Effects of Laser Peening on the Very High Cycle Fatigue Strength of Additively Manufactured Maraging Steel

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This study investigated the effect of laser peening (LP) on the very high cycle fatigue (VHCF) of additively manufactured (AM) maraging steels. Ultrasonic fatigue tests were performed on hourglass-shaped round bar specimens. When LP was applied, compressive residual stress was introduced to a depth of 0.2 mm, and tensile residual stress was introduced deeper than that. LP was highly effective in improving the fatigue life up to 10^7 cycles. However, the VHCF life of the LP specimens was shorter than that of the Non-LP specimens, and the 10^9-cycle fatigue strength decreased by 33%. The Smith–Watson–Topper model was applied to evaluate the effect of tensile residual stress on fatigue strength. Consequently, the VHCF lifetimes of the Non-LP and LP specimens were similar. Thus, the internal fracture in the LP specimens was strongly influenced by the tensile residual stress, which led to shorter fatigue in the LP specimens. The main factor in the reduced fatigue life after LP in the VHCF was the tensile residual stress accelerating the propagation of cracks initiated from the inner defects.

Keywords: *additive manufacturing, maraging steel, very high cycle fatigue, laser peening, ultrasonic fatigue testing*

1. Introduction

Recently, additive manufacturing has attracted interest as a new method for reducing the weight and manufacturing time of metal products. However, defects such as lack of fusion easily occur on the surface and inside the material during the building process, resulting in lower fatigue strength compared with materials created using conventional methods[1)]. For maraging steel, the fatigue strength of additively manufactured (AM) materials has been reported to be approximately one-third that of forged material[2)]. As parts are generally subjected to cyclic loading, the inferior fatigue strength of AM materials is a major barrier to expanding their use. Recently, the importance of fatigue properties in the very high cycle fatigue (VHCF) region has been emphasized because of the demand for longer service lives of parts. In this study, laser peening (LP), which can introduce deep compressive residual stress, was used to improve fatigue strength. Previous studies have shown that shot peening (SP) improves the 10^7 cycles fatigue strength of AM maraging steel[3, 4)]. LP improves the 10^7 cycles fatigue strength by 43%[5)]. However, these studies did not clarify fatigue strength characteristics in the VHCF region exceeding 10^8 cycles. Therefore, this study was conducted to clarify the effect of LP on the VHCF strength in AM maraging steel. Ultrasonic fatigue tests were conducted, and the results were evaluated based on the hardness distribution, residual stress distribution, and defect dimensions.

2. Test material and experimental method

AM maraging steel was used as the test material in this study. The chemical composition of the raw powder was 18%Ni-10%Co-5%Mo-1%Mn-bal.Fe. First, a square bar with a length of 60 mm, width of 12 mm, and thickness of 12 mm was fabricated using the selected laser melting method. The building was aligned along the thickness direction. Solution heat treatment was performed by heating the bars in a salt bath at 820 °C for 1 h, followed by water cooling. Hourglass-shaped round-bar specimens with a minimum cross-sectional diameter of 3 mm were machined. Aging heat treatment was performed by heating the specimens in a vacuum furnace at 480 °C for 3 h, followed by cooling in a furnace. After aging heat treatment, the tensile strength and 0.2% proof stress were 2224 and 2185 MPa, respectively. The aged specimens are referred to as "Non-LP" specimens. The specimens subjected to LP are referred to as "LP" specimens.

LP was applied around the entire area of the hourglass-shaped test section of the specimen according to the conditions described in Reference[5)]. The distributions of the hardness and residual stress in the depth direction were measured on the specimens before fatigue testing to clarify the influence of LP on the material properties of AM maraging steel. Because stress redistribution occurred after the removal of the surface layer, a stress correction calculation was performed for each measured result[6)].

The ultrasonic fatigue tests were conducted in air at room temperature with a stress ratio of $R = -1$ and a frequency of 20 kHz. Specimens subjected to 10^9 cycles were also fractured at a higher stress amplitude to confirm the size of the defect[7)]. During the ultrasonic fatigue tests, the specimens were air-cooled to prevent heat generation; however, intermittent tests were not performed. The surface temperature of the specimens was measured with a radiation thermometer, and we confirmed that the surface temperature of the specimens was less than 30 °C. After the fatigue test, the fracture surface of the specimen was observed using scanning electron microscopy (SEM), and the defect size at the fracture origin was measured.

3. Experimental results

3.1 Distributions of residual stress

Figure 1 shows the residual stress distribution from the surface to the depth. A compressive residual stress of 1040 MPa was observed at the top surface, and a maximum of 1290 MPa was observed at a depth of 0.01 mm for LP specimens. The point at which the residual stress shifted from compressive to tensile (crossing point) was approximately 0.2 mm. Beyond the crossing point, tensile residual stress was observed at a depth of approximately 0.5 mm.

3.2 Fatigue test results

Figure 2 shows the fatigue test results. The arrows in the figure indicate the specimens that ran for 10^9 cycles. These

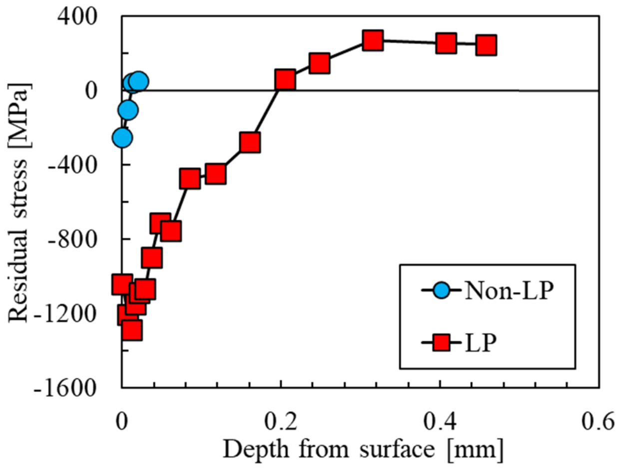


Figure 1 Distribution of the residual stress along the longitudinal direction.

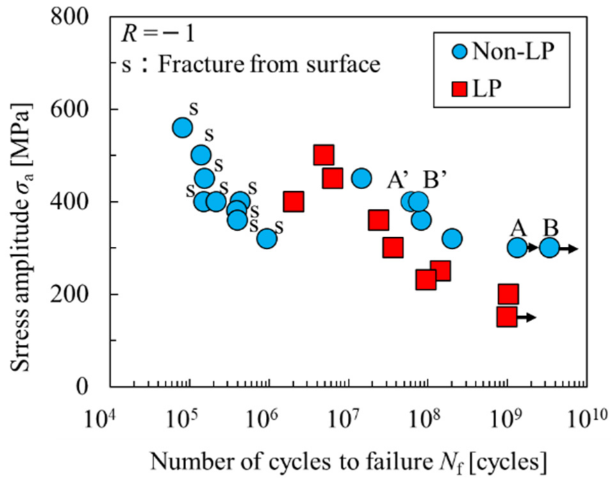
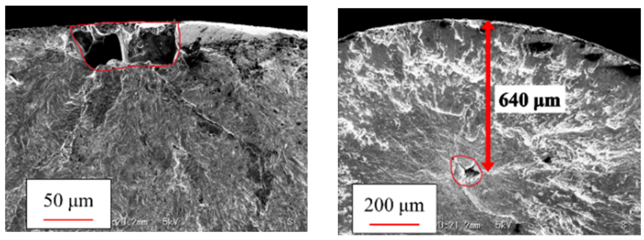


Figure 2 *S-N* curve for AM maraging steel.



(a) Non-LP 500 MPa, $N_f = 1.4 \times 10^5$, $\sqrt{area} = 71$ μm

(b) LP 200 MPa, $N_f = 1.0 \times 10^9$, $\sqrt{area} = 110$ μm

Figure 3 Fracture surface.

specimens were fatigue tested again to identify the fatal defect size that led to specimen fracture. For example, the data marked A and A' were obtained from identical specimens. The plots marked with "s" were specimens with surface fracture; the others were specimens with internal fracture.

Figures 3(a) and (b) show examples of the fracture surfaces observed using SEM for the Non-LP and LP specimens, respectively. Fatigue cracks were initiated owing to the lack-of-fusion defects. Both surface and internal fractures were observed in Non-LP specimens. Figure 3(a) shows a typical fracture surface in the case of fatigue failure from the surface in Non-LP specimen. In contrast, as shown in Figure 3(b), all LP specimens exhibited internal fractures.

In Non-LP specimens, the fatigue life of specimens with internal fractures was more than 100 times longer than that of specimens with surface fractures. For an arbitrarily shaped crack under tensile stress, the square root of the area of the crack projected in the direction of the maximum principal stress ($\sqrt{area}$) is correlated with the maximum stress intensity factor (K_{max}). For internal and surface cracks with the same $\sqrt{area}$, the K_{max} for an internal crack is approximately 23% lower than that for a surface cracks[8]. In addition, the fatigue crack growth rate inside a material is slower than that at the material surface because the condition inside the material is similar to a vacuum environment[9]. These factors may have contributed to the longer fatigue life for internal fractures compared with the case of surface fractures in the Non-LP specimens.

In the region where the fatigue life was less than 10^7 cycles, LP increased the fatigue life by approximately 60 times compared with the Non-LP specimens with surface failure. This result was consistent with the results of previous studies[3-5], in which SP and LP were applied to AM maraging steel. However, the fatigue life of the LP specimens was shorter than that of the Non-LP specimens in the region exceeding 10^7 cycles. The fatigue strength of the Non-LP specimen after 10^9 cycles was 300 MPa, whereas that of the LP specimen was 200 MPa. Thus, LP is not necessarily effective in improving fatigue strength in the VHCF range. The results of this study were similar to those of a study in which SP was applied to 2024-T351 aluminum alloy[10].

3.3 Effects of LP on the fatigue strength in the VHCF regime

As described in Section 3.2, the fatigue life of the LP specimens was shorter than that of the Non-LP specimens that fractured at the internal origin in the VHCF over 10^7 cycles. Figure 4 shows a schematic of the relationship between the net maximum stress and depth from the surface. The net maximum stress is the sum of the maximum tensile stress applied to the specimen and residual stress. In this figure, the nominal stress is σ_a = 400 MPa. The residual-stress distribution of the LP specimen, shown in Figure 1, was approximated using straight lines for each of the four regions, and the residual-stress distribution of the Non-LP specimen was assumed to be 0 MPa at all depths. As shown in the green region of the figure, the fracture origins of the LP specimens were located at depths of approximately 0.2 to 0.9 mm from the surface, all in areas where tensile residual stress was introduced. The net maximum stress acting at the initiation point in the LP specimen was higher than that in the Non-LP specimen owing to the addition of the tensile residual stress. Consequently, the LP specimen had a shorter fatigue life than the Non-LP specimen in the VHCF regime, which resulted in an internal failure.

The effect of the tensile residual stress on the fatigue life was evaluated in more detail using the Smith–Watson–Topper (SWT) model[11], as shown in Equation (1). In this evaluation, the tensile residual stress was considered equivalent to the mean stress.

$$\sigma_{ar} = \sqrt{\sigma_{\max}\sigma_a'} \quad (1)$$

where σ_{ar} is the equivalent stress amplitude, $\sigma_{\max} = \sigma_a' + \sigma_r$ is the maximum stress, σ_a' is the local stress amplitude calculated from the fracture surface diameter, and σ_r is the residual stress at the depth of the fracture origin.

Figure 5 shows the *S*-*N* diagram with σ_{ar} on the vertical axis and N_f on the horizontal axis. This figure shows that the fatigue lives of the Non-LP and LP samples were almost the same in the region exceeding 10^7 cycles. This result indicates that the tensile residual stress inside the material affected the fatigue life of the LP specimens.

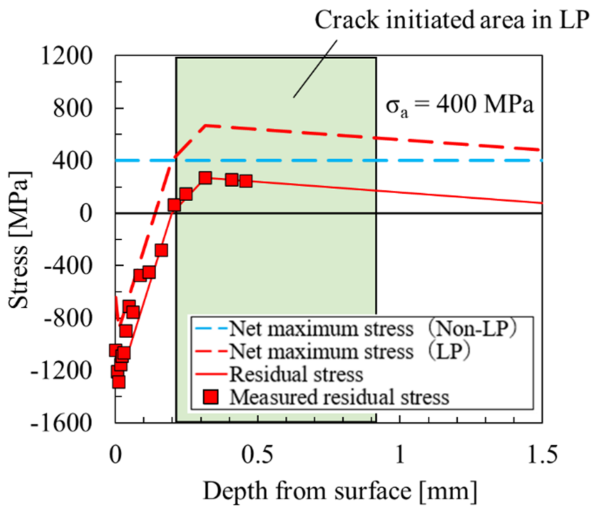


Figure 4 Relationship between net maximum stress and depth from surface.

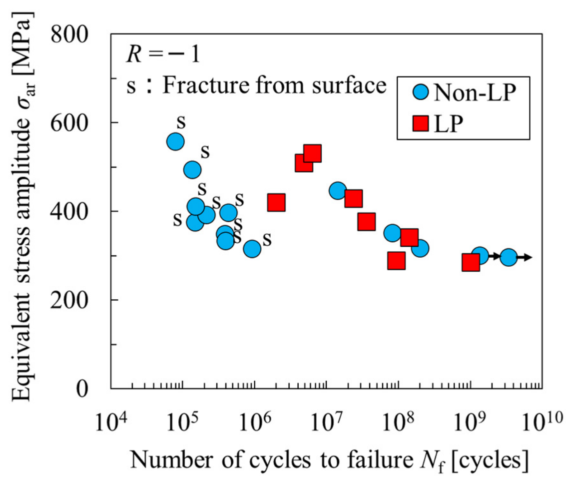


Figure 5 *S*-*N* curve based on the SWT model for AM maraging steel.

5. Conclusions

This study investigates the effect of LP on the VHCF strength of AM maraging steel. The following conclusions were drawn:

1) LP is effective in improving the fatigue strength up to approximately 10^7 cycles. However, LP was ineffective in improving the fatigue strength in the VHCF range of 10^7 cycles or more.

2) The fatigue test results were evaluated using the SWT model to investigate the effects of the tensile residual stress on the VHCF strength. Consequently, the fatigue life of the LP specimens evaluated using the SWT model was generally consistent with that of the Non-LP specimens whose fracture origin was inside the material. The tensile residual stress inside the material affected the VHCF life of the LP specimen.

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