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FATIGUE LIFE EXTENSION OF AUSTENITIC STAINLESS STEEL USING NANO-SIZED MARTENSITES FORMED AT INTERSECTIONS OF DISLOCATIONS

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ABSTRACT

A new fatigue strengthening method has been proposed. Dislocations are pinned at their intersections by the formation of nano-crystals after cold-work in this strengthening method. High cycle fatigue life of a cold-worked (tensile strain of 10%) 316-type austenitic stainless steel was extended by a cryogenic treatment and this is considered to be due to the pinning of dislocations by the formation of nano-sized α'-martensite particles. This fatigue strengthening did not decrease ductility of the material. This fatigue strengthening method is expected to be applicable for micro-sized materials.

KEYWORDS

fatigue life extension, dislocation pinning, ductility, nano-sized α'-martensite, micro-sized material

INTRODUCTION

Micromachines and/or MEMS devices have been intensively developed for the use in information technology, bio-medical technology and so on. The size of the components of these machines will be in the order of microns or sub-microns. Fatigue strength is one of the most important properties in micro-sized materials because the maintenance or the exchange of damaged elements is practically impossible in such tiny machines. Thus, the development of a fatigue strengthening method for micro-sized materials is extremely beneficial. It is necessary to construct a microstructure which is beneficial for the improvement in fatigue life in the order of nanometer, for the strengthening of micro-sized materials. Fatigue of metallic materials is mainly due to the accumulation of irreversible motion of dislocations. An increase in yield stress is, of course, fairly beneficial for fatigue strengthening. However, an increase in yield stress is generally accompanied by a decrease in ductility. We have already revealed that micro-sized materials also fail by fatigue crack propagation as is observed in ordinary sized materials [1-2]. A decrease in ductility, which generally degrades crack propagation resistance, should be avoided also in micro-sized materials, as done for ordinary-sized materials. In addition, a microcrack, which is initiated in the earlier stage of fatigue process, is considered to become fatal damage in micro-sized materials [1-2]. Thus it is necessary to suppress crack initiation using a nano-order structure which does not degrade ductility but restrains the accumulation of microscopic plastic deformation under cyclic stress, for fatigue strengthening of micro-sized materials.

We have proposed a new fatigue strengthening method. Dislocation pinning at their intersections by nano-crystals after cold-work is considered to be an effective method for the suppression of the accumulation of microscopic damage. Figure 1 shows a schematic illustration of the concept of the pinning. The motion of pinned dislocations is expected to become bowing motion and not to cause re-arrangement of dislocations under cyclic stress. Nano-crystals are expected not to be a crack initiation site and higher stress may unpin the dislocations. The cyclic plastic deformation in this case should be homogeneously distributed, and the formation of stress concentrated fields should be suppressed. Consequently, crack initiation should be retarded and fatigue lives of materials are expected to be extended using this strengthening method. It should be noted that this strengthening method is not supposed to suppress plastic deformation, but to suppress the accumulation of the plastic deformation under cyclic stress. This strengthening method is considered to be effective on both the micro-sized materials and the ordinary-sized materials.

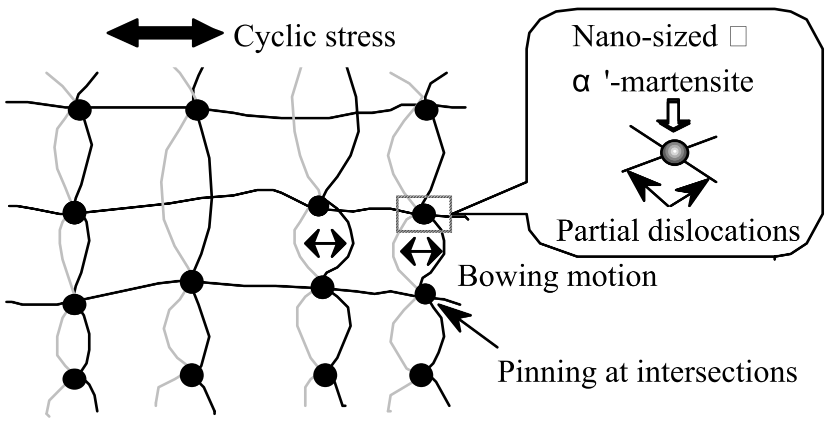

Figure 1: Schematic illustration of the concept of a new fatigue strengthening method. Dislocations are pinned at their intersections. Motion of pinned dislocations is considered to be bowing motion under cyclic stress. Our previous study using nano-sized α'-martensite particles indicates the validity of this strengthening method [x].

According to the model proposed by Bogers and Burgers [3], some of the intersections of partial dislocations in f.c.c. metals are expected to have b.c.c.-like stacking. It is well known that α'-martensitic transformation is caused by simple cooling and/or deformation in metastable austenitic stainless steels. In austenitic stainless steels, the b.c.c.-like stacking regions are considered to be preferential nucleation sites of α'-martensite. The b.c.c.-like stacking regions may transform into very fine α'-martensite particle by temperature control above $M_{s\alpha}{}^{b}$ during cooling. ($M_{s\alpha}{}^{b}$ is defined as the temperature at which spontaneous burst-like α'-martensitic transformation occurs during cooling in this study.) These very fine martensites are considered to be able to pin dislocations because b.c.c. stacking (nano-sized.martensite) is incoherent to f.c.c. stacking (austenite).

We have partly verified the effects of this method on fatigue life extension using ordinary-sized austenitic stainless steel specimens. In our previous study [4], high cycle fatigue life of ordinary-sized 316-type austenitic stainless steel specimens whose sub-surface area had been heavily cold-worked was extended by a cryogenic treatment above $M_{s\alpha}{}^{b}$. This fatigue life extension is considered to be due to the formation of nano-sized α'-martensites in the cold-worked sub-surface area of the specimens [4-5]. Observation of dislocation structure after fatigue loading suggested that the retardation of the rearrangement of dislocations is the origin of the fatigue life extension [4]. However, it has not been confirmed whether tensile properties (yield stress, UTS, fracture strain) are changed by the fatigue strengthening or not. The purpose of the present study is to investigate the tensile properties of a 316-type austenitic stainless steel specimen which have been fatigue strengthened by the pinning method.

EXPERIMENTAL PROCEDURE

The material used in this study were commercially available rods of 316-type(Fe-18Cr-10Ni-2Mn-0.06C) austenitic stainless steel (hot-rolled). Rotary bending fatigue specimens and monotonic tensile specimens were machined from the received rods after cold-work (tensile strain of 10 %) and thus, the entire specimen is cold-worked. Nano-sized α'-martensite should be formed and dispersed over the entire specimen by a cryogenic treatment at an adequate temperature. The cold-work of the received rods was performed at 573 K, not to cause any deformation induced martensitic transformation during this operation.

Nano-sized α'-martensites were formed by the cryogenic treatment at 195 K in the previous study [5]. However, the chemical composition of the received material is slightly different from that of used in the previous study [4-5]. Thus, formation temperature of the nano-sized α'-martensite may be different from that in the material used in the previous study. A cryogenic treatment at a temperature of either 240 K, 195 K, 175 K or 77 K for an hour was applied to each specimen to find adequate cryogenic temperature for fatigue life extension (adequate temperature for the formation of nano-sized α'-martensite). Microstructures of the specimens were observed using a scanning laser microscope (SLM) whose resolution is less than 1μm. The observation area was electrically polished using an acetic-perchloric acid solution and then, electro-etched using an oxalic acid solution.

Fatigue life tests were performed using an Ono-type four point rotary bending testing machine in air, at room temperature. The loading frequency was set to 2 ~ 10 Hz so that the temperature of the specimen surface did not exceed 313 K during the fatigue life tests. The stress amplitude under which specimen did not fail after 10^7 cycles was regarded as the fatigue limit in this study.

Monotonic tensile tests were performed using an Instron-type testing machine at room temperature. Strain rate , which was calculated from a cross head speed and the gage length of the specimen, was 8×10^{-4} / s.

RESULTS and DISCUSSION

No martensite phases (α' or ε martensite) were observed using the SLM after the cryogenic treatment at a temperature of either 240 K, 195K, 175 K. Figures 2 (a)~(c) show typical microstructures of (a) non-treated specimen, (b) 175 K-specimen and (c) 77K-specimen obtained by the SLM observation.

Non-treated specimens were fully austenite. A very small amount of martensites were observed in 77 K-specimen as shown in Fig. 2(c).

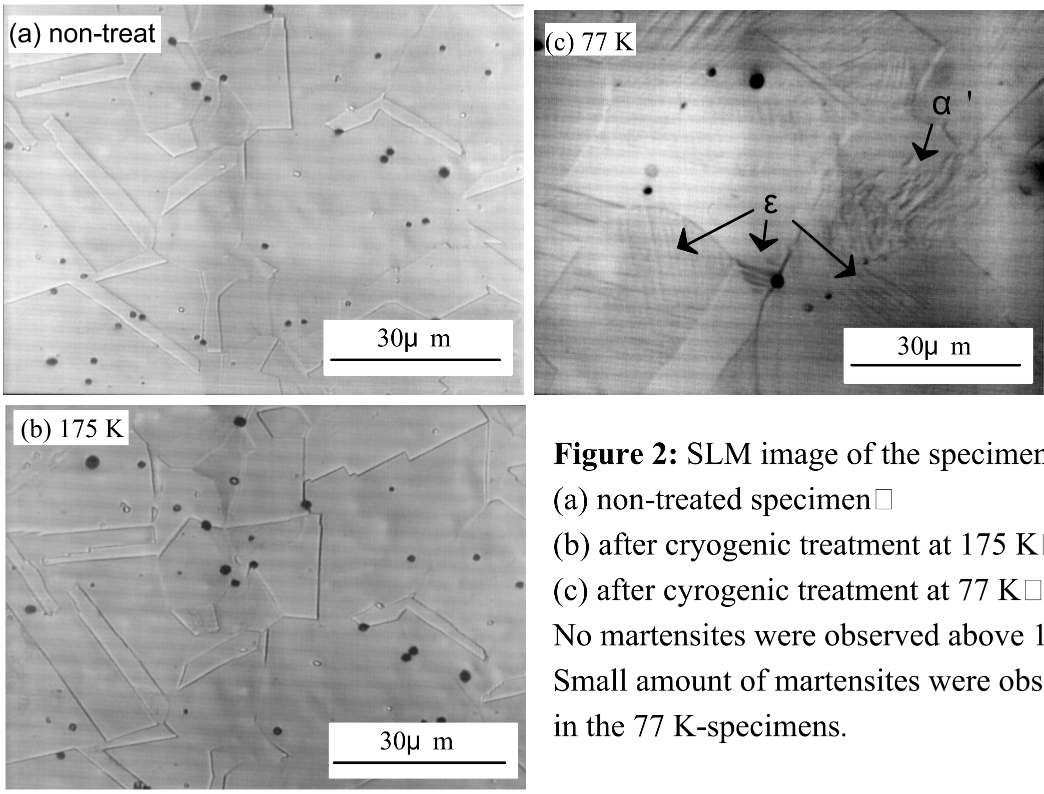

Figure 2: SLM image of the specimens
(a) non-treated specimen
(b) after cryogenic treatment at 175 K
(c) after cyrogenic treatment at 77 K
No martensites were observed above 175 K.
Small amount of martensites were observed in the 77 K-specimens.

S-N curves of non-treated, 175 K- and 77 K- specimens are shown in Fig. 3. The arrows indicate that the specimen did not fail after 10^7 cycles of loading. Fatigue lives of 240 K and 195 K specimens did not change compared to that of non-treated specimen. Thus, it is considered that no microstructural change was occurred by the cryogenic treatment at either of 240 K and 195 K (Fatigue data of 240 K and 195 K specimens are not plotted). No significant increase in fatigue lives was observed in 77 K-specimen. It has been reported that formation of α'-martensite which is optically visible has large influence on mechanical properties of austenitic stainless steels [6-9]. Small amount of optically visible α'-martensite (less than 30 volume % [6]) is beneficial, but large amount of it is detrimental [6-9] for fatigue life of an austenitic stainless stee[illegible] It is su[illegible]en was so small that no significant change in [illegible]

However, fatigue lives [illegible]n-treated specimen especially in a high cyc[illegible]d by the cryogenic treatment at 175 K. Thi[illegible]ble and effective on fatigue life ha been [illegible]agation in the 175 K-specimens is deduced [illegible]pearance which was accompanied by striatio[illegible]results obtained in a 304-type austenitic st[illegible]ispersed [4,10-11]. According to our previ[illegible]re considered to be formed in the 175 K-specimens used in this study. In 77 K specimen, no nano-sized martensites were suggested to be formed.

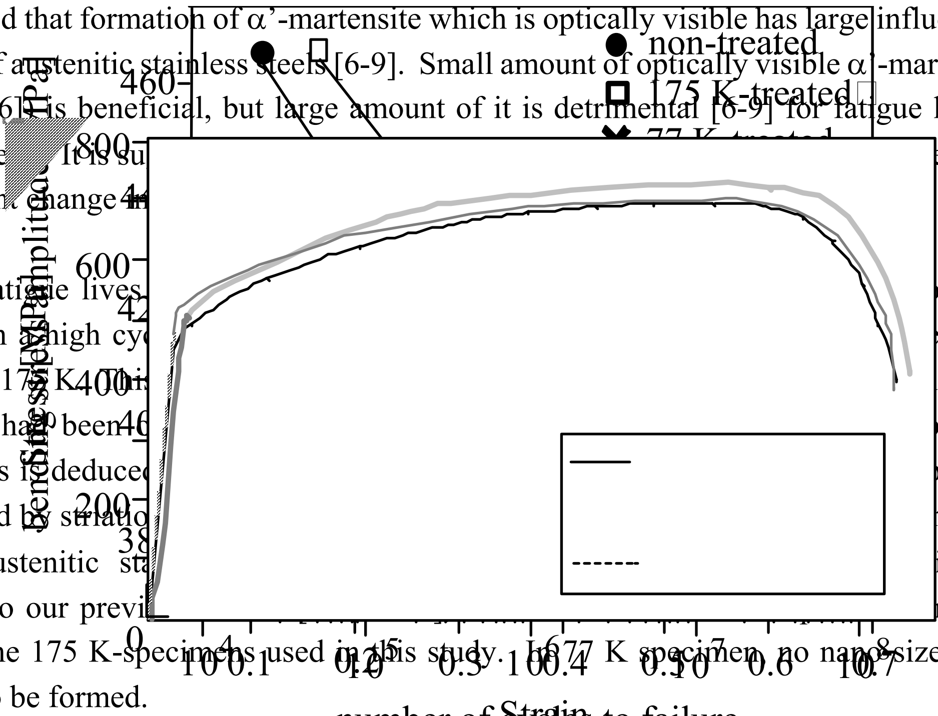

Figure 3: S-N curves of the 316-type austenitic stainless steel
Fatigue lives were extended especially in high cycle regime by the 175 K cryogenic treatment at 175 K.

Figure 4: Stress-strain curves of the specimens
No significant change in tensile properties was observed in the 175 K specimen though fatigue life was extended by the cryogenic treatment.

Figure 4 shows stress-strain curves of a non-treated, 175 K and 77 K specimens obtained by the monotonic tensile tests. Large fracture strain of approximately 70 % was observed. This is due to TRIP (Transformation induced plasticies) effect which generally appears in austenitic stainless steels. No significant change in tensile properties (yield stress, UTS and fracture strain) was observed in 175 K and 77 K compared to non-treated specimen. It is therefore deduced that the ductility of the 175 K specimen is not degraded by the cryogenic treatment though fatigue life was extended. Thus, the pinning by nano-sized α'-martensite particles are considered not to obstruct the motion of dislocations under greater stresses. This results should explain the results of fatigue life tests in which low cycle fatigue life was not significantly extended, and the crack propagation manner was not changed in the175 K-specimens.

In the case of micro-sized materials, it has been pointed out that the deformation behavior and/or fatigue behavior of the materials may be different from those of ordinary-sized materials due to "size-effects" [1]. Our latest studies [1-2] using a micro-fatigue testing machine (MFT 2000) suggested that fatigue fracture of micro-sized materials is also driven by cyclic plastic deformation. Thus, essential mechanism of the fatigue fracture is supposed not to be changed in micro-sized materials and this strengthening method is expected to be applicable for micro-sized materials.

CONCLUSION

High cycle fatigue life of 10 % cold-worked ordinary-sized 316-type austenitic stainless steel specimens was extended by the cryogenic treatment at 175 K. This fatigue life extension is considered to be due to the pinning of dislocation by nano-sized α'-martensite, according to our previous study. The tensile properties of the material were not changed by the fatigue strengthening and thus, ductility of the specimen is deduced not to be decreased by this strengthening method. This fatigue strengthening method is expected to be effective also on micro-sized materials.

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