

Effects of Sulfur Level and Anisotropy of Sulfide Inclusions on Tensile, Impact, and Fatigue Properties of SAE 4140 Steel

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ABSTRACT

During metal forming processes such as rolling and forging, deformable manganese sulfide (MnS) inclusions become elongated. Such elongated MnS inclusions can have considerable adverse effects on mechanical properties; if the inclusions are not aligned with the loading direction. The objectives of this study were to evaluate and compare fatigue, monotonic tensile and CVN impact behavior of SAE 4140 steel with high (0.077% S), low (0.012% S) and ultra low (0.004% S) sulfur contents at two hardness levels (40 HRC and 50 HRC). The longitudinally oriented samples at 40 HRC, where MnS inclusions were oriented along the loading direction, did not exhibit any significant sensitivity of tensile or fatigue properties to the sulfur content. For the transversely oriented MnS inclusions, however, the monotonic tensile test results indicate very low ductility of the high sulfur material at both hardness levels, where specimens failed shortly after yielding. The yield strength of the materials, however, did not differ significantly with the sulfur content. With regards to fatigue strength, the high sulfur material had up to 25% lower fatigue strength than the ultra low sulfur material under transverse loading. The scanning electron microscopy (SEM) inspection of failed fatigue test specimens revealed that the fracture topography of the high sulfur material were very rough and jagged, indicating several cracks originating from MnS inclusions. The fracture surfaces of the other two materials with lower sulfur content exhibited typical fatigue fracture surfaces with clear initiation and final fracture regions.

INTRODUCTION

Metal forming processes such as rolling and forging often result in anisotropic microstructure and elongation of deformable MnS inclusions. The elongated MnS inclusions are of different effective area when loaded along different axes. This results in anisotropy of fatigue and monotonic properties. Although the presence of

sulfur improves the machinability of steel, deformable MnS inclusions cause anisotropy in mechanical and fatigue properties.

In a study involving billet and bar specimens Furuya et al⁽¹⁾ reported that at 10^8 cycles the axial fatigue strength in the transverse direction was about half of that in the rolling direction, and that large but thin MnS inclusions were responsible for this deterioration in fatigue strength. Temmel et al⁽²⁾ studied the effect of MnS inclusions on axial fatigue limit by conducting tests on steels at two sulfur levels (0.004% S and 0.042% S) and reported a reduction of fatigue limit in the transverse direction at both sulfur levels. Increasing the sulfur content by a factor of 10 resulted in a decrease of the fatigue limit in the transverse direction by up to 38%. Temmel et al also reported that ductility was affected the most among the tensile properties of the higher sulfur steel under transverse loading.

Kage and Nisitani⁽³⁻⁸⁾ studied anisotropy in low carbon rolled steels under tension-compression, torsion and rotating bending loading conditions. Monotonic tension tests were conducted on specimens oriented at 0°, 22.5°, 45°, 67.5° and 90° to the rolling direction. These tests revealed that the yield strength was reduced in the 67.5° and 90° oriented specimens by about 25% when compared to the specimen oriented at 0°, the ultimate tensile strength reduced by 8%, the area contraction reduced by about 23% and the true stress at fracture by about 26%. The bending fatigue limit was reduced by 10.5% while no significant anisotropy was noticed in static or cyclic torsion tests⁽³⁾. Kage and Nisitani⁽⁴⁾ reported that annealing decreased the anisotropy of monotonic properties and fatigue limits under rotating bending loading conditions slightly.

For push-pull fatigue, Kage and Nisitani⁽⁵⁾ reported that there is remarkable anisotropy between the fatigue strength in the rolling and thickness directions. This was attributed to the fatigue crack initiating from slip bands and grain boundaries in the rolling direction.

while cracks initiated from inclusions in the thickness direction specimens. Both the life to crack nucleation and to final failure (propagation) were much lower in the transverse direction than in the rolling direction. They reported that anisotropy in low-cycle and high cycle torsional fatigue between the rolling and the thickness directions was not significant because the inclusions contributed to crack initiation in both orientations. This was further explained by the existence of similar effective inclusions along the maximum shear stress planes for both directions⁽⁵⁾.

Kage and Nisitani⁽⁷⁾ also compared the effects of bar-shaped and plate-shaped inclusions under torsion and bending loading conditions on specimens oriented at 0°, 45° and 90° to the rolling direction. They reported that the plate shaped inclusions had a more negative effect on fatigue life in both loading cases. It was observed that for the material with bar-shaped inclusions, only the failure of the thickness direction specimen in bending fatigue originated from inclusions. In the case of the material with plate shaped inclusions, it was observed that the failures of the 45° specimen and thickness direction specimens under bending loading condition originated from inclusions. In torsional fatigue, it was noted that fatigue cracks develop in all specimens from inclusions in the material with circular plate type inclusions. The authors state that in each specimen orientation, the fatigue limit in torsion was governed by the limiting condition for the non propagation of cracks that initiated from the inclusions, whereas in bending fatigue some cracks did not initiate from inclusions depending on the direction where the specimen was removed. In order to explain the anisotropy in fatigue life between the rolling direction and thickness direction in rotating bending, the authors assumed that the inclusions in the thickness direction could be regarded as cracks, so that the total life of the specimen in the thickness direction would be equal to the crack growth life. In the rolling direction specimens, the fatigue cracks mostly originated at the grain boundaries and the fracture surface at the boundaries was very smooth. The high inclusion transverse specimens were reported to exhibit very rough fracture surfaces as a result of multiple cracks originating from inclusions^(2,8).

Specimens prepared from the rolling and thickness direction of strength-anisotropic rolled steel subjected to a tensile pre-strain were tested in rotating bending fatigue tests (Kage and Nisitani)⁽⁶⁾. The tensile pre-strain caused the separation of inclusions from the material in the case of the thickness direction specimens and the fatigue limit increased. The authors state that regardless of the percentage of tensile pre-strain, the fatigue limit in the transverse direction was still determined by the propagating limit conditions for non-propagating cracks originating from inclusions. They report that for all cases of pre-strain, the inclusions did not have any relation to the crack initiation in rolling direction specimens. In both directions, the locations of concentration where the slip bands originated in the fatigue process were the same

for the pre-strained specimens as with the ones without pre-strain.

In the present study, SAE 4140 steel was produced to three different sulfur levels and two hardness levels and tested under axial fatigue, monotonic tensile and impact loading conditions. This paper presents the experimental procedures, the results obtained and the fractography analysis of the fracture surfaces.

MATERIAL AND SULFUR CONTENT

The material used in this study was SAE 4140, supplied in three different sulfur levels (high: 0.077%; low: 0.012% and ultra low: 0.004%). Table 1 shows the chemical composition of the three heats.

Table 1: Chemical composition of 4140 steels used

Element	High Sulfur (Wt.%)	Low Sulfur (Wt.%)	U. Low Sulfur (Wt.%)
Carbon, C	0.40	0.41	0.41
Manganese, Mn	0.85	0.94	0.87
Phosphorus, P	0.013	0.010	0.010
Sulfur, S	0.077	0.012	0.004
Silicon, Si	0.28	0.28	0.24
Nitrogen, N	N/A	0.0094	0.0058
Chromium, Cr	0.99	1.01	0.90
Aluminum, Al	0.010	0.028	0.020
Nickel, Ni	0.15	0.15	0.05
Molybdenum, Mo	0.21	0.22	0.18
Copper, Cu	0.23	0.17	0.10
Tin, Sn	0.009	0.007	0.005
DI	5.84	6.40	4.80

The material was continuous cast as a 150 mm square cross section. Pieces were reheated to 1180 °C, and forged into a 65 mm square cross section. The reduction ratio was 5.76 to 1. After forging, the material was normalized at 900 °C and transverse fatigue sample blanks were cut from the 1/4th thickness position. The specimens were then machined from square cross-sectioned 16 mm x 16 mm x 65 mm coupons. Figure 1 shows the sample arrangement for the testing of transverse fatigue samples where L in the figure designates the steel bar longitudinal direction. Charpy V-notch impact test samples were cut from the same 1/4 thickness position in both the L and T orientations. Partially machined specimens were reheated to 900 °C, quenched, and tempered to achieve the HRC 40 and 50 hardness levels.

Samples for longitudinal fatigue tests were obtained from 29.8 mm diameter hot rolled bars representing a reduction ratio of 33:1. Inclusion ratings were obtained

on samples representing the fatigue test specimen locations and fracture plane orientation.

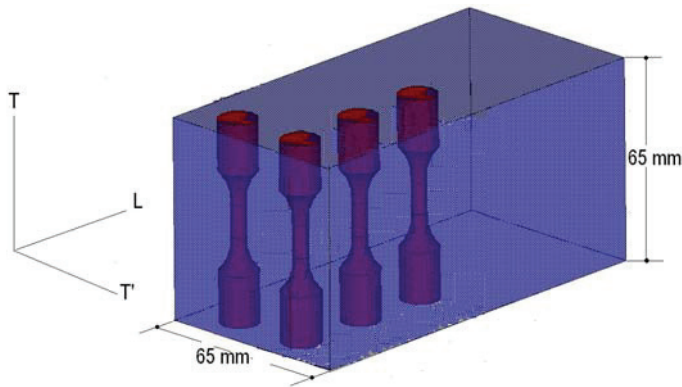


Figure 1: Sample cut-out direction for transverse specimens

Figure 2 shows the inclusion level in the plane perpendicular to the applied load for the longitudinal samples⁽⁹⁾. Figure 3 shows the inclusion level for the three transverse materials in the LT plane, as shown in Figure 1, along with the inclusion rating numbers. These pictures indicate large, elongated MnS inclusions in the plane perpendicular to the applied load for the transverse samples, while the MnS inclusions are round and of smaller size for the longitudinal samples. The inclusion type A (sulfides) ratings indicate that the high sulfur material has approximately seven times more sulfide inclusions than the lower sulfur materials. Also, the lower sulfur materials have no heavy sulfides. From the figure, the maximum inclusion size appears to be the same for the low sulfur and the ultra low sulfur materials, although the ultra low sulfur material has a much lower distribution of sulfides.

Inclusions were also characterized based on area fraction (standard JIS G0555⁽¹⁰⁾) and size distribution (DIN 50602 K rating)⁽¹¹⁾. Figure 4 shows the relation between the area fraction of the inclusions in the LT' direction and the sulfur content. It is apparent from the figure that the apparent area fraction is much larger for the transverse samples than the longitudinal samples for the same sulfur content. For the transverse samples, the sulfide area fractions were very close to the sulfur wt. %, while they were close to zero for both sulfur levels in the longitudinal direction. Therefore, the effective inclusions are of much larger area in the transverse direction, as compared to the longitudinal direction. Figure 4(b) for total inclusions and its similarity to Figure 4(a) for MnS inclusions indicates that the area fractions of the globular inclusions in all materials are much lower than the sulfide inclusions and that the total inclusions were predominantly sulfides. It should be noted that the detectability of MnS inclusions of the longitudinal sample cross sections is limited due to the small size and resolution of the rating method. Also, it is likely that the method counts the round MnS inclusions in the longitudinal orientation as globular inclusions.

Figure 5 shows inclusion characterization by standard DIN K. Figure 5(a) indicates the size distribution of inclusions in each material. Each material has a higher number of the smaller sized inclusions and the number of inclusions present decreases as the size increases. The ultra low sulfur material does not have any of the largest sized (i.e. 1600 sq. micron) MnS inclusions. Figure 5(b) indicates that the high sulfur transverse material has a much higher number of MnS inclusions of each size than the other materials.

The transverse samples of high, low and ultra low sulfur steels were each tested at two hardness levels of 40 HRC and 50 HRC. The longitudinal samples were tested at the hardness level of 40 HRC.

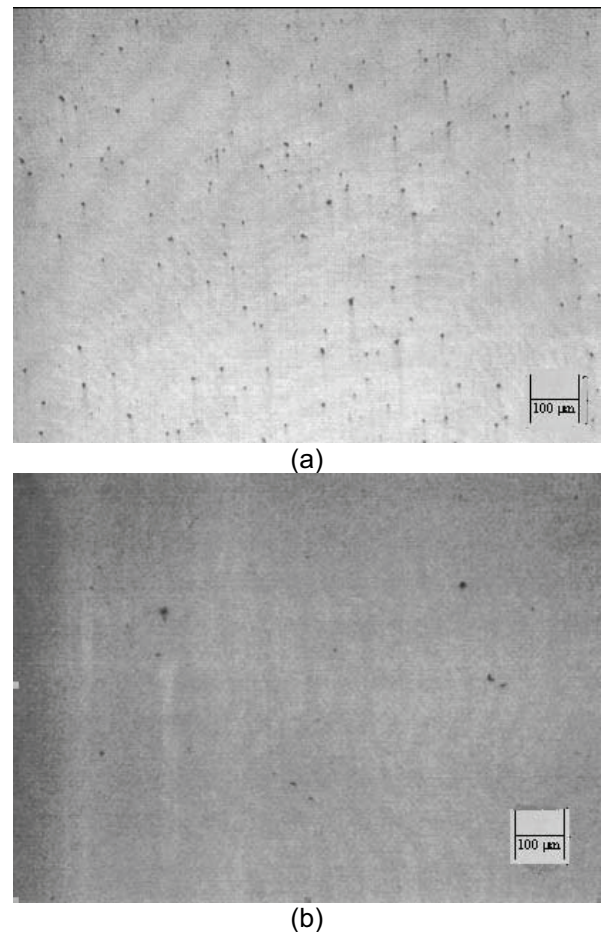


Figure 2: Photomicrographs of inclusions present in longitudinal samples with (a) High sulfur, rated as A thin = 2 and A heavy = 0, D thin = 1 and D heavy = 0 (no B or C), and (b) Low sulfur, rated as A thin = 0.5 and A heavy = 0, D thin = 1 and D heavy = 0 (no B or C)