General paper

**Effects of Prestraining on High-Cycle Fatigue Strength of High-Strength Low Alloy TRIP-Aided Steels**

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Abstract: The effects of prestraining on high-cycle fatigue strength of newly developed low alloy TRIP-aided steels with different matrix structures and different retained austenite characteristics were investigated for automotive applications. Prestraining to 10% in tension increased the fatigue limit of the TRIP-aided steels, especially in steel with a polygonal ferrite matrix. It was considered that the polygonal ferrite matrix brought on high a fatigue limit mainly due to TRIP of the retained austenite and high compressive internal stress in the matrix resulting from a hard second phase on prestraining. On the other hand, the steel with bainitic ferrite lath matrix exhibited only a small increase in the fatigue limit after prestraining. This was expected to be mainly due to “strain-induced martensite hardening” on prestraining, with small contributions of TRIP of compressive internal stress in the matrix. In addition, a very interesting finding was obtained that the internal stress is the most effective parameter among some parameters to increase the fatigue strength in low alloy TRIP-aided steels.

Key words: High cycle fatigue, Prestrain, Low alloy TRIP steel, High strength steel, Transformation induced plasticity, Retained austenite, Internal stress

1. INTRODUCTION

Newly developed high-strength low alloy TRIP-aided sheet steels with a polygonal ferrite matrix, annealed martensite matrix or bainitic ferrite matrix is very useful to achieve the drastic weight reduction and good crush safety for vehicles. The TRIP-aided steels possess an excellent formability due to TRIP effect of stable retained austenite of 5-15 vol% [1-4], as well as high fatigue strength [5-9] and high impact performance [10]. Therefore, some applications to suspension parts and impact members are intensely tried up to now.

Generally, the above parts are inserted into the main frame after press forming. If the TRIP-aided steels are applied to the suspension parts, low-cycle and high-cycle fatigue strengths after press forming need to be investigated because some of retained austenites in the TRIP-aided steels are strain-hardened and/or transformed on press forming. However, the high-cycle fatigue properties after press forming can not be found up to now, although a low-cycle fatigue property is already reported [9].

In the present study, the effects of prestraining on high-cycle fatigue strength in three types of TRIP-aided steels were examined. In addition, the fatigue strength was discussed through deformation-transformation behavior of the retained austenite, X-ray internal stress in the retained austenite and dislocation structure change in the matrix.

Received October 23, 2002
Accepted July 31, 2003

the integrated intensity of (200) \( \alpha \), (211) \( \alpha \), (200) \( \gamma \), \( \gamma \),
(311) \( \gamma \) peaks of Mo-K \( \alpha \) radiation [12]. The carbon
concentration \( C_\gamma \), mass\% was estimated by substituting the
lattice constant \( a_\gamma \times 10^{-10} \) m measured from the (220) \( \gamma \) peak
of Cr-K \( \alpha \) radiation, into the following equation [13];
\[
C_\gamma = \frac{\alpha_\gamma - 3.578}{0.033}.
\]

Deformation-transformation behavior of retained austenite and a long-range internal stress in retained austenite were investigated by X-ray diffractionometry and were observed using a transmission electron microscope. The 2\( \theta \)-\( \sin^2 \Psi \) method [14] was applied to X-ray studies of longitudinal internal stress of retained austenite. The measurement conditions and material constants are shown in Table 1. Also the line breadth at a half-maximum X-ray intensity corresponding to the amount of plastic strain and strain-hardening was measured from the (220) \( \gamma \) diffraction peak. Hereafter, the long-range internal stress is abbreviated as the internal stress.

\[ \begin{array}{|c|c|}
\hline
\text{X-ray} & \text{Cr-K} \alpha \\
\hline
\text{Filter} & \text{Monocrrometer} \\
\hline
\text{Voltage, Current} & 30 \text{ kV} - 10 \text{ mA} \\
\hline
\text{Collimator} & 2 \times 2 \text{ mm}^2 \\
\hline
\text{Fixed Time} & 30 \text{ s} \\
\hline
\text{\( \Psi \)} & 10, 16, 21, 25, 29, 32, 35, 38, 41 \text{ deg.} \\
\hline
\text{Diffraction Plane} & (220) \gamma \\
\hline
\text{Young's Modulus} & 192 \text{ GPa} \\
\hline
\text{Poisson's Ratio} & 0.28 \\
\hline
\text{Stress Constant} & -638 \text{ MPa/deg.} \\
\hline
\end{array} \]
3. RESULTS

3.1. Microstructure and Tensile Properties

Figure 2 shows micrographs of heat-treated TRIP-aided and dual-phase steels. The PF steel mainly consists of polygonal ferrite matrix and second phase (bainite plus retained austenite) along the ferrite grain boundaries. The AM steel is composed of annealed martensite lath matrix and interlath second phase (carbide-free bainite plus retained austenite). On the other hand, the BF steel mainly consists of bainitic ferrite lath matrix with high dislocation density and interlath second phase (retained austenite plus blocky martensite).

As shown in Table 2, the retained austenite content of the TRIP-aided steels are between 7.5 and 10.9 vol% and its carbon concentrations are ranging from 1.21 to 1.31 mass%. It is noteworthy that the AM steel possesses the most carbon-enriched retained austenite among the TRIP-aided steels.

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fatigue limit among the TRIP-aided steels.

(2) When subjected to prestrain, the largest increase in fatigue limit is obtained in the PF steel with polygonal ferrite matrix, similar to the dual-phase steel. Consequently, the PF steel, prestrained to 10%, completes the highest fatigue limit, despite the lowest initial fatigue limit.

(3) On the other hand, the BF steel with bainitic ferrite exhibits only a small increase in the fatigue limit by prestraining.

3.3. Microcrack Initiation and Development of Cell Structure

Figure 6 shows typical transmission electron micrographs of PF and BF steels cyclically deformed for 10^7 cycles at a fatigue limit after prestraining to 5%. Similar to a previous report [15], it was observed that the cell structure rarely develops in the matrix of all the TRIP-aided steels, although the dislocation density is considerably increased.

Figure 7 shows typical scanning electron micrographs of the specimen surfaces of PF and BF steels cyclically deformed under stress amplitude of 720MPa. It is found that short wavy slip bands develop in the matrix of the PF steel and most of the microcracks initiate inside the matrix. On the other hand, it is seen in the BF steel that long wavy slip bands develop along the bundle boundary and/or packet one. The slip bands seem to develop into microcracks after further fatigue deformation.

3.4. Deformation-Transformation Behavior and X-ray Internal Stress of Retained Austenite

Figures 8 shows variations in the ratio of untransformed retained austenite content to the initial one (f/0), and the ratio of line breadth at a half-maximum X-ray intensity of deformed retained austenite to that of the heat-treated one (Δθ/Δθ0) with the number of cycle (N). Fig. 9(a) shows the X-ray internal stress (σR) in the retained austenite with the number of cycle (N) for heat-treated or prestrained TRIP-aided steels. From these fatigue, the following is recognized.

(1) In as heat-treated steel, about 20–50% of initial retained austenite content transforms to martensite during fatigue deformation. In the prestrained steels, however, the retained austenite transforms to martensite only slightly during fatigue deformation, although about 20–40% of initial retained austenite content transforms on prestraining.

(2) The ratio of line breadth at a half-maximum X-ray intensity of deformed retained austenite to that of the
Effect of Prestraining of Fatigue Strength of TRIP steel

Fig. 8. Variations in (a) ratio of untransformed retained austenite content to initial one \( f_{\gamma}/f_{\gamma0} \) and (b) ratio of line breadth at a half maximum X-ray intensity of deformed retained austenite to that of heat-treated one \( \Delta \theta_{\gamma}/\Delta \theta_{\gamma0} \) with number of cycle \( N \) for PF (■, □), AM (○, ◦) and BF (●, ○) steels. (solid marks: \( \varepsilon_p=0\%, \sigma_R=700\text{MPa}, \) open marks: \( \varepsilon_p=5\%, \sigma_R=700\text{MPa} \))

Fig. 9. Variations in (a) X-ray internal stress in retained austenite \( \sigma_{\gamma} \) and (b) calculated equivalent internal stress in matrix \( \sigma_{\gamma'} \) with number of cycle \( N \) for PF (■, □), AM (○, ◦) and BF (●, ○) steels. (solid marks: \( \varepsilon_p=0\%, \sigma_R=700\text{MPa}, \) open marks: \( \varepsilon_p=5\%, \sigma_R=700\text{MPa} \))

heat-treated one \( \Delta \theta_{\gamma}/\Delta \theta_{\gamma0} \) value of heat-treated TRIP-aided steels increases during fatigue deformation, particularly in the PF steel. This means that retained austenite of the PF steel is highly plastically deformed or strain-hardened. In the prestrained TRIP-aided steels, however, the ratio of line breadth at a half-maximum X-ray intensity of deformed retained austenite to that of the heat-treated one \( \Delta \theta_{\gamma}/\Delta \theta_{\gamma0} \) value varies only slightly during fatigue deformation. It is noteworthy that the prestrained BF steel possesses a slightly larger the ratio of line breadth at a half-maximum X-ray intensity of deformed retained austenite to that of the heat-treated one \( \Delta \theta_{\gamma}/\Delta \theta_{\gamma0} \) value.

(3) In all heat-treated TRIP-aided steels, the \( \sigma_{\gamma'} \) value is considerably increased during fatigue deformation. However, the X-ray internal stress \( \sigma_{\gamma'} \) value is increased only a little with number of cycles in prestrained steels, although the X-ray internal stress \( \sigma_{\gamma'} \) value is significantly increased by prestraining.

4. DISCUSSION

In this study, it was found that the PF steel with polygonal ferrite matrix exhibited the largest increase in fatigue limit by prestraining among TRIP-aided steels (Fig. 5). In general, prestraining enhances the yield stress of the steels by \( \Delta \sigma' \) due to strain-hardening. The resultant fatigue limit is increased by \( \Delta F_L \). As seen in Fig. 10, when their ratio \( \Delta F_L/\Delta \sigma' \) was compared among the several steels, the ratio of fatigue limit increment to yield stress increment \( \Delta F_L/\Delta \sigma' \) values considerably differed. Namely, the PF steel exhibited the largest ratio \( \Delta F_L/\Delta \sigma'=0.84 \) and the BF steel represented the smallest value (0.24). This means that fatigue limit in the TRIP-aided steels after prestraining can not be absolutely estimated by only the increment of yield stress.

According to the previous study [5-9], high compressive internal stress develops in the matrix of heat-treated PF steel during fatigue deformation. This suggests that the compressive internal stress may control the ratio of fatigue limit increment to yield stress increment \( \Delta F_L/\Delta \sigma' \) value. Therefore, difference in the ratio of fatigue limit increment to yield stress increment \( \Delta F_L/\Delta \sigma' \) values between the PF, AM and BF steels were discussed on the basis of internal stress in the matrix, which was calculated from the X-ray internal stress in retained austenite by continuum theory proposed for two phase alloys [16]. Herein, a soft phase such as polygonal ferrite, annealed martensite or bainitic ferrite is called the matrix, and a hard phase containing retained austenite is called the second phase.
4.1. Deformation Theory of Low Alloy TRIP steel

According to a previous study [7], tensile deformation of TRIP-aided steels is principally controlled by the following: (i) increase in strain-induced martensite content and stress relaxation (or plastic relaxation) due to shear strain and expansion strain on the strain-induced transformation,

(ii) compressive internal stress in the matrix resulting from strain-hardened retained austenite and other hard second phases.

When (i) and (ii) above were applied to the deformation theory of two phase alloy [17], the increment of strain-hardening ($\Delta\sigma$), due to the second phase, is obtained from the following equation [7]:

$$\Delta\sigma = \sigma(\varepsilon) \cdot \sigma^M(\varepsilon) = \sigma_i(\varepsilon) + \sigma_t(\varepsilon) + \sigma_f(\varepsilon),$$

where $\varepsilon$ is a plastic-strain. $\sigma$ and $\sigma^M$ represent flow stresses of the TRIP-aided steel and the matrix, respectively. And $\sigma_i$, $\sigma_t$, and $\sigma_f$ are "mean internal stresses" (or long-range internal stress), "strain-induced martensite hardening" [7] and "forest-hardening" proposed by Ashby [18], respectively. They are given as follows;

$$\sigma_i(\varepsilon) = \mu \left( \frac{7-5}{5(1-v)} \right) \cdot \frac{f}{2r} \cdot \varepsilon_p^u,$$

$$\sigma_t(\varepsilon) = g(f_{am}^\ast),$$

$$\sigma_f(\varepsilon) = \zeta \cdot \mu \left( b \cdot f \cdot \varepsilon \right)^{1/2},$$

where $v$ and $\mu$ are Poisson’s ratio and the shear modulus of each phase, respectively.$\varepsilon_p^u$ is eigen strain [16], $f$ is the volume fraction of the second phase, and $g(f_{am}^\ast)$ is obtained as a function of the volume fraction of strain-induced martensite content $f_{am}^\ast$. The term $\zeta$ is a constant, $b$ is the Burgers vector and $r$ denotes the mean diameter of the second phase particles.

If the mean internal stress of the second phase is assumed to be equal to that of the retained austenite particles, then the mean internal stress in the matrix ($\sigma_i^\ast$) of TRIP-aided steel is estimated and (ii), in the same way as tensile deformation. Both items by substituting the X-ray internal stress ($\sigma_{Xm}^\ast$) measured in retained austenite (Fig. 9(a)) into the following equation [17];

$$\sigma_i^\ast(\varepsilon) = -\frac{3}{2} \cdot f \cdot \sigma_{Xm}(\varepsilon).$$

4.2. Role of Prestrain on Fatigue Limit

According to previous reports [5, 6], fatigue limits of heat-treated TRIP-aided steels were controlled by the above (i) were expected to play a part of suppressing microcrack initiation and propagation. Namely, (ii) from above, principally enhances the fatigue limit in the PF steel. On the other hand, the fatigue limit of the BF steel is increased by above (i), as well as uniform fine lath structure and the increased dislocation density in the matrix. Fig. 9(b) shows the equivalent internal stress in matrix ($\sigma_i^\ast$) value calculated by substituting the measured X-ray internal stress in retained austenite ($\sigma_{Xm}^\ast$) value (Fig. 9(a)) into equation (6). In this case, the mean internal stress in the second phase was assumed to be equal to that of the retained austenite [7]. From Figs. 8 and 9(b), it is found that the equivalent internal stress in matrix ($\sigma_i^\ast$) value of prestrained specimens, as well as variations in volume fraction and line breadth at a half-maximum X-ray intensity of retained austenite, varied only a little during fatigue deformation, differing from the case of heat-treated specimens. This means that the difference in the ratio of fatigue limit increment to yield stress increment ($\Delta FL/\DeltaYS$) value needs to be discussed in terms of the volume fraction of retained austenite, line breadth at a half-maximum X-ray intensity of retained austenite and mean internal stress of matrix just after prestraining, not during fatigue deformation.

First, let us discuss the reason why the PF steel exhibits a high ratio of fatigue limit increment to yield stress increment ($\Delta FL/\DeltaYS$) value. The microstructure of the PF steel was characterized by more stable retained austenite and a softer matrix than those of the BF steel, resulting in a small ratio of strain-induced martensite content to initial retained austenite one ($1-f_{am}^\ast/f_{am}^0$) and the ratio of line breadth at a half-maximum X-ray intensity of deformed retained austenite to that of the heat-treated one ($\Delta \theta_{Xr}^\ast/\Delta \theta_{Xr}^0$) value on prestraining. Also the PF steel possessed a larger amount of second phase than the BF steel. Thus, significant compressive internal stress developed in the matrix on prestraining. As the equivalent internal stress increment in matrix ($\Delta \sigma_i^\ast$) value and the absolute slope the ratio of fatigue limit increment to yield stress increment ($\Delta FL/\DeltaYS$) was about 0.1 in both cases of $N=0$ cycles and $1 \times 10^4$ cycles. Also it was observed that fatigue-cracks initiated inside the matrix in the PF steel, as shown in Fig. 7(a). From results, it was concluded that a high compressive internal stress developed on prestraining suppressed the crack initiation in the matrix and consequently increased the fatigue limit and the ratio of fatigue limit increment to yield stress increment ($\Delta FL/\DeltaYS$) value. In this case, localized stress relaxation or plastic relaxation on
strain-induced transformation [5] is also considered to improve the fatigue limit through suppressing the microcrack initiation and propagation. Also strain-induced martensite may contribute to increase the fatigue limit by blocking the crack propagation.

In the BF steel, higher internal stress developed inside the retained austenite on presnting and during fatigue deformation, but the compressive internal stress in the matrix was estimated to be low due to a small amount of second phase. Also, cell structure hardly developed in the matrix during fatigue deformation, similar to the PF steel (Fig. 6(b)). Furthermore, it was supposed that the strain-induced transformation slightly relaxes the localized stress concentration at slip bands or microcracks because of a small amount of untransformed retained austenite after prestraining. Therefore, another factor other than the TRIP effect of retained austenite, the internal stress and cell structure, namely, the strain-induced martensite hardening may mainly contribute to the increased fatigue limit. The strain-induced martensites in the BF steel are closely distributed along the bainitic ferrite lath boundary, so that they may effectively block the crack propagation along the lath boundary. However, it is supposed that contribution of the strain-induced martensite hardening is not large so much because the fatigue limit increment ($\Delta F_L$) and the ratio of fatigue limit increment to yield stress increment ($\Delta F_L / \Delta YS$) values were small.

The reason why the AM steel exhibited relatively large the ratio of fatigue limit increment to yield stress increment ($\Delta F_L / \Delta YS$) value was not investigated in this study. However, the reason is likely to be an intermediate between PF and BF steels.

5. CONCLUSIONS

The effects of prestraining on high-cycle fatigue strength of three types of TRIP-aided steels were examined. In addition, the effects were discussed in terms of the dislocation structure change, deformation-transformation behavior of the retained austenite and variation in mean internal stress. The results are summarized as follows.

(1) The fatigue limits of TRIP-aided steels were increased by prestraining. However, its increment was the largest in PF steel with a polygonal ferrite matrix and the BF steel with bainitic ferrite lath matrix exhibited the smallest. In the AM steel with annealed martensite lath matrix, the increment of fatigue limit was between those of the PF and the BF steels.

(2) In the PF steel, a significant increase in fatigue limit by prestraining was considered to be due to development of high compressive internal stress in the matrix on prestraining and the TRIP effect of stable retained austenite.

(3) On the other hand, in the BF steel, a small increase in fatigue limit by prestraining was mainly due to a contribution of strain-induced martensite hardening. In this case, compressive internal stress in the matrix and TRIP effect, hardly contributed to improvement of the fatigue limit.

(4) It was proposed that the development of high compressive internal stress in the matrix was very effective to enhance the fatigue limit of the TRIP-aided steels, particularly for prestrained steels.

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