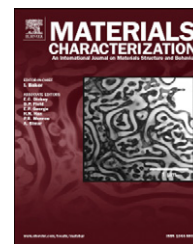


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Variation of carbon concentration in proeutectoid ferrite during austenitization in hypoeutectoid steel



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ABSTRACT

The variation of the C concentration in proeutectoid ferrite (α_{PF}) during austenitization in hypoeutectoid steels was quantitatively investigated using the massive transformation confocal laser scanning microscopy and hardness of α_{PF} . The C concentration in α_{PF} at T_m in hypoeutectoid steels increased with increasing total C concentration up to approximately 0.2 wt.% during heating. The hardness of α_{PF} with isothermal holding time at 775 °C in S20C steel revealed C enrichment in α_{PF} at the early stage of isothermal holding and its reduction with further holding. These results explain the redistribution of the C in α_{PF} during austenitization as follows: free C atoms released from cementite during pearlite decomposition diffuse excessively into neighboring α_{PF} as well as pearlitic ferrite. The supersaturated C concentration in α_{PF} is reduced during the long-range diffusive transformation of α_{PF} to γ . However, some of the excess C atoms still remain in α_{PF} until α_{PF} starts to massively transform to γ .

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1. Introduction

Hypoeutectoid steels have been used as various mechanical parts for machines, automobiles, ships, aircrafts, and so on. Their final microstructures and mechanical properties are influenced by heat treatment. In particular, austenitization before cooling is important because it affects phase transformations during cooling and resultant mechanical properties. Austenitization has been extensively investigated in various aspects of initial microstructure, heating rate, and chemical composition [1–6] and computational modeling on austenitization has also been performed [7–12].

Austenitization in pure iron proceeds by the nucleation of austenite (γ) at grain boundaries of ferrite (α) and by the interface-controlled migration of γ/α interphase boundaries, which is called the polymorphic transformation [13]. In eutectoid steel, a large number of pearlitic ferrite (α_P)/cementite (θ) boundaries act as nucleation sites for the formation of γ . The migration rate of the γ/α_P interface is controlled by long-range C diffusion to the γ/α_P interface from the γ/θ interface through γ [2]. In hypoeutectoid steel consisting of pearlite (P) and proeutectoid ferrite (α_{PF}), P is first transformed to C-rich γ , which is surrounded by untransformed C-poor α_{PF} . As the temperature or the isothermal holding time increases,

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austenitization continues to proceed into α_{PF} , which is controlled by long-range C diffusion through γ toward the γ/α_{PF} interface [1].

Recently, *in-situ* observation of microstructural changes in alloys at high temperature became possible using high-temperature confocal laser scanning microscopy (HT-CLSM) [14–19]. Schmidt et al. [17] observed by HT-CLSM that the reverse transformation of α_{PF} to γ changed from the long-range diffusive transformation to the massive transformation during continuous heating with the rates over $2.5\text{ }^{\circ}\text{C s}^{-1}$ in a hypoeutectoid steel. This transition in transformation mechanism took place at temperatures just above T_0 , which is defined as a temperature where both α_{PF} and γ phases have the same Gibbs free energy. They assumed that the C concentration in α_{PF} was fixed to be the paraequilibrium C concentration in α_{PF} at the eutectoid temperature (A_{e1}) during the reverse transformation of α_{PF} to γ . Therefore, the start temperature of the massive transformation (T_m) during continuous heating was regarded as constant T_0 .

Meanwhile, Akbay et al. [7] at first made an austenitization kinetics model without C diffusion from γ into α_{PF} , and then improved the model by considering C diffusion into α_{PF} up to its equilibrium solubility [8]. The incubation time for austenitization calculated with C diffusion into α_{PF} was slightly longer than that predicted without C diffusion into α_{PF} . Jeong et al. [3] reported that the neighboring α_{PF} grains were supersaturated with C in during the austenitization of P by observing the variation in the hardness value of α_{PF} grains. Recently, Savran et al. [6] studied the nucleation and growth of γ from the α_{PF}/P structure using three-dimensional X-ray diffraction microscopy. They observed strong acceleration of growth of γ corresponding to massive transformation. At T_m , the C concentration in α_{PF} was converted using the thermodynamic relationship between the C concentration and T_0 under the assumption that T_m is equal to T_0 . The converted C concentration is slightly higher than the equilibrium C concentration of α_{PF} .

These studies imply that the α_{PF} can be supersaturated with C during austenitization in hypoeutectoid steel and the C concentration can change depending on heat treatment condition and/or the initial C concentration. This variation of the C concentration in α_{PF} during austenitization gives rise to the variation of T_m . Therefore, if a quantitative relationship between T_m and T_0 is given, the C concentration in α_{PF} can be predicted from measured T_m using the relationship between the C concentration and T_0 . Nevertheless, there are few reports on the quantitative evaluation of the C variation in α_{PF} .

Therefore, the objective of the present study was to quantitatively investigate the variation of the C concentration in α_{PF} during austenitization in hypoeutectoid steels. For this purpose, the quantitative relationship between T_m and T_0 was

first set and then the variation of the C concentration in α_{PF} during austenitization was evaluated using the relationship between T_m and T_0 and T_m values measured using HT-CLSM. The C redistribution in α_{PF} during austenitization was also examined through micro-Vickers hardness.

2. Experimental Procedure

The plates of interstitial-free (IF) and hypoeutectoid steels with different C concentrations (S10C, S20C, and S45C steels) were used in the present study. The size of the plates was approximately $20 \times 20 \times 2\text{ mm}^3$. The chemical compositions of the steels are listed in Table 1. The plates were annealed at $1200\text{ }^{\circ}\text{C}$ for 1 h and then furnace-cooled under a protective atmosphere for the homogeneous microstructure with coarse grains of α_{PF} . The average grain size of α_{PF} and the volume percent of P in annealed specimens, which were measured using an image analyzer (Olympus, TS Material) [20,21], are also listed in Table 1.

Precipitates in the annealed IF steel were examined using carbon extraction replicas in conjunction with a field emission transmission electron microscope (FE-TEM, JEOL, JEM2100F) and an energy dispersive X-ray spectrometer (EDXS, Oxford, INCA Energy).

The austenitization process in annealed specimens was examined through *in-situ* observations of surface relief occurring during continuous heating using a high-temperature confocal laser scanning microscope (CLSM, Laser-tec Inc., VL2000) [15,16]. To accurately measure the surface temperature of specimens, an extra-R-type thermocouple, which has high resistance to oxidation and corrosion and works up to $1540\text{ }^{\circ}\text{C}$, was attached to the observed surface of each specimen. To maintain the reduced-oxidation atmosphere at high temperatures, the heating chamber was filled with the 99.9% Ar gas and then evacuated repeatedly at least three times at room temperature ($20\text{ }^{\circ}\text{C}$). Finally, after the Ar gas was allowed to flow into the chamber and to exit for longer than 20 min, specimens were austenitized with two different heating conditions; continuous heating and step heating.

For continuous heating, specimens were heated up to $1000\text{ }^{\circ}\text{C}$ with different rates of 5 to $20\text{ }^{\circ}\text{C s}^{-1}$. For step-heating, specimens were heated until $775\text{ }^{\circ}\text{C}$ with a rate of $15\text{ }^{\circ}\text{C s}^{-1}$, followed by isothermal holding for 1 to 20 min at that temperature, and then reheated up to $1000\text{ }^{\circ}\text{C}$ with a rate of $15\text{ }^{\circ}\text{C s}^{-1}$. The isothermal holding temperature ($775\text{ }^{\circ}\text{C}$), where the equilibrium volume percent of α_{PF} of S20C steel is 50% (calculated by Thermo-Calc with TCFE5 database [22]), was determined with expectations of both the completion of the P to γ transformation and a large volume fraction of α_{PF} . After the S20C steel specimen was isothermally held for 1 to 20 min

Table 1 – Chemical composition (wt.%), average grain size of proeutectoid ferrite (α_{PF}), and pearlite volume percent (V_P) of the steels used in the present study.

Steel	C	Mn	Si	Ni	Cr	Cu	Ti	P	S	N	Grain size (μm)	V_P (vol.%)
IF	0.002	0.53	0.003	0.02	0.06	0.002	0.023	0.001	0.001	0.002	180	0
S10C	0.12	0.46	0.21	0.03	0.10	0.10	–	0.02	0.01	0.003	70	15
S20C	0.23	0.46	0.22	0.03	0.09	0.10	–	0.02	0.02	0.003	85	35
S45C	0.45	0.43	0.23	0.01	0.03	0.04	–	0.02	0.01	0.003	30	85

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