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Note

Effects of Vanadium Addition on Strain Distribution, Crack Initiation and Propagation during Low-cycle Fatigue Test in Ferrite and Martensite Dual-phase Steel

Norimitsu KOGA,[1)]* Akihiro KASEYA,[2)]
Osamu UMEZAWA,[3,4)] Hiroshi NAKATA[5)] and
Shunsuke TOYODA[6)]

1) Faculty of Mechanical Engineering, Institute of Science and Engineering, Kanazawa University, Kakuma-machi Kanazawa Ishikawa, 920-1192 Japan.
2) Graduate School of Engineering, Yokohama National University. Now at JFE Steel Corporation, 1 Kokan-cho, Fukuyama, Hiroshima, 721-8510 Japan.
3) Faculty of Engineering, Yokohama National University, 79-5 Tokiwadai, Hodogaya, Yokohama, 240-8501 Japan.
4) Center of Advanced Innovation Technologies, Vysoká Škola Báňská - Technical University of Ostrava, 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic.
5) JFE Steel Corporation, 1-1 Minamiwatarida-cho, Kawasaki-ku, Kawasaki, 210-0855 Japan.
6) JFE Steel Corporation, 2-2-3 Uchisaiwaicho, Chiyoda-ku, Tokyo, 100-0011 Japan.

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Effects of vanadium (V) addition on strain distribution, crack initiation and propagation behavior during low-cycle fatigue test in ferrite and martensite dual phase (DP) steel were revealed. V addition effectively extended the low-cycle fatigue life, even though the tensile properties were approximately identical between V-added DP and DP steels. The stress amplitude suddenly decreased just before fracture in the V-added DP steel. The fatigue crack initiated from the surface and propagated inside, and the brittle fracture occurred in the crack propagation region in the V-added DP steel. The strain distribution introduced during the low-cycle fatigue test was more inhomogeneous for the V-added DP steel than that for the DP steel, and the fatigue crack was generated from the high-strain region. Considering that the number of cycles for crack initiation in the V-added DP steel was larger than that in DP steel, the inhomogeneous strain distribution in the V-added steel promoted crack nucleation but suppressed crack growth in the crack initiation stage. Cracks propagated independent of the strain distribution in the V-added DP steel in the crack propagation stage. The crack propagation rate in the V-added DP steel was remarkably higher than that in DP steel in the crack propagation stage. Thus, V addition effectively extended the number of cycles for crack initiation but caused brittle fracture and faster crack propagation.

KEY WORDS: low-cycle fatigue; crack initiation; crack propagation; strain distribution; digital image correlation method; vanadium.

1. Introduction

Low-cycle fatigue properties are important for the application of structural materials in actual environments. Our previous study[1)] revealed that the ferrite and martensite dual-phase (DP) steel exhibits a longer fatigue life during a low-cycle fatigue test than the tempered martensite (Mt) steel although these steels have identical high tensile strength. Furthermore, a certain amount of strain was inhomogeneously distributed in both steels during the low-cycle fatigue test, and a fatigue crack initiated and propagated along the high-tensile strain regions. The strain distribution in the Mt steel was more inhomogeneous as compared to that in DP steel. Thus, it was suggested that the inhomogeneity of strain distribution affects low-cycle fatigue properties.

Vanadium is an alloy element that enhances strength of steels through the precipitation strengthening of vanadium carbide.[2)] Kamikawa *et al.*[3)] revealed that V addition to DP steels allows the preferential strengthening of the ferrite phase because of the preferential precipitation of VC in the ferrite phase and the achievement of the high strength-elongation balance. Furthermore, they demonstrated that strain distribution introduced during a tensile test becomes homogeneous because of V addition owing to the small difference in strength between the strengthened ferrite phase and the martensite phase. It was confirmed that V addition was effective for extending the fatigue life of different types of steel;[4–6)] however, the mechanism for the improvement of fatigue properties due to V addition has not been discussed in depth.

In this study, the effects of V addition to DP steel on strain distribution, crack initiation and propagation during a low-cycle fatigue test were revealed.

2. Experimental Procedure

The V-added DP steel (Fe-0.155%C-0.4%Si-2.0%Mn-1.0%Cr-0.22%V, in mass%) was used in this study, where only V was added to the DP steel (Fe-0.152%C-0.4%Si-2.0%Mn-1.0%Cr, in mass%) used in previous study.[1)] The DP steel was fabricated by solution treatment at 1 033 K for 0.09 ks, subsequently water-quenched. The V-added DP steel was fabricated by isothermal heat-treatment at 1 023 K for 0.09 ks for precipitating VC, subsequently water-quenched.

Tensile tests were conducted using round-bar specimens with 30 mm gauge length and 3.5 mm diameter at a strain rate of $2.78 \times 10^{-4}\ s^{-1}$. Low-cycle fatigue tests were conducted using round-bar specimens with 10 mm gauge length and 4.5 mm diameter under total strain amplitude (ε_t) control from 0 to 0.01 by using an extensometer. The fatigue test was terminated when the applied stress reached 75% of the initial stress, and the cycling number was defined as the number of cycles to failure (N_f) in this study.

An acetyl cellulose replicating film (Bioden R.F.A.) was taken from the surface during the low-cycle fatigue test to observe cracks and analyze the strain distribution. The detailed method for obtaining a replica film was explained in a previous study.[1)] The microstructure was observed by using field-emission scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The specimen for TEM was prepared using a twin-jet electropolisher with acetic acid/perchloric acid solution (volume ratio of 95:5).

Strain distribution was analyzed using the digital image correlation (DIC) software (VIC-2D). The SEM image of the replica film before deformation was used as a reference for DIC analysis. The subset size and step in the DIC analysis were 41 and 3 pixels, respectively.

3. Results and Discussion

Figure 1 shows (a) SEM and (b) TEM images of the V-added DP steel. The low contrast regions, as indicated by white arrows in Fig. 1(a), correspond to the ferrite phases,

* Corresponding author: E-mail: koga-norimitsu@se.kanazawa-u.ac.jp

whereas the other regions ascribed to the martensite phases. The volume fraction of the ferrite phase in the V-added DP steel was approximately 46%, which is remarkably higher than that in the DP steel (5%).[1)] In the ferrite region, precipitates of approximately 40 nm were detected, as indicated by red arrows in Fig. 1(b); these were identified as VC from the diffraction pattern. **Figure 2** shows nominal stress and nominal strain (SS) curves of the V-added DP and DP steels.[1)] The SS curves were almost identical between the two steels although the volume fraction of the ferrite phase in them was significantly different, indicating that VC precipitates significantly strengthened the ferrite phase. The tensile stress was more than 1 GPa in both the steels; thus, these steels are categorized as high-strength steel. Since the N_f was significantly different between the DP and Mt steels within the range from ε_t of 0.008 to 0.02, as shown in the previous study,[1)] the low-cycle fatigue test in this study was conducted at ε_t of 0.01.

Figure 3 shows the ratio of the stress amplitude at each cycle to the stress amplitude at five cycles (R_a) as a function of the number of cycles at ε_t of 0.01 for the V-added DP and DP steels. The N_f (= 14 000) for the V-added DP steel was higher than that (= 9 000) for the DP steel although these steels showed identical SS curves, suggesting that V addition extends the low-cycle fatigue life of the DP steel, which is similar to the previous reports.[4–6)] The R_a of the DP steel continuously decreased with increasing number of cycles, and work-softening of the microstructure occurred. While R_a remained at a high level and decreased suddenly just before fracture in the V-added DP steel. Therefore, in the V-added DP steel, the work-softening of the microstructure hardly occurred, and the decrease in R_a was attributed to fatigue crack initiation and propagation as discussed later. The sudden decrease in R_a at around 1 000 cycles may be caused by the generation of a subcrack that is not the main fatigue crack.

Figure 4 shows (a) SEM images of the fracture surface at ε_t of 0.01 and the enlarged images within the square in the (b) crack initiation and (c) propagation regions for the V-added DP steel. The area of the fatigue fracture surface of the V-added DP steel determined from the SEM image (Fig. 4(a)) was 4.07 mm^2, which was remarkably larger than that of the DP steel (0.34 mm^2). This confirms the occurrence of the low work-softening of the microstructure in the V-added DP steel. The facet region, which corresponds to the crack initiation region, was located beneath the surface of the V-added DP steel, as indicated by dotted lines in Fig. 4(b), indicating that the fatigue crack initiated from the surface and propagated inside, similar to that in the DP steel.[1)] The fracture surface in the crack propagation region in the V-added DP steel exhibited the low-energy flat surface without striations detected in the DP steel.[1)] Thus, the crack propagation behavior was different for the V-added DP and DP steels.

Figure 5 shows (a) SEM image of the replica film at 7 000 cycles and (b) ε_{yy} strain distribution in the same region with (a) at 4 000 cycles at ε_t of 0.01 for the V-added DP steel. The large crack was detected at 7 000 cycles, as indicated by the white arrow in Fig. 5(a), and its size exceeded the facet size measured from Fig. 4(b). In accordance with the definition in the previous study,[1)] the number of cycles for crack initiation could be estimated to be 7 000 cycles for the V-added DP steel, which is larger than that for the DP steel (3 000 cycles).[1)] Thus, V addition was effective to delay crack initiation. The crack initiated from the high-strain region as shown in Fig. 5(b), similar to that in DP and Mt steels.[1)] The standard deviation of the histogram of strain at 4 000 cycles at ε_t of 0.1 for the V-added DP steel was 0.026, which is remarkably larger than that in the DP steel (0.002).[1)] It suggests that the strain distribution in the V-added DP steel was more inhomogeneous than that in the DP steel.[1)] This finding contradicts the expectation that V addition induces homogeneous strain distribution. Through high-resolution DIC analysis, Tsuchiyama *et al.*[7)] revealed that strain concentration occurred around the VC precipitates. Therefore,

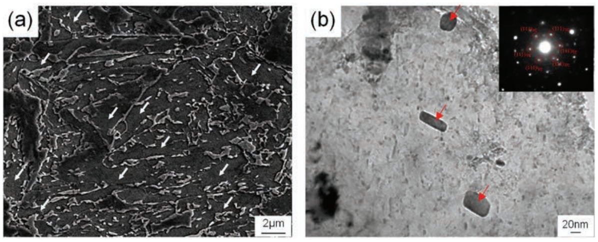

Fig. 1. (a) SEM and (b) TEM images in the V-add DP steel. (Online version in color.)

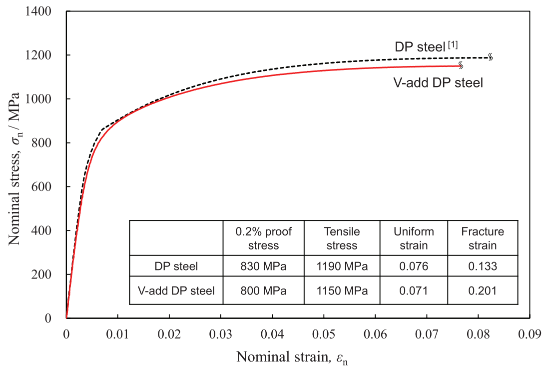

Fig. 2. Nominal stress and nominal strain curves in V-add DP and DP steels. (Online version in color.)

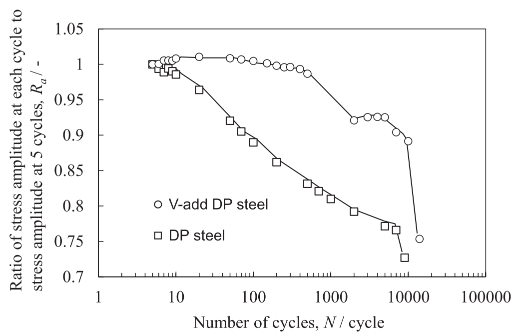

Fig. 3. Ratio of stress amplitude at each cycle to stress amplitude at 5 cycles as a function of number of cycles at the ε_t of 0.1 in V-add DP and DP steels.

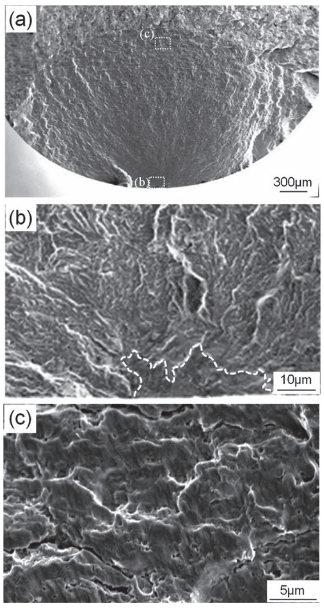

Fig. 4. (a) SEM images of fracture surface at the ε_t of 0.01 and enlarged images within the square in (b) crack initiation and (c) propagation regions in the V-add DP steel.

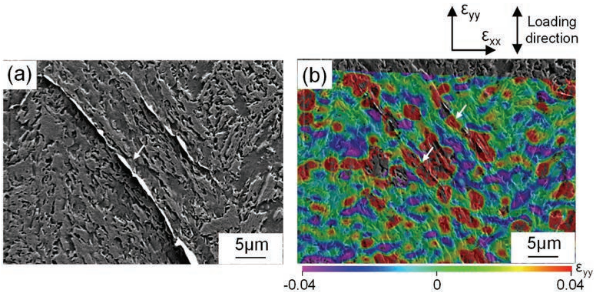

Fig. 5. (a) SEM image of replica film at 7 000 cycles and (b) ε_{yy} strain distribution at 4 000 cycles in the identical region in (a) at ε_t = 0.01 in the V-add DP steel. White arrow indicate fatigue crack. (Online version in color.)

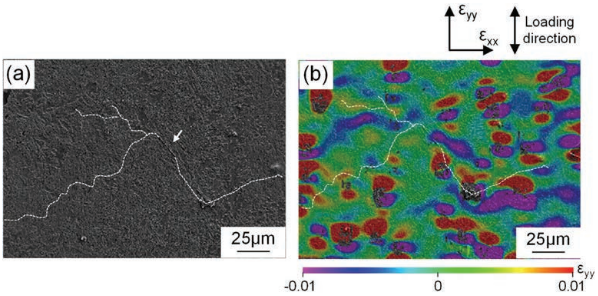

Fig. 6. (a) low-magnification SEM image of replica film at 7 000 cycles around fatigue crack identical with Fig. 5 and (b) ε_{yy} strain distribution at 4 000 cycles in the identical region in (a) at ε_t = 0.01 in the V-add DP steel. White arrow indicate fatigue crack. (Online version in color.)

although V addition leads to a decrease in the difference of strain between the ferrite and martensite phases, it causes inhomogeneous strain distribution in the ferrite phase. The inhomogeneous strain distribution in the V-added DP steel promotes crack nucleation; however, VC precipitates may suppress crack growth, resulting in the later crack initiation, which is defined that the number of cycles when the size of the crack exceeds the facet size, of the V-added DP steel compared to that of the DP steel. In fact, the number density of fatigue cracks was 170 mm^{-2} for the V-added DP steel at 7 000 cycles, which was remarkably larger than that for the DP steel at 4 000 cycles (20 mm^{-2}). These results suggest that the low-cycle fatigue property is influenced by not only strain distribution but also the microstructure.

Figure 6 shows (a) the low-magnification SEM image of the replica film around the fatigue crack identical to that in Fig. 5 and (b) the ε_{yy} strain distribution in the same region in (a) at 4 000 cycles at ε_t of 0.01 for the V-added DP steel. The white dotted line denotes the crack positions at 8 500 cycles. In the previous study,[1] cracks preferentially propagated along the high-strain region in DP and Mt steels; however, the crack in the V-added DP steel propagated independent of the strain distribution as shown in Fig. 6(b). In the DP steel, the fatigue crack propagated through the plastic deformation in front of the crack tip,[1] which is referred to as the blunting and resharpening mechanism.[8] While, for the V-added DP steel, because the flat fracture surface was observed in the crack propagation region (Fig. 4(c)), the crack propagated through the brittle fracture. This difference in the crack propagation mechanism led to the contradictory relationship between crack propagation and strain distribution for the V-added DP and DP steels. The brittle fracture during crack propagation in the V-added DP steel must be caused by the VC precipitates in the ferrite phase because the VC precipitates enhance strength but decrease local elongation.[9] The crack propagation rate from 7 000 cycles (crack initiation) to 8 500 cycles was 0.363 μm/cycle, which was remarkably higher than that from 4 000 to 7 200 cycles for the DP steel (0.145 μm/cycle). It caused a sudden decrease in R_a just before fracture in the V-added DP steel (Fig. 3).

V addition suppressed crack initiation effectively although the strain distribution in the ferrite phase became more inhomogeneous because of the presence of VC precipitates. However, it caused brittle fracture during crack propagation, resulting in the sudden decrease in R_a and the fracture. The positive effect of V addition on the fatigue property was stronger than the negative effect in the V-added DP steel, resulting in a longer fatigue life. If the brittle fracture could be suppressed, the fatigue life would be even more through V addition. A more detailed observation of crack initiation and propagation behavior using such as high-resolution electron-channeling contrast image method is needed for revealing the effect of VC on the fatigue crack.

4. Conclusion

The effects of V addition to ferrite and martensite DP steels on the strain distribution, crack initiation, and propagation during the low-cycle fatigue test were revealed. The main results are summarized as follows:

(1) The V-added DP steel, in which VC precipitated in the ferrite region, exhibited a longer fatigue life at a total strain amplitude of 0.01 more than the DP steel even though the steels had the same nominal stress-strain curves.

(2) Stress amplitude continuously decreased with the increasing cyclic number in the DP steel, while it suddenly decreased just before fracture in the V-added DP steel.

(3) In the V-added DP steel, the crack initiated from the specimen surface and propagated inside. The low-energy fracture surface appeared in the crack propagation region.

(4) The strain distribution introduced during the low-cycle fatigue test was more inhomogeneous for the V-added DP steel than that for the DP steel. The fatigue crack was generated from the high-strain region. Considering that the number of cycles for crack initiation in the V-added DP steel was larger than that in the DP steel, VC precipitates were attributable for the inhomogeneous strain distribution in the ferrite region and promoted clack nucleation, but suppressed crack growth.

(5) Cracks propagated independent of the strain distribution in the V-added DP steel. The crack propagation rate in the V-added DP steel was remarkably higher than that in the DP steel. VC precipitates caused crack propagation through brittle fracture, resulting in the immediate crack propagation and sudden decrease in the stress amplitude in the V-added DP steel.

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