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The Effect of Bainitic Transformation on Martensite Start Temperature of a Fe-C-Mn-Si Alloy

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Abstract. The martensite start temperature (Ms) of a Fe-0.40%C-1.87%Mn-1.65%Si alloy with bainite and martensite dual phases was studied. The phase transformation dilation curves were measured and Ms temperatures of deformed and non-deformed specimens were obtained. Finally the effect of bainitic transformation upon Ms was investigated. The results show that bainitic phase transition affects the Ms and the increase of transformation results in the decrease of Ms. The mechanical stabilization of austenite due to ausforming is partially eliminated by bainitic transformation, which weakens the effect of ausforming on Ms.

Introduction

A lot of researches on martensite transformation have been reported and the mechanical stabilization of austenite (MSA) due to ausforming is well-known [1~3]. Several researchers suggested empirical formulae for Ms that reflect the influence, in general, of the chemical compositions upon Ms[4~7]. The other factors, such as ausforming, were not taken into account in these formulae. It is known that the Ms affected by not only composition but also ausforming and bainitic phase transition etc. The Ms of a Fe-0.4%C-1.80Mn-1.65%Si alloy was studied at aiming to investigate the influence law of these factors on Ms.

Experimental Material and Procedure

The steel used for this investigation was cast in the form of a 40kg ingot using laboratory-scale vacuum furnace at Dofasco-ArcelorMittal (Hamilton, Canada). The material was then hot-forged and air-cooled to room temperature. The steel was subsequently tempered at 650˚C for 15 hrs in order to facilitate the machining of specimens. The main composition of the alloy is 0.40wt%C, 1.87wt%Mn and 1.65wt%Si.

The thermomechanical treatments were performed on a Gleeble 1500 thermomechanical simulator. Round specimens were used with a diameter of 8 mm and a height of 15 mm. Three processing schedules were used as illustrated in Fig.1. In the first schedule, Fig.1(a), the specimen was heated to 860˚C and kept for 10 min for austenitization followed by air-cooling at approximately 15˚C/s to room temperature to measure bainite start temperature (Bs) and Ms at continuous condition. In the second schedule, Fig.1(b), no deformation was applied to the material; the specimen was austenitized at 860˚C for 10 min before being cooled at approximately 15˚C/s to 300˚C and isothermally transformed for 30 min and 120 min. After isothermal holding, the specimens were cooled to room temperature at a cooling rate of 15˚C/s. The effect of deformation on Ms was investigated at strain rate of 50%. Schedule (c) was used to study the influence of ausforming on the Ms, in which the specimens were first austenitized for 10 min at 860˚C followed by cooling to 760˚C and being compressed to strain of 0.5 at 760˚C. Then the deformed specimens were cooled to 300˚C and isothermally held for 30 min and 120 min at 300˚C before finally cooling to room temperature at a cooling rate of 15˚C/s. The diameter change during the phase transformation was measured using a laser extensometer.

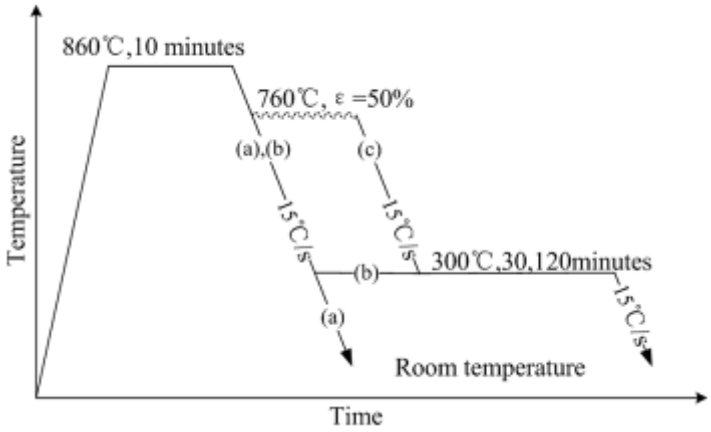

Fig. 1 Experimental schedules

The specimens for optical metallography were taken from centre of the deformed specimen, where maximum deformation occurred during compression. The specimens were mechanically polished and then etched in 2% nital solution. The transmission electron microscopy (TEM) specimens were obtained by punching disks from the same region. The discs were thinned to 80μm in thickness by polishing on silicon carbide paper and finished by twin-jet electro-polishing using a mixture solution of 10% perchloric acid in methanol with an applied voltage of 16 V at -30˚C. TEM observations were performed using a PHILIPS CM12 transmission electron microscope operated at 120 kV.

Experimental Results

Ms of Non-deformed Material. The continuous cooling test was conducted using Gleeble 1500 simulator according to the experimental schedule shown in Fig.1(a) and the dilation curve during cooling process is given in Fig.2(a), from which one can get that the Bs and Ms temperatures for study steel are 410˚C and 218˚C. The calculated Ms using several empirical formulae are listed in Table 1. Fig.2(b) is microstructure corresponding to cooling rate in Fig.2(a) .

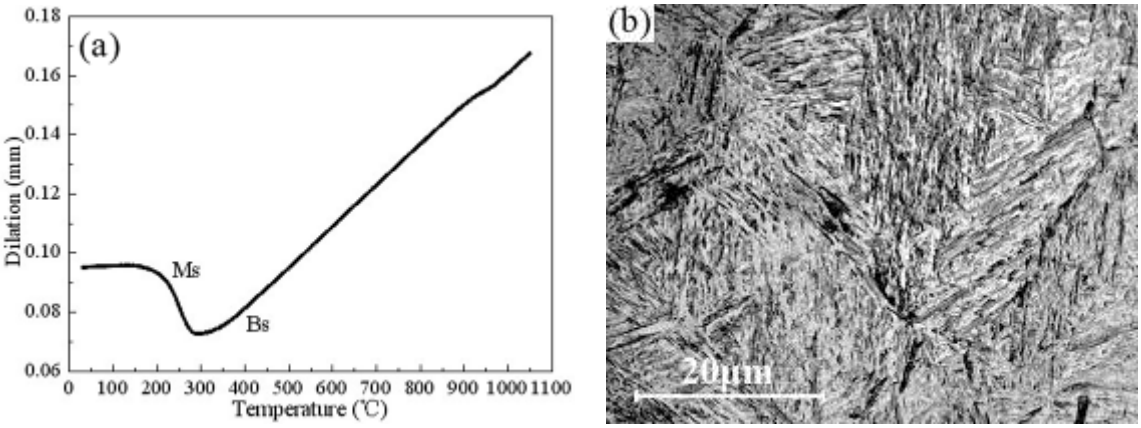

Fig.2 a)Dilation curve at the cooling rate of 15˚C/s; b) corresponding microstructure

Table 1 Calculated Ms temperatures

References	Ms Formulae /˚C	Ms/˚C
Wang et al.[4]	Ms=545-470.4C-3.96Si-37.7Mn-21.5Cr+38.9Mo	243.5
Makinson et al.[5]	Ms=500-333C-34Mn-35V-20Cr-17Ni-11Mo-10Cu-5W-15Co+30Al	269.5
Andrews[6]	Ms=539-423C-30.4Mn-12.1Cr-17.7Ni-7.5Mo+(10Co-7.5Si)	270.6
Steven and Haynes [7]	Ms=561-474C-33Mn-17Cr-17Ni-21Mo+(10Co-7.5Si)	265.3

The transformation tests without deformation were performed according to the schedule given in Fig.1(b). The dilation curves during experiments are illustrated in Fig.3, in which AB is corresponding to bainitic transformation at 300˚C because the isothermal holding temperature is higher than Ms. The specimens should continuously shrink with the decrease of temperature. The slope of dilation, however, changes from point Ms due to the starting of martensite transition at point Ms. Point Ms in Fig.3, therefore, is corresponding to martensite transformation, from which one can get the Ms temperature. It is shown that Ms drops from 205.76˚C to 92.46˚C when the bainitic transition time increases from 30min to 120min.

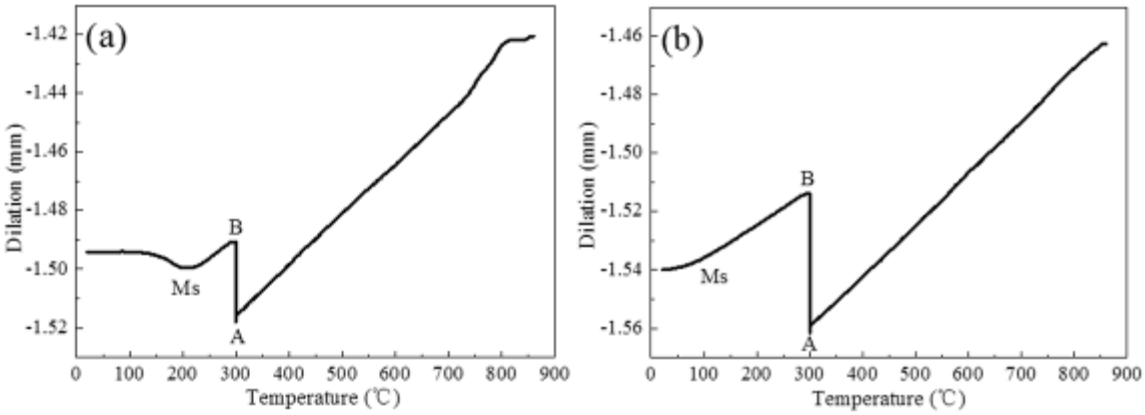

Fig.3 Dilation curves of non-deformed samples, a) isothermal holding 30min at 300˚C; b) isothermal holding 120min at 300˚C

Ms of Deformed Material. The specimens were deformed to strain of 50% at 760˚C and strain rate of 1/10 s^{-1}, followed by cooling to 300˚C and isothermal holding for 30min and 120min before finally cooling to room temperature at cooling rate of 15˚C/s. The dilation curves are shown in Fig.4, from which one can see that Ms drops from 205.76˚C to 108.23˚C when the bainitic transition time increases from 30min to 120min.

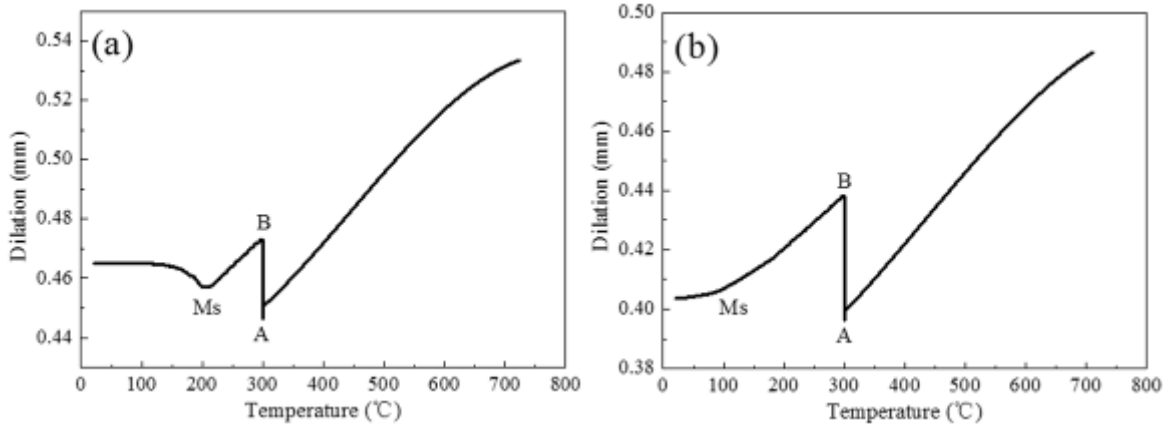

Fig.4 Dilation curves of deformed samples, a) isothermal holding 30min at 300˚C; b) isothermal holding 120min at 300˚C

Discussions

The Ms temperatures calculated by empirical equations are close to the measured Ms temperature except Wang's formula (Table 1), which demonstrates the well fitting between Ms temperatures predicted by these formulae and experiment result. It is interesting to note that all predicted Ms temperatures are higher than tested Ms. This can be explained by small amount of bainitic transition during cooling process, which leads to the higher carbon content in non-transformed austenite and lower Ms temperature, while the empirical formulae only considered the influences of composition upon Ms.

Ms affected by bainitic transformation before martensite transition and Ms decreases with the increase of bainitic transformation time whether the materials are deformed or not. This result can be explained by the increase of carbon content in non-transformed austenite. On the one hand, high content of silicon in steel suppresses the precipitate of carbides in bainite ferrite. On the other hand, the solubility of carbon in ferrite is smaller than that in austenite. The redundant carbon resulted from transformation of $\gamma \rightarrow \alpha$ will deposit in non-deformed austenite, which suppress Ms to lower temperature.

Figs.5(a) and (b) gives the optical macrographs of non-deformed specimens with different bainitic transition time, from which one can see that the bainite volume increases and martensite decreases after longer bainitic transformation. More austenite transforms to bainite if the transformation time extends to 120min, which result in less non-transformed austenite and finally less martesite.

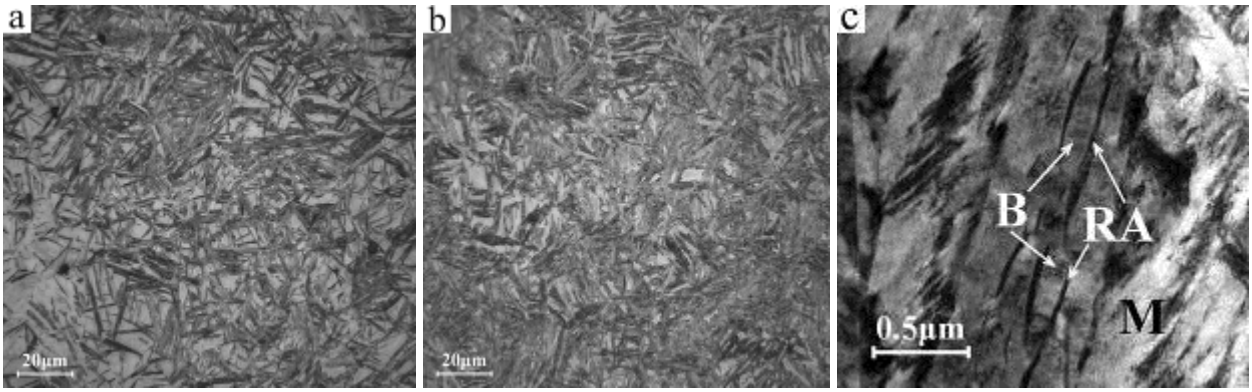

Fig.5 Optical micrographs of non-deformed specimens(bamboo-shaped is bainite and grey area is martensite), a) isothermal holding for 30min at 300˚C; b) isothermal holding for 120min at 300˚C; c: TEM micrograph of non-deformed sample transformed for 30min at 300˚C

The detailed microstructure of non-deformed specimen after isothermal holding for 30min is shown in Fig.5(c), in which the plate-like phase is the baomboo-shaped bainite and light grey area with high dislocation density is corresponding to the martensite in Fig.5(a) and (b).

Some researchers claimed that ausforming may result in mechanical stabilization of austenite (MSA) and thus decrease the Ms temperature[1~3]. Strife et al. pointed out that ausforming at a certain temperature above Md may retard the martensite transformation, reduce the Ms and increase the retained austenite (RA) amount [1]. They termed this phenomenon as MSA. MSA results from the more crystal defects induced by ausforming and retarding function of more crystal defects to martensite transformation. But no obvious MSA occurs among deformed specimens. From Figs.3 and 4, it can be seen that the Ms temperature of ausformed sample with 50% prestrain isothermal holding for 30min is almost the same as that of non-deformed sample, whereas the Ms temperature of ausformed sample with 50% prestrain isothermal holding for 120min increases to 108.23˚C compared with the 92.46˚C of non-deformed sample. The main reason perhaps is due to the elimination of deformation defects caused by bainitic transformation before martensite transition. At the same time, isothermal holding process also removes some defects such as dislocation. These two factors alleviate the effect of MSA.

The microstructures of ausformed samples are shown in Fig.6. Same as non-deformed samples, both the martensite volume and Ms of ausformed samples decrease with the increase of baintic transformation time. Comparing Figs. 5 and 6, one can find that microstructure consists of more martensite and less bainite after the materials is deformed to 50% strain, which means that MSA caused by ausforming reduces the bainitic transition and more non-transformed austenite retains. The non-transformed austenite transforms to martensite during the cooling after bainitic transition. In addition, more non-transformed austenite results from less bainite volume fraction in microstructure and low carbon content in austenite leads to the higher Ms temperature of 108.23˚C in the specimen deformed to 50% strain.

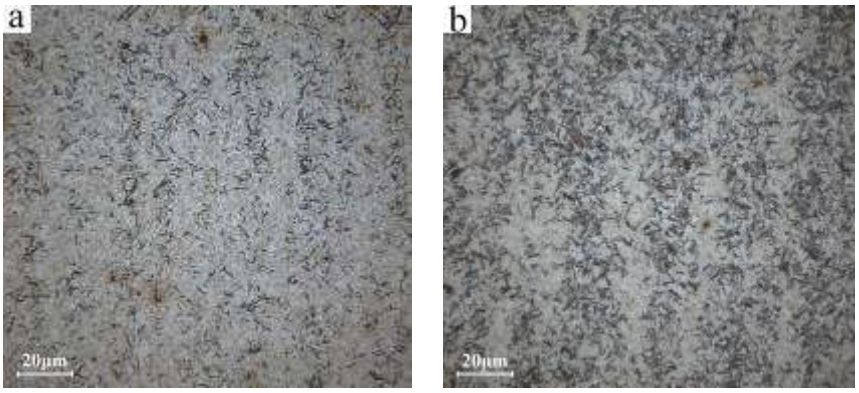

Fig.6 Optical micrographs of specimens deformed to 50% strain(dark area is bainite and light grey area is martensite), a)isothermal holding for 30min at 300˚C; b)isothermal holding for 120min at 300˚C

Conclusions

The effects of bainitic transformation and ausforming upon Ms were studied for a Fe-Mn-Si alloy. The dilation curves were measured using hot simulator and the microstructure of ausformed material was investigated. The following conclusions can be obtained:

(1) Bainitic transformation is retarded by MSA resulted from prestrain of austenite at high temperature.

(1) The longer bainitic transformation results in lower Ms temperature;

(2) Ausforming leads to the MSA. However, the bainitic transformation and isothermal holding alleviate the effect of MSA and weaken the effect of MSA on Ms.

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