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MICROSTRUCTURAL CHARACTERIZATION OF LASER HEAT TREATED AISI 4140 STEEL WITH IMPROVED FATIGUE BEHAVIOR

CHARAKTERYSTYKA MIKROSTRUKTURY STALI AISI 4140 PO LASEROWEJ OBRÓBCE CIEPLNEJ I Z POPRAWIONĄ ODPORNOŚCIĄ NA ZMĘCZENIE

The influence of surface heat treatment using laser radiation on the fatigue strength and corresponding microstructural evolution of AISI 4140 alloy steel was investigated in this research. The AISI 4140 alloy steel was radiated by a diode laser to give surface temperatures in the range between 600 and 800°C, and subsequently underwent vibration peening. The fatigue behavior of surface-treated specimens was examined using a giga-cycle ultrasonic fatigue test, and it was compared with that of non-treated and only-peened specimens. Fatigue fractured surfaces and microstructural evolution with respect to the laser treatment temperatures were investigated using an optical microscope. Hardness distribution was measured using Vickers micro-hardness. Higher laser temperature resulted in higher fatigue strength, attributed to the phase transformation.

Keywords: laser heat treatment, vibration peening, fatigue properties, ultrasonic fatigue test, alloy steel

1. Introduction

AISI 4140 alloy (JIS SCM-440) has been widely used for structural parts in automotive industry and for dies or molds in metal forming industry. Although the AISI 4140 alloy steel exhibits excellent properties, such as strength, wear resistance, or toughness, the surface of the alloy is often treated to further improve its surface properties, especially the fatigue strength. Various surface hardening processes have been applied to high-strength steels, such as surface coating, peening, and heat treatment, which generally use external energies to improve the surface properties [1-4].

The laser heat treatment is a promising industrial technology for enhancing the surface properties of engineering components utilizing high intensity diode laser beam. The surface hardening is achieved through self-quenching of the laser-heated surface of material by rapid heat dissipation into the bulk material. The main advantages of using a laser are attributed to: (1) its small size and (ii) its easy manipulation. The small diameter of laser beam allows a selective heat treatment without affecting unnecessary regions, and the easy manipulation of its power and spot size allows an ability to tailor the thickness of heat affected zone (HAZ) [5-10].

Vibration peening is also one of the surface hardening processes utilizing mechanical impacts to produce refined grains and compressive residual stress on the surface, which confer resistance to metal fatigue. In practice, shot peening is more popular than vibration peening to create such stress on the surface, however, the main drawbacks of using the shot peening are non-uniformity and shallow thickness of the treated layer [11-13].

In the present study, the influence of surface heat treatment using laser radiation and vibration peening on the fatigue strength of AISI 4140 alloy steel was investigated, and corresponding microstructural evolution was discussed in detail.

2. Experimental

The conventionally processed AISI 4140 alloy steel was used in this study, and its chemical composition is shown in TABLE 1. Specimens for ultrasonic fatigue tests were machined in the hourglass shape as per ASTM E468-08, as shown in Fig. 1a.

The fatigue specimens are subsequently heat-treated using a high power diode laser. The central neck portion of the hourglass-shaped fatigue specimens was radiated by the laser with simultaneous rotation of specimens for uniform treatment over the neck circumference, as shown in Fig. 1b. The laser was 1kw diode laser (Laserline LDM-1000-100), and its power was finely controlled to give constant temperatures, 600, 700, and 800°C, measured using a pyrometer. The laser heating zone was set to ±5 mm from the center of specimens. Then, the laser heat-treated fatigue specimens underwent the vibration peeing using a magnetostrictive transducer, as shown in Fig. 1c. 1.2 mm tungsten carbide tip peened the laser-treated

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surface with a resonant frequency of 9.3 kHz and a displacement of 8 μm. The specimens were rotated with 30 rpm and fed in a speed of 0.1 mm/min along the perpendicular to the peening direction. The ultrasonic fatigue tests were performed for all specimens, as shown in Fig. 1d, with a frequency of 20 kHz, stress ratio of R=-1, and displacement range up to 20 μm.

The micro-Vickers hardness was measured using a load of 25gf, and then color-coded contour maps were constructed using measured hardness values to provide visual presentation of the hardness distributions. Microstructural characterization was carried out using scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD).

TABLE 1

Elemental composition of AISI 4140 steel

Elements	C	Cr	Si	Mn	Ni	Mo	Fe
Wt. %	0.39	0.18	0.21	0.67	0.07	0.15	Bal.

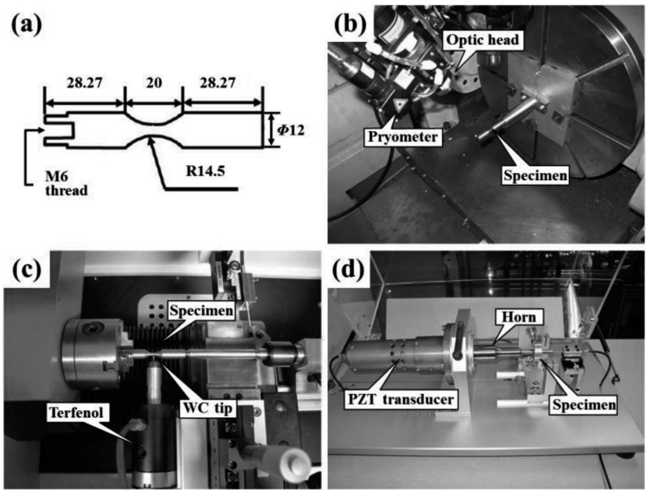

Fig. 1. (a) Fatigue test specimen of AISI 4140, (b) laser heat treatment system, (c) vibration peening system, and (d) ultrasonic fatigue tester

3. Results and discussion

Fig. 2 shows five S-N curves from the AISI 4140 alloy with different treatment methods and conditions: untreated, peening only, and laser treated with three different temperatures (600, 700, and 800°C) then subsequently peened. Untreated specimen exhibited the lowest fatigue limit of 230 MPa, however it was increased to 285 MPa after the vibration peening. At a stress level of 305 MPa, untreated specimen was fractured before 10^6 cycles, and the stress amplitude was significantly decreased to 232 MPa for a fatigue life of 6.7×10^7 cycles. In case of peening-only specimen, the fatigue life at 305 MPa was similar to that of untreated specimen. However, as stress amplitude decreases slightly from 305 to 277 MPa, the fatigue life of peening-only specimen was significantly extended from 6.6×10^5 to 7.5×10^7 cycles, more than 100 times. During the vibration peening, mechanical impacts produce residual compressive stress on the surface and effectively reduce crack propagation from the surface.

The fatigue limit was further increased after the laser heat treatment. As shown in Fig. 2, the fatigue limits of peened specimens with previous laser treatment at 600, 700, and 800°C were 300, 310, and 320 MPa, respectively. These fatigue stress values after laser treatment and peening are 30-40% increased from that of the untreated condition. For mid- or low-carbon steels, the heat treatment using laser is generally accompanied by phase transformation into the martensite, resulting in the improvement of fatigue strength. Also, the fatigue limits increases as the laser temperature increases from 600 to 800°C, as shown in Fig. 2. A rapid cooling (quenching) is achieved when the surface was irradiated by higher temperature laser, causing the phase transformation to the martensite phase.

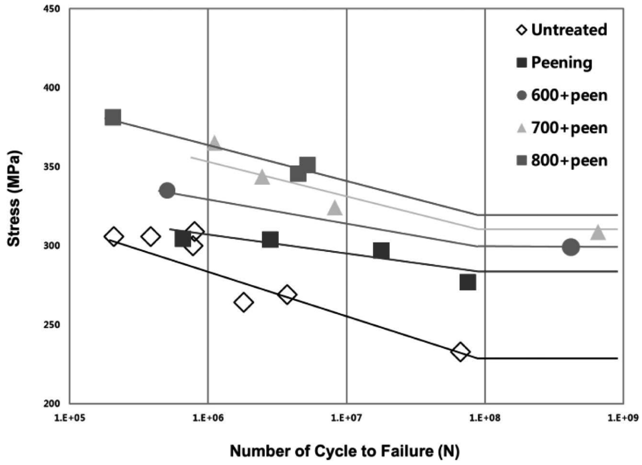

Fig. 2. S-N curves of AISI 4140 from the ultrasonic fatigue test depending on different surface treatment conditions

The fatigue fracture surfaces of untreated, peening-only, and laser heat treated at 800°C then peened specimens are shown in Fig. 3, respectively. The untreated specimen was fractured at 268 MPa and 3.3×10^6 cycles, and its fracture surface exhibited a single point of fatigue crack initiation on the surface, as shown in Fig. 3a, which correspond well with a typical behavior of fatigue failure by surface crack initiation and propagation. This mechanism consists of several steps: (i) the micro-cracks are generally formed at certain points on the surface, such as intrusions or pits, (ii) the stress is concentrated at the crack tips during cyclic loading, and (iii) those cracks propagate toward the inside of material, leading to the final rupture.

Fig. 3b shows the fatigue fracture surface of peening-only specimen, which was fractured at 304 MPa and 1.8×10^7 cycles. It is obvious that the fatigue crack was initiated at ~500 μm below the surface after the peening treatment. As mentioned above, the compressive residual stress is produced by the transfer of kinetic energy from the vibration impacts into the material, creating plastic deformation on the surface. Therefore, the propagation of micro-cracks from a surface is restrained, resulting in the significant improvement of fatigue strength and life.

The fatigue fracture surface of 800°C laser treated and peened specimen is shown in Fig. 3c, which was fractured at 309 MPa and 6.6×10^8 cycles. In this case, the fatigue crack is found to be initiated at ~1 mm from the surface, which is further inside than that of peening-only specimen. This translocation of crack initiation site toward the inside of material after laser heat treatment is attributed to phase transformation in the heat affected zone (HAZ) of AISI 4140 alloy. The phase transformation in the HAZ will be discussed in detail later on this article with further microstructural analysis.

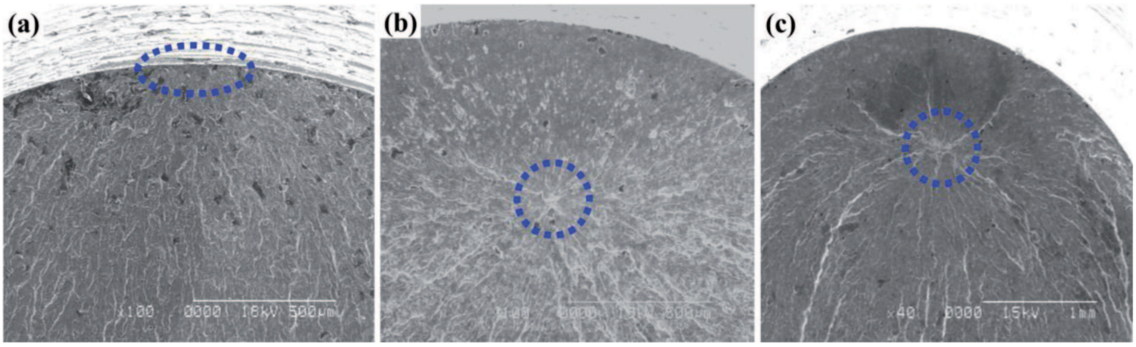

Fig. 3. Fatigue fracture surfaces of (a) untreated, (b) peening-only, and (c) laser heat-treated at 800°C then subsequently peened specimens. The circle indicates crack initiation sites

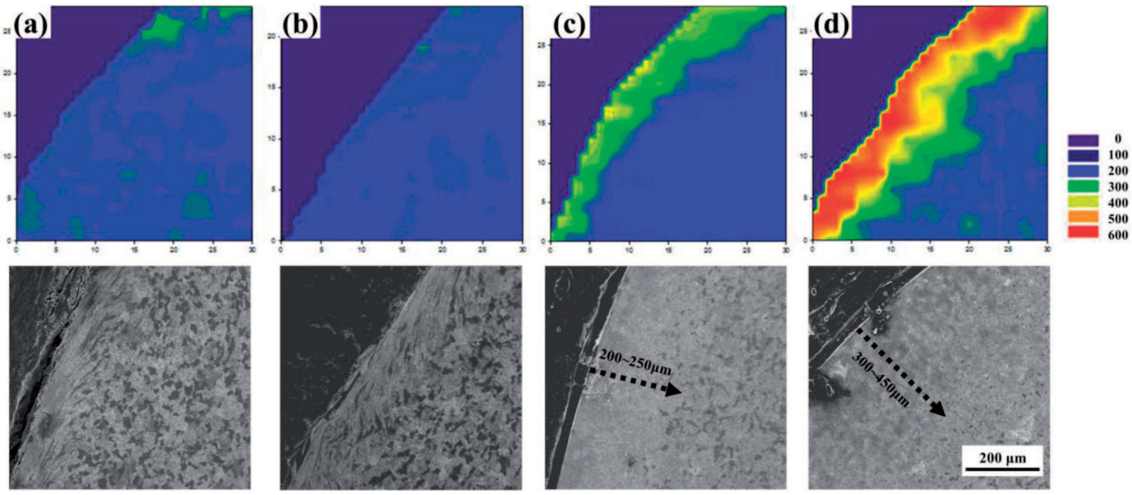

Fig. 4. Distribution of micro-Vickers hardness and corresponding SEM micrographs from the specimens treated by (a) peening-only, (b) 600°C laser heat treatment plus peening, (c) 700°C laser plus peening, and (d) 800°C laser plus peening

Fig. 4 shows the variations of micro-Vickers hardness from the cross section underneath fracture tips and corresponding SEM micrographs. Both peening-only specimen and laser treated at 600°C then peened specimen exhibited virtually no difference in hardness distribution, mostly about 200 Hv, as shown in Fig. 4a and 4b, respectively. Also, the microstructure of both materials shows no evidence of HAZ formation, but grain flow lines were observed which were produced by the mechanical impacts during the vibration peening. No HAZ in both materials means that the temperature of 600°C was insufficient for phase transformation into martensite, although the vibration peening produced compressive residual stress on the surface.

In Fig. 4c, the specimen treated by 700°C laser and peening shows the hardened surface greater than 350 Hv, compared with peening-only specimen or laser treated at 600°C plus peened specimen. Also, the SEM micrograph in Fig. 4c shows the HAZ formed until 200-250 μm depth from the surface. The temperature of 700°C is very close to the eutectoid temperature in a regular iron-carbon alloy system, where the martensitic transformation is likely to occur if the material is quenched. Therefore, the enhanced surface hardness in the specimen treated by 700°C laser and peening is attributed to slight amount of martensite phase transformed from austenite by the 700°C laser heat treatment and rapid cooling.

However, when the material was heat-treated by 800°C laser and subsequently peened, the surface hardness was significantly increased, more than 600 Hv as shown in Fig. 4d, which is about three times greater than that of peening-only specimen. The corresponding SEM micrograph exhibits the HAZ until 350-450 μm depth from the surface. The temperature of 800°C is high enough for proeutectoid ferrite and pearlite structures to fully transform into the γ solid solution, austenite. Also, the higher temperature laser facilitates the martensitic phase transformation, because the cooling rate becomes faster with high temperature laser.

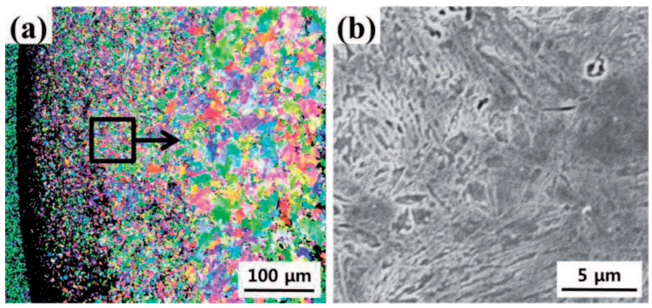

Fig. 5. Microstructure of 800°C laser treated and peened specimen: (a) an EBSD inverse pole figure map and (b) an SEM micrograph showing martensite structure in HAZ

Fig. 5a shows an EBSD inverse pole figure map from the specimen treated by 800°C laser and peening. Fine grains were observed in the range between the surface and depth of ~300 μm, as shown in Fig. 5a. The microstructure appears to be finer near the surface compared with the inside. This grain refinement is primarily attributed to the mechanical impact during the vibration peening, which provides the strengthening effect on the surface according to Hall-Petch relationship. Fig. 5b shows an SEM micrograph from the part in the middle of HAZ indicated using a square in Fig. 5a. It represents a typical microstructure of martensite phase with fine needle-shaped grains. The martensite is a non-equilibrium single-phase structure that results from a diffusionless transformation of austenite, and this transformation occurs only when the quenching rate is rapid enough to prevent carbon diffusion. Therefore, in the present study, the laser heat treatment at 800°C provided sufficient thermal energy for ferrite and pearlite to austenize, and the rapid quenching after laser irradiation promoted the martensitic transformation, resulting in the most improved fatigue behavior of AISI 4140 steel.

4. Conclusions

In this study, the microstructural evolution of AISI 4140 steel depending on the vibration peening and laser heat treatment was investigated to improve the fatigue behavior. The peening process significantly enhanced the fatigue limit by generating compressive residual stress on the surface to restrain fatigue crack propagation, and by refining grains to strengthen the surface. The laser heat treatment prior to the peening further improved the fatigue behavior by promoting the phase transformation into the martensite. However, various laser temperatures between 600, 700, and 800°C caused a difference in austenization of proeutectoid ferrite and pearlite phases, affecting the fatigue behavior by the amount of martensitic transformation. With the 600°C laser, no phase transformation occurred because the temperature is far below the eutectoid temperature of iron-carbon alloy system. The temperature of 700°C is near the eutectoid temperature so that only small portion of ferrite and pearlite was austenized and transformed into the martensite. At the laser temperature of 800°C, the proeutectoid ferrite and pearlite phases are fully austenized and transformed into the martensite in the surface regions. In conclusion, the greatest fatigue behavior was achieved in this study when the specimen was heat treated by 800°C laser and subsequently peened, which is about 40% enhanced fatigue limit compared with the untreated condition. This improvement is attributed to appropriate contribution of the martensitic transformation and compressive residual stress on the surface.

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