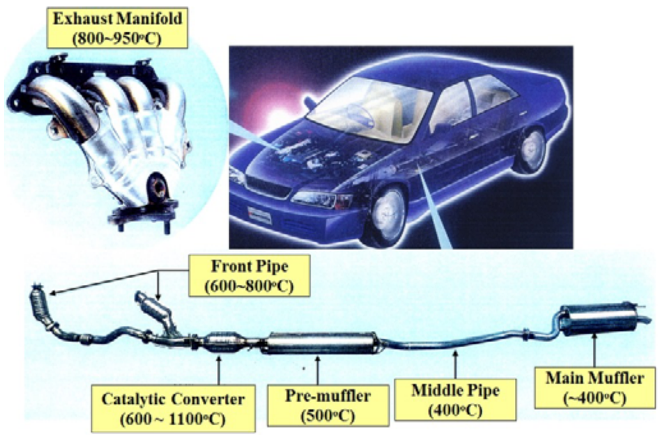

Fig. 1 Automotive exhaust system components

Iron-chromium-aluminum alloys, which form Al_2O_3 scales, have excellent high-temperature oxidation resistance; they are widely used as materials in high-temperature applications. In recent years, such alloys have been studied for possible application as a substrate material for honeycomb-style catalytic converters, which reduce the amount of harmful gases, such as NO_x, SO_x, and HCN in the exhaust gas, from vehicles. A suitable temperature is considered to be approximately 800°C;

however, the temperature at particular locations on the catalytic converter may reach more than 1000°C [2]. However, previous works were most focused on the oxidation behavior of Fe-Cr-Al alloys and investigations on the hot deformation behavior are very rare so far.

In the present study, high temperature deformation behavior of as-cast Fe-20Cr-5Al stainless steel has been studied by performing tensile and compression tests at temperatures ranging from 1100 to 1200°C and the microstructure evolution was also observed.

II. Experimental Procedures

The material used in this study was Fe-20Cr-5Al stainless steel ingot produced by vacuum induction melting, of which the chemical compositions are 20% Cr, 1.0% Si, 5.0% Al, 0.1% N, 0.1% Y, and 0.1% C in weight percent. Appearance of the ingot was shown in Fig. 2, and the dimensions were 300 mm in width, 300 mm in height, and 100 mm in thickness.

Fig. 2 Appearance of the Fe-20Cr-5Al ferritic stainless steel 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 $5\times10^{-4}/s^{-1}$. Cylindrical compressive specimens with a diameter of 8 mm and a height of 12 mm were prepared by electro-discharge machining. Tensile specimens with a gage length of 6 mm and a diameter of 6 mm were also prepared and the appearance is given in Fig. 3, 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. A thremo-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.

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

Fig. 3 Appearance of tensile (a) and compressive (b) specimen used in this study

III. Results and Discussion

Fig. 4 is the results obtained from thermodynamic calculation using FactSage® and showing stable phases and their weight fractions of Fe-20Cr-5Al stainless steel. It is apparent that most stable phase is ferrite fully solidified 1400°C and $M_{23}C_6$ type carbide of which the amount of 2% can be formed at temperature from 1100°C. Interestingly, a little amount of AlN can also be formed at 1300°C.

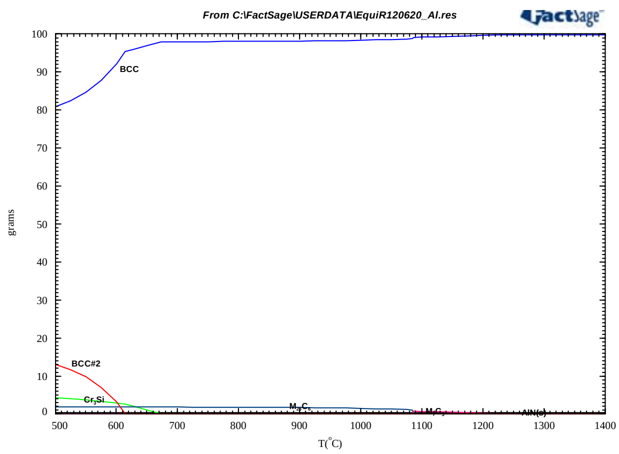

Fig. 4 Calculated phase equilibrium showing stable phases and their weight fractions of Fe-20Cr-5Al stainless steel

As-cast microstructures of Fe-20Cr-5Al 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 small carbide particles in matrix and long carbides along grain. Along the grain boundaries, fragmented $M_{23}C_6$ type carbides were found to precipitate and the thickness was measured as about 1.2 μm.

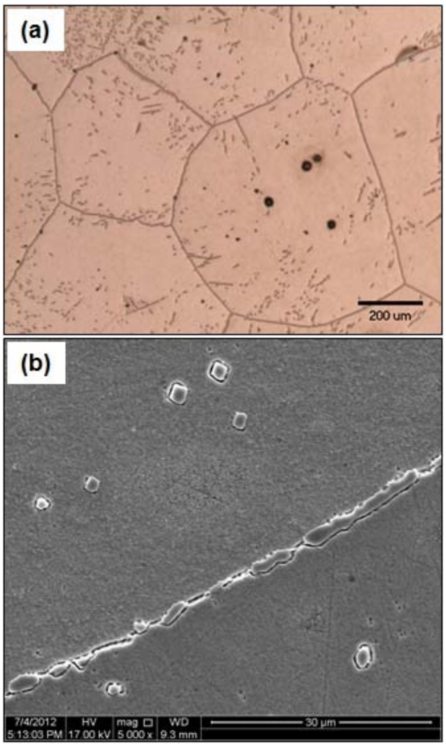

Fig. 5 Optical micrograph (a) and SEM image (b) showing typical microstructure of as-cast Fe-20Cr-5Al stainless steel

Fig. 6 shows appearances of specimens after tensile and compression tests at temperature of 1200°C, in which fracture surfaces of specimens, with very poor reduction of area were easily observed. In the figure, evidence of plastic deformation was apparent in both cases.

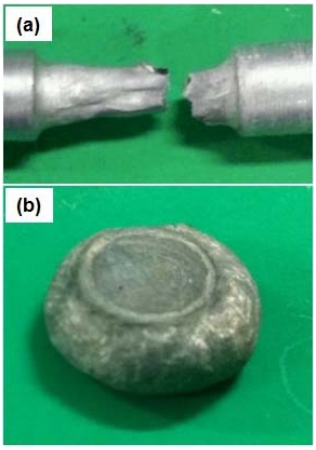

Fig. 6 Appearances of specimens after tensile (a) and compression tests conducted at temperatures of 1200°C

True stress-true strain curves obtained from tensile and compression tests at temperature of 1100°C were summarized in Fig 7. It is very interesting to note that the elongation of as-cast Fe-20Cr-5Al stainless steel reaches up to 80% in tensile test. Very severe serration is clearly observed [5]. Yield strength of as-cast Fe-20Cr-5Al stainless steel is much higher in compression mode than in tensile mode at 1100°C, while very similar to each other 1200°C as summarized in Table I.

TABLE I
MECHANICAL PROPERTIES OF AS-CAST FE-20CR-5AL STAINLESS STEEL.

Tension	1100°C	1200°C
YS (MPa)	9.12	4.01
UTS (MPa)	10.8	4.02
Elongation (%)	81.3	16.3
Compression	1000°C	1200°C
YS (MPa)	11.9	3.49
Peak Stress (MPa)	14.2	4.92

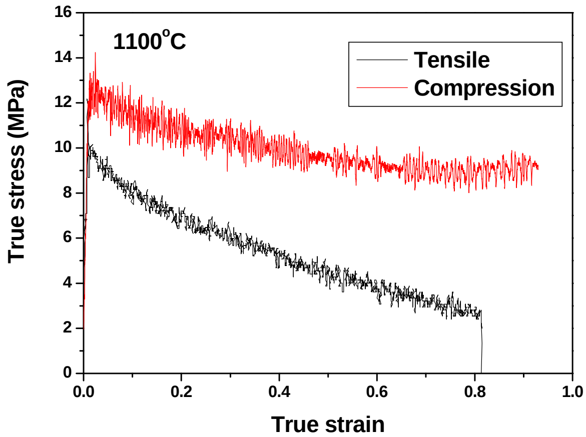

Fig. 7 True stress-true strain curves obtained from tensile and compression tests conducted on as-cast Fe-20Cr-5Al stainless steel at 1100°C

After exposition at 1200°C for long period of time up to 200 hrs, hardness was measured and the results were given in Fig. 8, showing hardness was increased from that of as-cast specimen. During hot exposition at 1200°C, precipitation of $M_{23}C_6$ carbides was presumably occurred and X-ray diffraction result given in Fig. 9 supports it. Microstructure observation revealed the evidence for precipitation of carbides along the grain boundaries and in the matrix as shown in Fig. 10.

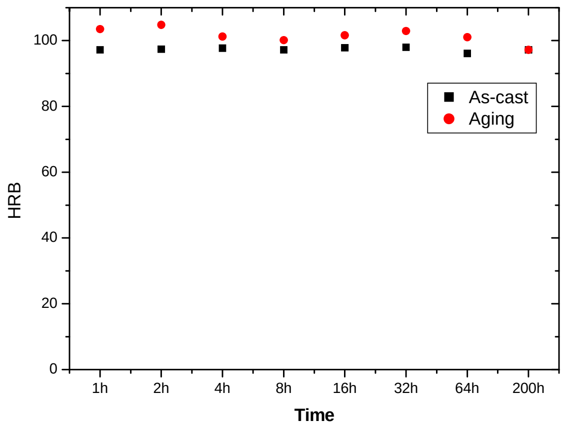

Fig. 8 Hardness measured after exposition at 1200°C for various time intervals

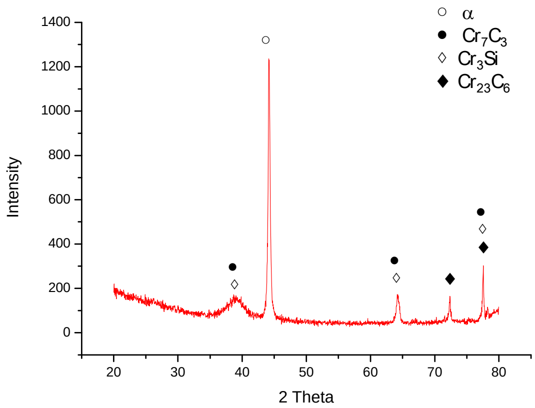

Fig. 9 X-ray diffraction results obtained on the specimen exposed at 1200°C for 64 hrs

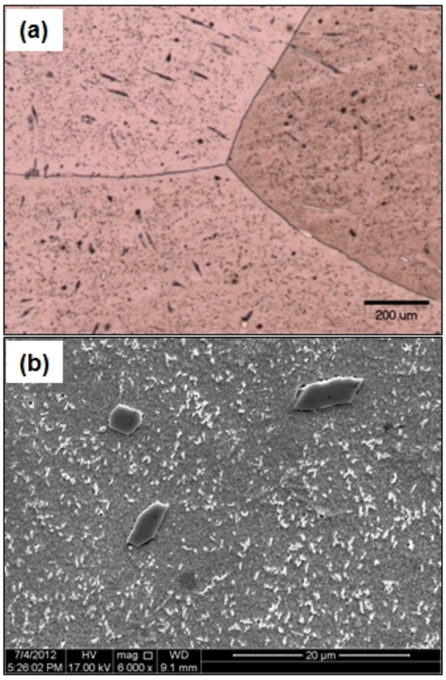

Fig. 10 Optical micrograph (a) and SEM image (b) showing carbides precipitated during hot exposition at 1200°C for 200 hrs

IV. Conclusions

In this study, high temperature deformation behavior of as-cast Fe-20Cr-5Al stainless steel has been studied by performing tensile and compression tests at temperatures ranging from 1100 to 1200°C and the microstructure evolution was also observed. Most stable phase is ferrite fully solidified 1400°C and $M_{23}C_6$ type carbide of which the amount of 2% can be formed at temperature from 1100°C. A little amount of AlN can also be formed at 1300°C. Typical feature of single phase with large grain size and without severe precipitations can be observed. Elongation of as-cast Fe-20Cr-5Al stainless steel reached up to 80% in tensile test. Very severe serration is clearly observed in flow curves obtained from both tensile and compression tests. Yield strength of as-cast Fe-20Cr-5Al stainless steel is much higher in compression mode than in tensile mode at 1100°C, while very similar to each other at 1200°C.

Acknowledgment

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