Effect of Pre-Deformation on Fracture Behavior Transition due to Strain-Rate Change in Fe-5%Si Alloy

by

Takashi MIZUGUCHI^{*}, Ryota OOUCHI^{**} and Yasuhiro TANAKA^{**}

Fracture behavior transition due to strain rate change in Fe-5%Si alloy with dislocation microstructures was studied to investigate the effect of pre-deformation on toughness. The Fe-5%Si alloy was multi-passed rolled (pre-deformed) at 1073K to various reductions up to 50% to introduce dislocation microstructure. The room temperature tensile deformation was conducted at various strain rates from 10^{-5} to 10^0 /s. Electron backscattering diffraction measurements clarified that the dislocations were successfully introduced within the grains. All rolled alloys were fractured with local elongation (necking) at slower strain rate. When strain rate was faster, the local elongation disappeared and the fracture manner was turned to brittle. The strain rate at which fracture behavior changed increased with increasing of the reduction. On the other hand, the almost fully recrystallized Si steel was fractured in the brittle manner at any strain rate and the transition strain rate was not found. The fractured tensile specimen with no local elongations contains deformation twins; however, these deformation twins were not observed in the fractured specimen with local elongations. This result indicates that the dislocation structure evolved during rolling suppressed the twinning and that the dislocation structure is effective for the enhancement of both ductility and toughness in Fe-5%Si alloy.

Key words : *Magnetic steel sheet, Ductile-brittle transition, Deformation twin, Strain rate, Dislocation structure, Pre-strain*

1 Introduction

Fe-Si steels containing 1.5–3.5 mass% Si are widely used in magnetic steel sheet production. Magnetic steel sheets with more appropriate magnetic and mechanical properties are required to prevent global warming. The soft magnetic property of Si steel sheets is improved by increasing the Si content.^{1), 2)} However, workability is dramatically reduced and brittle-like fractures are likely to occur. Therefore, it is important to understand the brittle fracture behavior of Fe-high Si steels containing more than 3.5% Si and to reduce their brittleness. Previous studies^{3), 4)} have focused on the ductile-brittle transition temperature (DBTT) of Fe-Si alloys, which is the toughness benchmark. If the fracture process is controlled by thermally activated motion of dislocation, we can correlate temperature with strain rate, which is a possible parameter alternative to temperature. In other words, low temperature deformation is equivalent to high strain rate deformation, implying that a ductile-brittle transition due to strain rate changes can be predicted. Magnetic steel sheets are used at ambient temperature and are produced by rolling to obtain a particular strain rate. It has been reported that (1) Fe-high Si alloys show a fracture behavior transition due to strain-rate changes, (2) the toughness of Si steel can be evaluated using fracture behavior transition due to strain-rate changes^{5), 6)} and (3) brittle fracture is closely related with the existence of

deformation twins.^{4)~8)} In other words, the suppression of deformation twinning is important to improve the brittleness of Si steel.

The suppression of twinning in Fe^{9)~13)} and Fe-Si alloy⁴⁾ by small amount of pre-deformation has been reported by various researchers. For example, Narita et al.⁴⁾ reported dislocation substructures such as sub-boundary and mobile dislocations introduced by the pre-deformation improved the ductility of Fe-Si alloy. This means that deformation microstructure suppresses the brittle fracture. Uenishi et al.¹⁴⁾ and Aronsson et al.¹⁵⁾ investigated stress-strain behaviors of Si steels; however, there has been no systematic study of the effect of pre-deformation and strain rate on fracture behavior. This study aims to clarify the fracture behavior in Fe-high Si alloy using the room temperature tensile tests at wide range of strain rates (10^{-5} to 10^0 /s) to clarify the effect of pre-deformation on the fracture behavior due to strain rate change.

2 Experimental Procedure

Fe-5mass%Si alloy with hot rolled ferritic microstructure with the thickness of 15mm was prepared by the furnace melting method. The chemical composition of Fe-5%Si alloy used in this study is shown in Table 1. This alloy ingot was multi-pass rolled (pre-deformed) at 1073K to reduce their thickness by 20%, 40%, or 50%, followed by air-cooling in order to introduce dislocations substructures. A tensile test was conducted at room temperature

† 原稿受理 平成 25 年 5 月 9 日 Received May 9, 2013 ©2014 The Society of Materials Science, Japan

* Member : Faculty of Engineering, Kagawa Univ., Hayashi-cho, Takamatsu, 761-0396 Japan

** Faculty of Engineering, Kagawa Univ., Hayashi-cho, Takamatsu, 761-0396 Japan

Table 1 Chemical composition of Fe-5%Si alloy used in this study.

C	Si	Mn	P	S	sol.Al	N
mass%	mass%	mass%	mass%	mass%	mass%	mass%
0.0047	4.99	<0.01	0.002	0.0009	0.002	0.0022

using an Instron-type testing machine at various strain rates ranging from 10^{-5} to 10^0 /s. The gauge length, width and thickness of the test pieces for tensile tests were 6.0, 2.0 and 1.2 mm, respectively. The tensile axis was parallel to the rolling direction (RD). Microstructural observations were conducted using an optical microscope and scanning electron microscope (SEM) equipped with an electron backscattering diffraction (EBSD) system. SEM observations and EBSD measurements were conducted with an accelerating voltage of 15kV. The EBSD measurements were performed with a step size of $0.25\mu\text{m}$ to clarify the existence of deformation twins.

3 Results and discussion

3.1 Microstructure before tensile test

Fig. 1 shows the optical microstructures of 0% rolled (a), 20% rolled (b), 40% rolled (c) and 50% rolled (d) alloys before tensile test. Figure 2 shows the band contrast maps obtained from the EBSD measurement of 0% rolled (a), 20% rolled (b), and 50% rolled (c) alloys before tensile test. In the band contrast maps, bold and narrow solid lines indicate high-angle boundaries and low-angle boundaries with misorientations between adjacent measurement points are being larger and smaller than 15° , respectively. The boundaries with misorientation smaller than 1.5° were ignored to eliminate inaccuracy in EBSD analysis. The 0% rolled alloy had elongated grains along the RD. However, each grain can be regarded as almost fully recrystallized ferritic grain, because there are few low-angle boundaries within the grains. Similar elongated grains were observed from the optical micrographs in rolled alloys by the reduction of 20%, 40% and 50%. In these cases, some low angle boundaries were introduced. This means that the dislocations were introduced within the grains. No deformation twins were observed in any alloy because rolling was conducted at high temperature.

Fig. 1 Optical microstructures of 0% rolled (a), 20% rolled (b), 40% rolled (c), and 50% rolled (d) alloys. Observations were conducted from the TD.

Fig. 2 Band contrast maps obtained from EBSD measurements of 0% rolled (a), 20% rolled (b), 50% rolled (c) alloys, respectively. EBSD analyses were conducted from the RD.

3.2 Effect of pre-deformation on fracture behavior transition due to strain rate change

Fig. 3 shows the optical micrographs of the fractured specimen by thickness reduction of 0% (a), 20% (b), 40% (c), and 50% (d) after the tensile test at a strain rate of 10^{-4} /s. The gauge widths as a function of distance

Fig. 3 Appearances of the fractured tensile specimens in 0% rolled (a), 20% rolled (b), 40% rolled (c), and 50% rolled alloys (d) at the strain rate of 10^{-4} /s. The gauge widths as a function of distance from the fractured surface in 0% and 50% rolled alloys were plotted in (e).

Fig. 4 Nominal stress-nominal plastic strain curves of various strain rates in 0% rolled (a), 20% rolled (b), 40% rolled (c), and 50% rolled (d) alloys.

from the fractured surface in 0% and 50% rolled specimen were measured by measuring microscope and plotted in Fig. 3 (e). All tensile specimens were fractured near the center of the gauge. In addition, 0% rolled specimen was fractured without any necking and surface change indicating a completely brittle manner. For this specimen, the gauge width near the fracture surface was about 2.0 mm, indicating that the tensile specimen was fractured in completely brittle manner. On the other hand, in the rolled specimen, deep and complicated relief appeared on the surface. The gauge width was decreased as approaching the fracture surface. This means that slight necking due to local plastic deformation was observed near the fractured plane.

Fig. 4 shows the nominal stress-nominal plastic strain curves at various strain rates obtained from 0% rolled (a), 20% rolled (b), 40% rolled (c), and 50% rolled (d) alloys. The tensile specimen of 0% rolled alloy broke down without the reduction of nominal stress, (i.e. the localization of plastic deformation) at any examined strain rates. The stress-strain curves similar to those of the 0% rolled alloy were observed for the 20% rolled alloy at a strain rate equal or higher than $10^{-3}/s$. On the other hand, when the 20% rolled alloy was examined at the strain rate of $10^{-4}/s$, the elongation with local elongation (deformation after maximum load) was largely recovered. This tendency was also observed in the 40% and 50% rolled alloys. The existence of local elongation shown in the stress-

strain curves corresponded well with the appearance of necking in the fractured tensile specimens (Fig. 3). This result indicates that the Fe-5%Si alloys with dislocations by rolling have fracture behavior transition (with/without local elongation) due to the strain-rate change. Similar transition has been observed in fully recrystallized Fe-4%Si alloy.^{5), 6)} Note that regardless of the fracture manner or occurrence of necking, the elongation becomes larger when rolling reduction increases. This point is discussed later in Fig. 7.

Fig. 5 shows the true stress and work hardening rate as a function of true strain in the 0% rolled (a) and the 50% rolled (b) alloys. The work-hardening rate corresponds to the slope of the true stress-true plastic strain curve. In the 0% rolled alloy, the tensile specimen was fractured before the true stress became equivalent to the work-hardening rate. This means that the specimens were fractured until the maximum stress during the work hardening process. A similar tendency was observed in the 50% rolled alloy in the case when the specimen was fractured without local elongation (at a strain rate of $10^{-1}/s$). On the other hand, fracture approximately took place when the true stress was equivalent to work hardening rate in the case when the specimen was fractured with local elongation.

Fig. 6 (a-1) and (b-1) shows the SEM images of the fractured plane at a strain rate of $10^{-4}/s$ in the 0% rolled (with no local elongation) and 50% rolled specimen

Fig. 5 True stress-true strain curves and work hardening rate-true strain curves in 0% rolled (a) and 50% rolled (b) alloys.

(with local elongation), respectively. The SEM low magnification images are also shown in the upper-right part of the images. The tensile specimen of 0% rolled alloy was fractured in a brittle transgranular cleavage manner without necking because the surface was smooth. The fractured surface of this alloy was also covered with cleavage fractured pattern. In this case, the fractured surface was relatively rough with slight necking, indicating that the specimen was fractured in a completely brittle intergranular cleavage manner. It was also found that the fractured surfaces of both alloys had many cracks as indicated by arrows. However, the length of the crack on the as-received sample (larger than a few hundred μm) was somewhat larger than that of the 50% rolled specimen (approximately a few hundred μm). This difference probably indicates that the propagation of the cleavage crack can be suppressed by the dislocation microstructure introduced by hot rolling. High-magnification SEM images of Fig. 6 (a-1) and (b-1) are shown in Fig. 6 (a-2) and (b-2), respectively. From Fig. 6 (a-2), many band-like contrasts were observed on the fracture surface. These contrasts were considered to be deformation twins, which is discussed later in Fig. 8. This indicates that fracture with no local elongation is associated with deformation twins and that twin boundaries act as a crack initiation site.¹⁶⁾ On the other hand, fewer deformation twins were observed on the fractured surface in the 50% rolled alloy with local elongation. In this case, it is considered that dislocations piled up against obstacles, such as grain boundary, leads to initiation of cleavage fracture⁷⁾

Fig. 6 SEM secondary electron images of the fractured tensile specimen at a strain rate of $10^{-4}/\text{s}$ in the 0% rolled (a) and 50% rolled (b) alloy. High-magnification images of (a-1) and (b-1) are shown in (a-2) and (b-2), respectively.

and that the crack initiation site in Fe-5%Si alloy was changed with/without local elongation. It is difficult to detect a change of the fracture manner from brittle to ductile by conventional fractography clearly because all tensile specimen examined fractured in a brittle manner. Alternatively, in this study, the fracture behavior was classified by the existence or non existence of local elongation.

Fig. 7 summarizes the relationship between the strain rate and tensile properties of the Fe-5%Si alloys with various microstructures. The 0.2% proof strength (a) and tensile stress (b) tended to increase with the increasing of the reduction and strain rate. This strength is likely to be caused by the dislocations introduced by rolling. The total elongation (c) tended to increase with the increase of the reduction by the rolling when the data were compared at the same strain rate. This indicates that the introduction of dislocation substructures enhances the ductility of Fe-high Si alloy. In addition, the rolled alloys showed discontinuous large drops in total elongation, as denoted by the arrows in Fig. 7. For example, the total elongation in the 20% rolled alloy decreased drastically at a strain rate between $10^{-4}/\text{s}$ to $10^{-3}/\text{s}$. The strain rate at which this drop takes place corresponds well with the strain rate at which local elongation disappeared, as shown in Fig. 4. Thus, the strain rate at which the elongation drops drastically can be regarded as a threshold value that indicates the transition of the fracture behavior. The threshold strain rate increased with the increasing of the reduction. It is occasionally considered that fracture process is controlled by thermally activated motion of dislocation. In this sense, low-temperature deformation is equivalent to high strain rate deformation.

Fig. 7 0.2% proof stress (a), tensile stress (b) and total elongation (c) of Fe-5%Si alloys with various rolling reductions at various strain rates.

The higher strain rate at which ductile-brittle transition occurs corresponds with the lower ductile-brittle transition temperature. It is also considered that the transition temperature is a benchmark of toughness in Fe-Si alloy. Consequently, it can be mentioned that the introducing of dislocation substructure by larger pre-strain improves both ductility and toughness of the Si steel effectively.

It is generally considered that brittle fracture with no plastic deformation takes place when stress reaches the cleavage fracture stress determined by the composition¹⁷⁾ and the microstructure. However, the fracture in brittle manner in all Fe-5%Si alloys occurs after some plastic deformation. This means that the brittle fracture in Si steel cannot be explained by the conventional comparison of the fracture and yield stresses,¹⁸⁾ because the influence of the deformation microstructure, such as dislocation substructure and deformation twins evolved by plastic deformation before fracture, can be predicted. Fig. 8 (a) and (b) shows the SEM backscattering electron images of the fractured tensile specimen at 10^{-4} /s in 0% rolled

Fig. 8 SEM backscattered images of the fractured tensile specimen in the 0% rolled (a) and 50% rolled (b) alloy at a strain rate of 10^{-4} /s. SEM backscattered image and crystal-orientation map taken of the same area obtained from a fractured specimen were also shown.¹⁹⁾

(with no local elongation) and 50% rolled (with local elongation) alloy. Band-like features with a thickness in the order of a micrometer across the grain were identified. Previous study of our group¹⁹⁾ reported that similar band-like features identified by SEM backscattered images from a fractured specimen in Fe-5%Si alloy and that these were determined to be deformation twins because the crystal orientation of this area is quite different from that of the grain, and the boundaries between them were characterized to be twin boundaries of $\Sigma 3$ type (Fig. 8 (c)). Therefore, these features shown in Fig. 8 (a) and (b) were classified to be deformation twins. As shown in these figures, both fractured tensile specimens contain deformation twins (as indicated by arrows in Fig. 8 (a) and (b)) near the fractured plane, however, the number density of twins in the 0% rolled alloy was much higher than that of the 50% rolled alloy. This corresponds with the SEM observation of the cracks, shown in Fig. 6. This indicates that the initiation of the twinning was inhibited by the dislocation substructure as shown in Fig. 6 (a-2) and (b-2). Some researchers^{4), 13)} suggest that dislocation substructures such as mobile dislocations introduced by pre-deformation improve the ductility of Fe-high Si alloys. Unfortunately, it has not been clarified if dislocations induced by rolling were mobile dislocations. However, our obtained results indicate that the dislocation substructures evolved by rolling suppressed the initiation of twinning.

4 Conclusions

The fully recrystallized Fe-5%Si alloys were fractured in the brittle manner at different strain rates and the transition strain rate was not found. The Fe-5%Si alloys with dislocations introduced by rolling exhibited fracture behavior transition due to strain-rate change. All rolled alloys were fractured with necking at slower strain rates. When the strain rate became higher than the threshold

value, the local elongation (necking) disappeared and the fracture manner changed to brittle. The threshold strain rate is higher with increasing of the rolling reduction. The fractography and microstructures in the fractured samples indicated that dislocations substructures are effective for inhibiting the initiation of the deformation twins. Consequently the enhancement of both toughness and ductility in Fe-high Si alloy can be achieved.

This study was financially supported by JSPS KAKENHI Grant Number 23760700 and by the fund for Kagawa University Young Scientists 2010. The author gratefully appreciates all of the support received.

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