HIGH-CYCLE FATIGUE PROPERTIES OF FINE PARTICLE PEENED FE-3MASS%SI STEEL SHEETS

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ABSTRACT: Effects of heavy peen with fine particles and grain size on both tensile and fatigue properties of Fe-3mass%Si steel sheets have been studied. Fine grain structure resulted in higher tensile strength and 10^7 cycles fatigue one. The fine particle peen increased tensile elongation and fatigue strength. The increase of about 14% in 10^7 cycles fatigue strength by fine particle peening was available for the materials over several ten μm in grain diameter, while there was no big difference for the material with finer grain size. Mobile dislocations in the specimen surface were employed more homogeneous plastic deformation there and resulted in higher resistance against crack generation, since strain incompatibility at grain boundaries due to heterogeneous planer slip causes local stress concentration. Electron backscatter diffraction analyses made clear fatigue damage structures such as plastic deformation in the surface layer, crystal rotation in grains and localized deformation bands in large grains.

KEY WORDS: high-cycle fatigue, shot peen, electro-magnetic steel, mobile dislocation, electron backscatter diffraction

微粒子ピーニングを施した FE-3MASS%SI 鋼の高サイクル疲労特性

概要: Fe-3mass%Si 鋼薄板の引張特性と疲労特性に及ぼす微粒子ハードピーニングと結晶粒サイズの影響について検討した。結晶粒微細化では引張強度および 10^7 回疲労強度の増大が得られた。微粒子ピーニング処理の結果、引張延性と疲労強度が向上した。微粒子ピーニング処理では、結晶粒径が数十 μm 以上の粗大粒組織において 10^7 回疲労強度は 14%程度の向上が認められたが、微細粒材では微粒子ピーニングの効果は少なかった。これは、試験片表層に導入した可動転位によってより均一な塑性変形が表層部で得られ、き裂発生抵抗が高まったためである。なぜならば、不均一な平面的すべりにより粒界に生じるひずみ不整合が局所的応力集中をもたらすからである。EBSD 解析の結果、表層部の塑性変形、結晶粒内の方位回転、粗大粒内の変形帯といった疲労損傷が明確となった。

VYSOKOCYKLOVÁ ÚNAVA TENKÝCH PLECHŮ FE - 3 HM.% SI PO TRYSKÁNÍ JEMNÝMI ČÁSTICEMI

ABSTRAKT: Byly studovány vlivy zpevnění tryskáním jemnými částicemi a velikosti zrna na tahové a únavové vlastnosti tenkých plechů Fe – 3hm.%Si. Jemnozrná struktura má vysokou pevnost a vysokou mez únavy 107 cyklů. Tryskáním jemnozrnnými částicemi se dosahuje zvýšení meze pevnosti a meze únavy. U materiálů s velikostí zrna v desítkách μm bylo zpevněním povrchu tryskáním jemnými částicemi dosaženo 14% zvýšení meze únavy 107 cyklů, zatímco u jemnozrnné struktury nebyl zjištěn významný rozdíl. Mobilita dislokací na povrchu vzorku vyvolaná homogennější plastickou deformací způsobovala vyšší odolnost proti vzniku trhlin vzhledem k deformační rozdílnosti na hranicích zrn v důsledku heterogenních planárních skluzů zapříčiněných

1 INTRODUCTION

Since planer slip with primary system is dominant in cyclic deformation of Fe-3mass%Si steel,[1] stress concentration is produced in the vicinity of grain boundary, especially for large grain structure. The stress concentration affects on fracture behavior of the steel, and fine grain structure results in higher fatigue strength.[2] Fine particle peen [3] is one of the process to install compressive residual stress in the specimen surface regime, where mobile dislocations may also exist. Mobile dislocations dispersed in grains increase plastic strain and decrease a strain incompatibility at grain boundaries after cyclic deformation.[4] In the case of thin sheet, stress condition under cycle loading is approximated with the plane stress condition. It is not clear, however, how the installed plastic strain in the surface regime of the sheets with various grain sizes increases their fatigue strength. Therefore, effects of fine particle peen and grain size on both tensile and fatigue properties of Fe-3mass%Si steel sheets have been studied.

2 EXPERIMENTAL PROCEDURE

2.1 Test material

Cold-rolled Fe-3mass%Si steel sheet with the thickness of 0.5 mm was annealed at the temperatures from 1073K to 1373K. Average grain sizes of the sheets were 45µm (No.1), 73µm (No.2), 105µm (No.3) and 273µm (No.4) in diameter. Heavy peen with fine particle applied to each specimen surface in the following conditions: high-speed-steel shot, pressure of 0.5 MPa and coverage of 100 %.

2.2 Tensile test and fatigue test

Tensile test of the thin sheets was carried out at the initial strain rate of 2.1 x 10^{-4} sec^{-1} at 293K. A load controlled axial fatigue test was done with the stress ratio (minimum cyclic stress / maximum cyclic stress), $R=\sigma_{min}/\sigma_{max}$, of 0.01 at 293 K using the specimen shown in Fig.1.

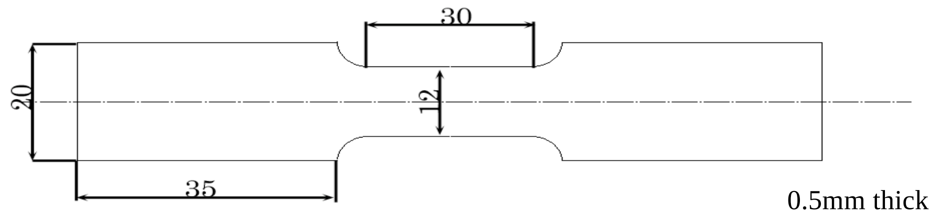


Fig.1: Configuration of fatigue test specimen of the steel sheets.

2.3 Microscopy

The microstructure and fracture surfaces were studied by scanning electron microscopy (SEM). Electron backscattered diffraction (EBSD) pattern analysis with

SEM was performed to determine the matrix structure. A data set of point analyses with every 0.1 or 0.05 μm beam scanning in hexagonal grids yielded image and orientation maps characterizing the matrix structure. Transmission microscopy (TEM) was also employed to characterize the microstructure produced by the peening.

3 RESULTS AND DISCUSSION

3.1 Tensile properties

Figure 2 shows stress-strain curves of the test materials. The finer grain size is, the higher ultimate tensile strength, σ_B, is. There is no big difference in strength between annealed material and peened one. But the peened materials show higher elongation than unpeened ones, respectively.

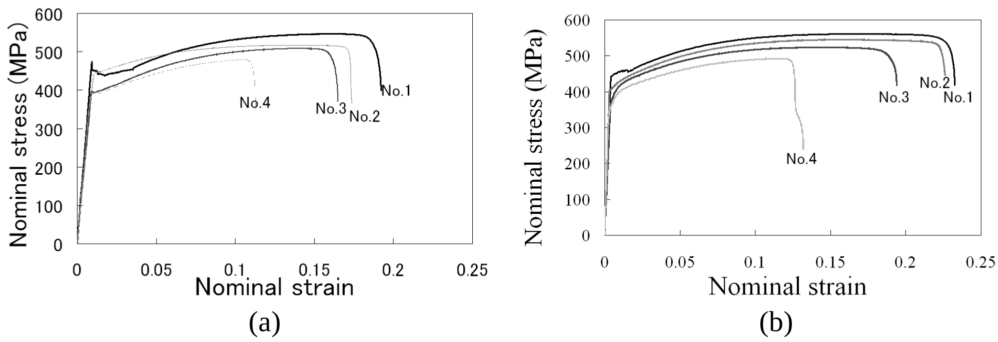
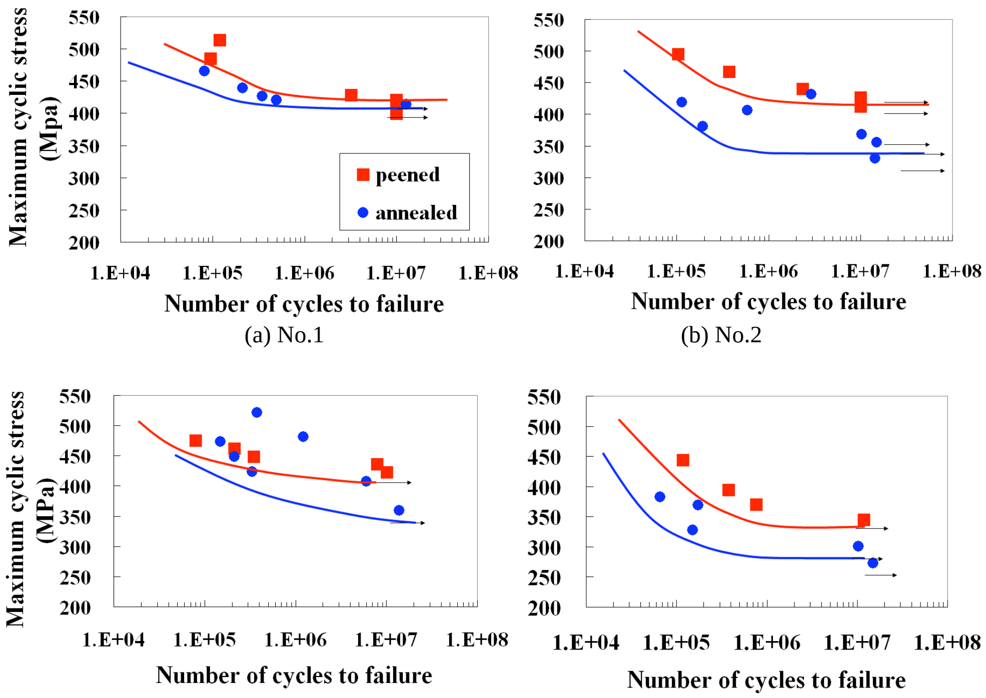


Fig.2: Stress-strain curves of materials as annealed (a) and peened (b).

3.2 S-N data

Figure 3 shows the S-N curves of Fe-3mass%Si steel sheets and also describes the data from a previous work.[2] Fine grain structure provided higher 10^7 cycles fatigue strength among peened materials as well as annealed ones.

The fine particle peen increased tensile elongation and fatigue strength. The increases of about 14% in 10^7 cycles fatigue strength was available for the materials over 60 μm in grain diameter, while there was no big difference for the material with finer grain size. The fatigue strength in low-cycle regime of peened No.1 is slightly higher than that of unpeened one. The 10^7 cycles fatigue strength of peened Nos.2 and 3 is almost as high as that of No.1. Thus not only the compressive residual stress installed in the surface layer of the specimens but also plastic deformation behavior should be taken into account for the increase of fatigue strength by the peening.



(a) No.1 (b) No.2 (c) No.3 (d) No.4

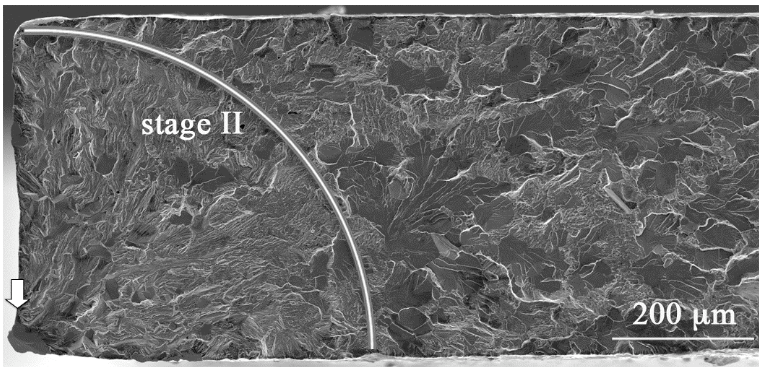
Fig.3: S-N data of test materials.

3.3 Fracture surface

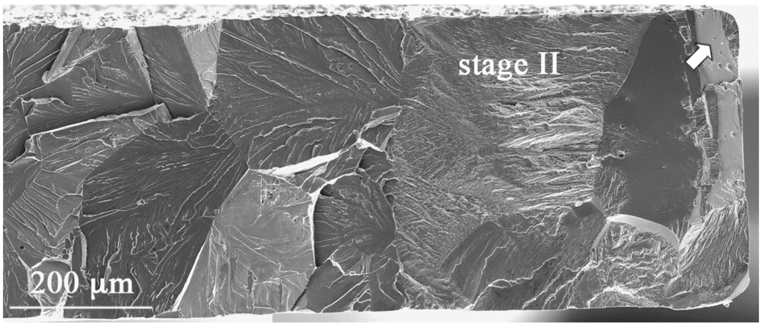
Tensile fracture behavior strongly depended on grain size. The samples of No.3 and No.4 showed quasi-brittle and ductile manners on their surface, although those of No.1 and No.2 showed fully ductile.

Figure 4 represents fatigue fracture surfaces of No.1 and No.4 samples. Crack initiation site are detected at an edge of the specimen surface as shown by arrows in the figure. At the sites a facet is seen. Crack growth regime, stage II, and rapidly fracture one are clearly seen. Mostly quasi-cleavage fracture and river patterns appear on the rapidly fracture surface. In the No.1 ductile fracture manner was also observed in the final fracture part. The rapidly fracture surface was similar to the tensile fracture one.

In each material, no remarkable influence of fine particle peen on fracture surface was detected.



(a) σ_{max}=0.77σ_B, 497,844 cycles



(b) σ_{max}=0.69σ_B, 151,954 cycles

Fig.4: Fatigue fracture surface of specimens as annealed (a) No.1 and (b) No.4.

3.4 Plastic deformation and strain distribution

Sub-grains with about 200 nm in diameter and dislocations were observed in the surface layer for the peened materials. Plastically homogenous deformed region was built in the surface layer with about 50 μm in depth for the fatigued materials in both as annealed and peened conditions. Such deformation region was clearly distinguished from matrix structure. In the vicinity of those boundary, a steep deformation gradient with crystal rotation in matrix grains appeared. Crystal rotation in matrix grains and localized deformation bands in large grains were also detected.
It is likely that mobile dislocations in the specimen surface are employed more homogeneous plastic deformation and result in higher resistance against crack generation, since strain incompatibility at grain boundaries due to heterogeneous planer slip causes local stress concentration.

4 CONCLUSIONS

Effects of heavy peen with fine particles and grain size on both tensile and fatigue properties of Fe-3mass%Si steel sheets were studied. Major results were concluded as follows:

(1) Fine grain structure provided higher tensile strength and 10^7 cycles fatigue strength.
(2) The fine particle peen increased tensile elongation and fatigue strength. The increases of about 14% in 10^7 cycles fatigue strength was available for the materials over 60 μm in grain diameter, while there was no big difference for the material with finer grain size.
(3) Fracture behavior strongly depended on grain size. In each material, almost no influence of fine particle peen on fracture surface was detected. Crack initiation site was detected at an edge of the specimen surface. Crack growth regime and rapidly fracture one were clearly seen.
(4) Electron backscatter diffraction analyses made clear fatigue damage structures such as plastic deformation in the surface layer (about 50 μm in depth), crystal rotation in grains and localized deformation bands in large grains. Thus mobile dislocations in the specimen surface were employed more homogeneous plastic deformation and resulted in higher resistance against crack generation, since strain incompatibility at grain boundaries due to heterogeneous planer slip causes local stress concentration.

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