Effect of Si content on fatigue fracture behavior of hot-rolled high-silicon steels

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Abstract. As the Si content was increased from 1.5 to 5 mass%, both the yield stress and ultimate tensile strength were increased, respectively. The work hardening rate was also increased as the increase of Si content. On the contrary, the elongation was decreased as the increase of Si content, and the fracture manner was shifted from ductile to brittle. The $10^7$ cycles fatigue strength was higher as the increase of Si content. The small misorientation distribution as ladder-like was detected in the grains of 1.5 mass%Si steel. Around the grain boundary, the strain incompatibility was detected in the steels containing over 3 mass%Si. The lattice rotation was locally detected in the vicinity of grain boundaries.

1. Introduction
The addition of Si in α-iron (bcc) presumably lowers its stacking fault energy so that cross slip is strongly suppressed.[1] Such slip manner provides planar dislocation structures under fatigue deformation. The subsurface fatigue crack generation in titanium alloys (hcp) and austenitic steels (fcc), which has been commonly reported in high-cycle regime and at low temperature,[2,3] is closely related with heterogeneous deformation due to the restriction of slip systems.[4,5] Si addition in steel causes the restriction to {110} <111> primary slips, especially over 3.8 mass% Si content at room temperature.[6] The deformation and fatigue fracture behavior in Si steels depend on their Si content and are highly reflected on their crystal orientation and microstructure. Ushioda et al.[7] investigated the evolution of dislocation structures in Fe–Si alloys with 0, 0.5 and 1 mass%Si during a cyclic bending test. In the 1 mass%Si steel, the vein structure developed, and many intergranular cracks were detected. The mixed cleavage mode and crack front branching on the fatigue crack growth were detected in 2 mass%Si steel.[8] In 3 mass%Si steel, the fatigue crack initiation sites were mostly located at the grain boundaries and that fatigue crack growth rate was lowered at some grain boundaries.[9] The <111> slip bands and regular arrays of dislocation wall structure like “labyrinth” were seen around fatigue crack tip region.[10] Therefore, the deformation behavior in the vicinity of grain boundaries should make an important role on fatigue crack generation and crack growth in high Si steels. Few studies, however, have been done on the cyclic deformation structure and crack generation in polycrystalline high Si steels. In the present study, the effects of Si content on high-cyclic fatigue fracture and deformation structure in the polycrystalline steels containing Si as 1.5, 3, 4 and 5 mass% have been studied.
2. Experimental

2.1. Test materials
The Fe-Si alloys containing 1.56, 3.00, 3.95 or 4.86 mass%Si were hot-rolled either by flat rolling (FR: heating at 1373 K for 60 min + heating at 1373 K for 60 min) or grooved-rolling (GR: heating at 1373 K for 30 min + 1273 K for 30 min). The materials were named as FR1.5, FR3, FR4, FR5, GR1.5, GR3, GR4 and GR5. Their average grain sizes were from 535 µm to 570 µm in diameter for the FR and from 263 µm to 298 µm in diameter for the GR. Although almost no dislocations were detected in the FR materials, some mobile dislocations were dispersed in the GR materials.

2.2. Testing
The round bar type specimens with a diameter of 4 mm for both tensile and fatigue tests were machined from the plates or rods as parallel to the rolling direction. Tensile test (displacement-controlled) was carried out at an initial strain rate of about 4 x 10^-4 sec^-1 using a screw-driven machine at room temperature. Yield strength was evaluated by the offset value of 0.2% proof stress using an extensometer. Load-controlled fatigue test was carried out in the air using a servo-hydraulic machine. The sinusoidal waveform loading was uniaxial with a minimum-to-maximum stress ratio, R (σ_min/σ_max), of 0.01 and the test frequency was 20 Hz.

2.3. Microscopy and characterization
The microstructure and fatigue-crack-initiation sites and fracture surfaces were studied by scanning electron microscopy (SEM). The electron backscatter diffraction (EBSD) analysis with SEM was performed to characterize deformation microstructure and orientation. The EBSD-Wilkinson measurements [11] was adopted to elastic strain field analysis. Transmission electron microscopy (TEM) was also applied to determine the dislocation structure. For fatigued specimens, TEM disks about 600 µm thick were sectioned from beneath the fracture surface. They were cut perpendicular to the principal stress axis and were reduced to less than 100 µm in thickness by abrasion with No. 600 emery paper. Both the TEM foils and EBSD samples were finally prepared by a conventional electrical-jet polishing technique in a stirred solution of 20 pct perchloric acid, 70 pct ethanol and 10 glycerol.

3. Results and discussion

3.1. Tensile properties
Figure 1 represents the stress – strain curves of the GR materials, and Table 1 summarized the tensile properties of tested materials. As the Si content was increased from 1.5 to 5 mass%, both the yield stress and ultimate tensile strength were increased from 239 MPa to 471 MPa and from 365 MPa to 713 MPa, respectively. The FR materials showed similar stress – strain curves as the GR ones, but their tensile strength was lower as from 322 MPa to 682 MPa due to larger grain sizes. The work hardening rates were increased as the increase of Si content, too. On the contrary, the total elongation and reduction of area were decreased from 25.5% to 6.9% and from 88% to 5% in the GR as the increase of Si content. The FR1.5 and GR1.5 appeared a ductile fracture surface covered with dimples, and the fracture manner was shifted from ductile to brittle as the increase of Si content.

3.2. Fatigue properties
The 10^7 cycles fatigue strength was higher as the increase of Si content in the FR and GR materials. In every alloy, the 10^7 cycles fatigue strength in the GR material was higher than that in the FR one. It may be resulted from the smaller grain size in the GR materials. On the contrary, the ratio of 10^7 cycles fatigue strength by ultimate tensile strength was lowered as the increase of Si content. Their ratios were less than 0.5 in the FR materials. The GR1.5 was 0.84, and the others were about 0.75.
The FR1.5 showed a ductile fracture manner in the stage III as shown in Figure 3(a). The GR1.5 and GR3 fractured with low cycles also showed a ductile fracture manner in the stage III. The others appeared brittle manner. Fatigue crack initiation sites in FR5.0 were detected at the specimen interior as shown in Figure 3(b).

![Figure 1. Nominal stress – nominal strain curves of the GR materials.](image1)

### Table 1. Tensile properties of test materials.

| Materials | Average grain size (µm) | Ultimate tensile strength (MPa) | 0.2% proof stress (MPa) | Elongation (%) | Reduction of area (%) |
|-----------|-------------------------|--------------------------------|------------------------|----------------|-----------------------|
| FR1.5     | 570                     | 322                            | 207                    | 21             | 90                    |
| FR3       | 547                     | 432                            | 338                    | 14             | 73                    |
| FR4       | 561                     | 566                            | 472                    | 15             | 48                    |
| FR5       | 535                     | 682                            | 560                    | 11             | 8                     |
| GR1.5     | 263                     | 365                            | 239                    | 37             | 88                    |
| GR3       | 298                     | 481                            | 312                    | 26             | 62                    |
| GR4       | 294                     | 605                            | 428                    | 22             | 55                    |
| GR5       | 286                     | 713                            | 471                    | 7              | 5                     |

![Figure 2. S-N data of the FR (a) and GR (b).](image2)
3.3. Strain incompatibility at grain boundaries
Both Si content and cycle stress were significantly influenced the evolution of the dislocation structure. The dislocation structure was more rectilinear as the increase of Si content or the decrease of cycle stress. In the GR1.5, the Vein structure of saturated dislocation arrangement was well developed. In the FR1.5, the cellular structure was also developed by cyclic deformation as shown in Figure 4(a). As Si content was increased, dislocation arrangement became planar and its density was lowered as the sub-boundary structure shown in Figure 4(b).

The strain and misorientations were detected in both grain boundaries and cell boundaries. The small misorientation distribution as ladder-like was detected in the grains of the FR1.5 and GR1.5 as shown in Figure 5(c) and Figure 6(a). It may reflect on the cellular structure or Vein structure. In the FR5 and GR5, on the other hand, no strain distribution in grains but sub-grains along the grain boundary were detected as shown in Figure 5(d) and Figure 6(c).

According to the EBSD-Wilkinson measurements, the elastic strain was partitioned among the grains in the FR1.5 as shown in Figure 6(b). On the other hand, the lattice rotation was detected in the vicinity of grain boundaries in the FR5 as shown in Figure 6(d). It may give a local stress concentration and a site of cracking.

Therefore, Si addition enhanced the strain gradient at grain boundaries, which may strongly influence on the fatigue crack generation and fatigue strength of high Si steels.
Figure 5. Back scatter electron images of microstructure after $10^7$ cycles: (a),(b) FR1.5 ($\sigma_{\text{max}}=258$ MPa) and (c),(d) FR5 ($\sigma_{\text{max}}=362$ MPa).

Figure 6. Kernel average misorientation and rotation angle ($W_{12}$) of near the boundaries after $10^7$ cycles: (a),(b) FR1.5 ($\sigma_{\text{max}}=258$ MPa) and (c),(d) FR5 ($\sigma_{\text{max}}=362$ MPa).

4. Conclusions
The effect of Si content on high-cyclic fatigue fracture behaviour in the steels containing Si as 1.5, 3, 4 and 5 mass% were studied. Major results were summarized as follows:
(1) Both tensile strength and yield strength were increased as the increase of Si content, although the fracture manner was shifted from ductile to brittle. The work hardening rate was increased as the increase of Si content, too.

(2) The $10^7$ cycles fatigue strength was higher as the increase of Si content.

(3) The small misorientation distribution as ladder-like was detected in the grains of 1.5 mass%Si steel. It may be reflected on the cellular structure or Vein structure of saturated dislocation arrangement developed by cyclic deformation. The elastic strain was partitioned among the grains.

(4) Around the grain boundary, the strain incompatibility was detected in high Si steels, e.g. 5 mass%Si steel. The lattice rotation was detected in the vicinity of grain boundaries. It may give a local stress concentration and a site of cracking.

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