A Study for Uniform Laser Hardening of Steel Parts with Convex and Concave Corners

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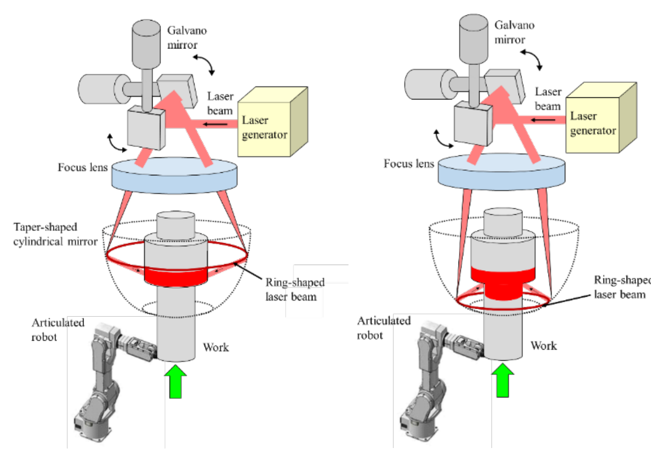
This study aims to establish a laser-hardening technique for uniformly hardening the entire surface of stepped shafts. Our previous study investigated the laser hardening of a straight steel shaft and proposed an all-round hardening method using a high-speed scanning laser and cylindrical inner mirror. The study results confirmed that a hardened reagion could be formed around the entire shaft circumference without soft zones, which significant challenge for conventional methods. This study initially targeted a staircase-shaped workpiece for the convex and concave corners of stepped shafts. A method that changes the laser irradiation conditions according to the difference in the heat capacity of the laser-irradiated part was devised, and the effectiveness of this method was verified experimentally and theoretically.

1. Introduction

Many shaft parts that require hardening are used as machine parts. For such parts, some laser-hardening methods for the entire shaft circumference using a spot laser beam with shaft rotation have been reported [1,2]. In addition to straight shafts, bent and eccentric shafts are used as machine parts. These shafts are important components of almost all machines, including automobiles. Additionally, high reliability is required because shaft failure is directly linked to fatal machine errors. Therefore, hardening is typically conducted to improve shaft strength and wear resistance. However, it is difficult to form a uniform hardened depth for the entire circumference using the laser irradiation method with workpiece rotation, because misalignment of laser irradiation occurs in such shafts during rotation. There are also stepped shafts, but it is difficult to harden the concave corner part, where hardening is essential, using the conventional laser irradiation method from the normal direction to the machined surface.

Therefore, we proposed a high-precision laser-hardening system for the entire circumference of the shaft, as shown in Fig. 1. Figure 1(a) shows the case of applying laser hardening to the entire circumference of the shaft, and Fig. 1(b) shows the application of laser hardening to the concave corner of a stepped shaft. A ring beam is created using a galvanometer scanner, and the reflection angle can be varied by changing the axial position at which the curved inner mirror reflects the beam. Therefore, the laser irradiation method shown in Fig. 1 can



(a) for circumference (b) for convex and concave corners

Fig. 1 Laser-hardening system for stepped shaft

form a uniform hardened region not only on the periphery of the stepped shaft, but also on the entire surface, including the convex and concave corners. A previous study introduced the concept of our laser-hardening system and the results of fundamental experiments carried out to verify the feasibility of the proposed method using a straight shaft [3].

In this study, a basic investigation was conducted to establish a uniform laser-hardening technique for the entire convex and concave corners of a stepped steel shaft. Experiments and simulations were

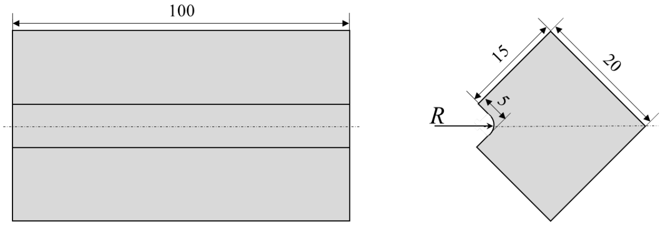


Fig. 2 Workpiece shape and dimensions

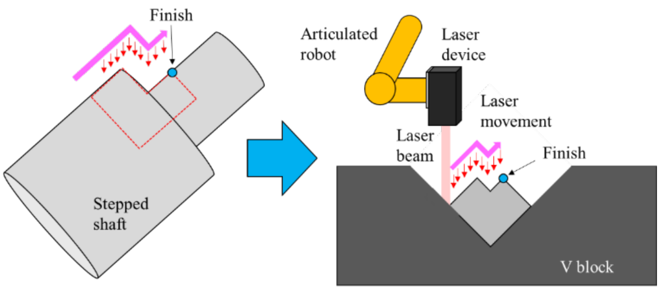


Fig. 3 Laser irradiation method

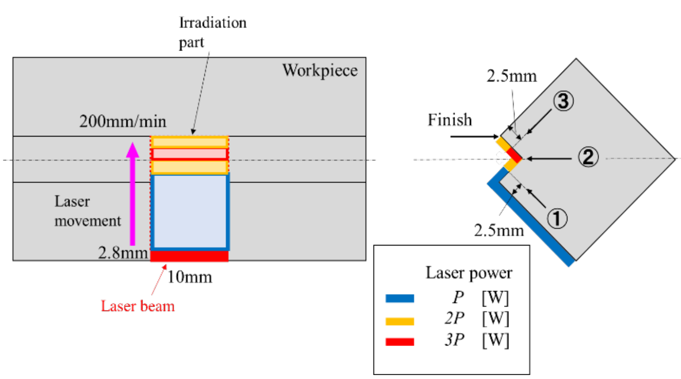


Fig. 4 Laser irradiation condition

performed on a plane-step-shaped workpiece as a preliminary stage for the convex and concave corners of the stepped shaft.

2. Methods

2.1 Specimen

The workpiece was made of JIS: S50C, a carbon steel for machine structural use that is widely used as a material for machine parts. Figure 2 shows the dimensions and geometry of the staircase shapes of the specimens. The external dimensions were 20 mm; the dimensions of the staircase were 5 mm; and the corner radii *R* were 0, 0.5, and 2 mm.

2.2 Experiment

Figure 3 shows the laser irradiation method. A diode laser irradiation system (LDF5000-60, Laserline GmbH) was used to irradiate a top-hat rectangular laser (beam size: 2.8 × 10 mm) at a feed speed of 200 mm/min. Preliminary experiments under the laser irradiation conditions of constant power and constant feed speed confirmed a

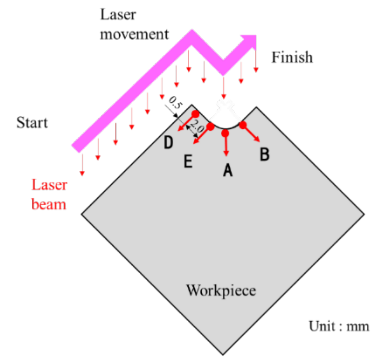


Fig. 5 Measuring position of hardness

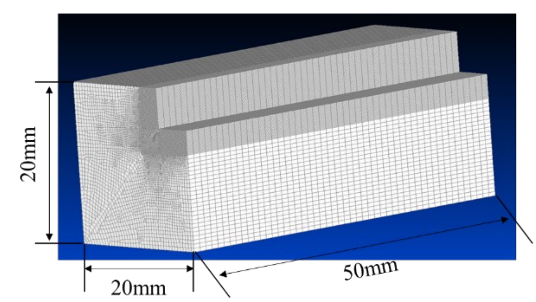


Fig. 6 FEM model for simulation

tendency to overheat and melt at the convex corner and under heatting and not harden at the concave part. Therefore, a laser irradiation method that changes the laser power (heat input) according to the differences in the heat capacity at the corners was devised, and the effectiveness of this method was examined.

Figure 4 shows the laser irradiation conditions. The heat capacities of the flat and concave parts are considered double and triple that of the convex part, respectively. In this experiment, the laser power was changed such that the heat input to the flat and concave parts was doubled and tripled, respectively, based on the laser power *P* W to the convex corner.

At the four locations (A, B, D, and E) shown in Fig. 5, the hardness distribution was investigated in the depth depth direction from the surface. Regions with hardness greater than HV 450 were defined as hardened regions.

2.3 Simulation

An unsteady heat conduction analysis using the finite element method was conducted to examine the effects of laser irradiation based on temperature history. FEMAP with NX NASTRAN was used for the analysis. The finite element model was divided into a 0.1-mm mesh only for the staircase section, where the temperature distribution was evaluated in detail, and a 0.5-mm mesh was used for the rest of the model, as shown in Fig. 6. The boundary condition was heat insulation on all the surfaces. The following thermophysical properties of the material were assumed: 7830 kg/m^3 density, 11×10^{-5} m/°C

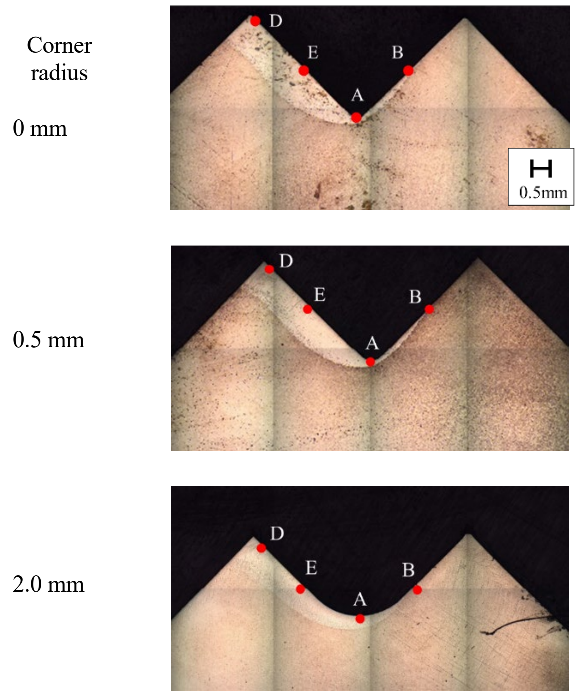


Fig. 7 Results of hardness measurement

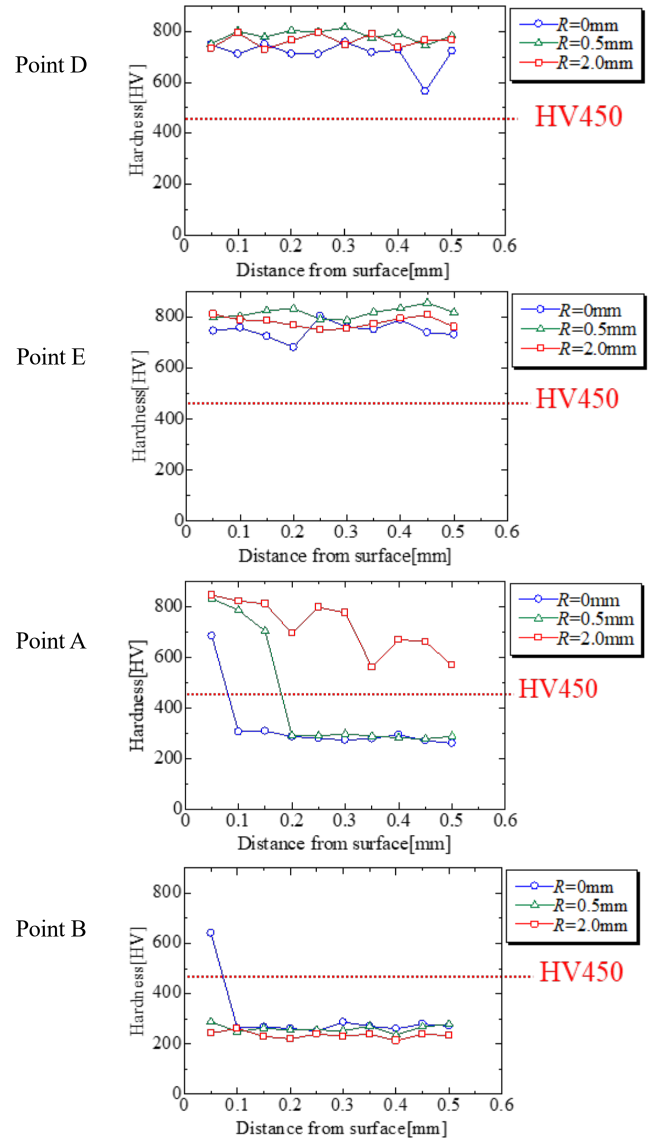


Fig. 8 Results of hardness measurement

temperature diffusivity, 50 W/(m・°C) thermal conductivity, 420 J/(kg・°C) specific heat, and 0.5 absorption coefficient. The initial temperature was set to 25°C, and the effect of the latent heat was ignored. A rectangular heat flux of the same top-hat type as in the laser irradiation experiment was moved to evaluate the temperature change at positions corresponding to the hardness distribution measurement points. The beam size was 2.8 × 10 mm, and the feed speed was 200 mm/min. The hardened region was estimated to be the region that cooled down to the martensitic transformation starting temperature (320°C) at a critical cooling rate (250°C/s) or faster after reaching 800°C or higher, which is the hardening temperature of S50C.

3. Results and discussion

3.1 Experiment

Figure 7 shows digital-microscope images of the cross-sections of the specimens after nital etching in the case of laser irradiation with P = 600 W. The bright region near the workpiece surface are areas where the microstructure changed due to laser irradiation and are considered to correspond to regions hardened by martensitic transformation. As the corner radius decreases, the depth of the hardened region tends to decrease at the concave corner. No melting was observed at the convex corner. Figure 8 shows the results of the hardness distribution. The formation of hardened regions can be confirmed at both the convex and concave corners, demonstrating the effectiveness of the proposed method. At point A (concave corner), the smaller the corner radius R, the smaller the hardened region, suggesting that there may be suitable irradiation conditions depending on the size of the corner radius.

3.2 Simulation

First, the analysis was performed under the same conditions as those used in the laser irradiation experiment. The temperature change at a depth of 0.5 mm was examined for each location where hardness was evaluated. Consequently, the maximum temperatures at the convex corner (point D) and flat part (point E) reached or exceeded the hardening temperature under all conditions. However, no temperature increase up to the hardening temperature was observed at the concave corner (point A) and flat part (point B). It was deduced that a hardened region could not be formed because the power density was low, and the heat input to the concave corner, where heat diffuses easily, was considered insufficient.

Therefore, a smaller beam size (2.0 × 10 mm) was used to increase the power density. A finite-element model with a corner radius R of 0 was used to investigate the conditions under which a sufficiently hardened region could be formed in the concave corner. Analyses were conducted using P = 600, 700, and 800 W laser power conditions. The

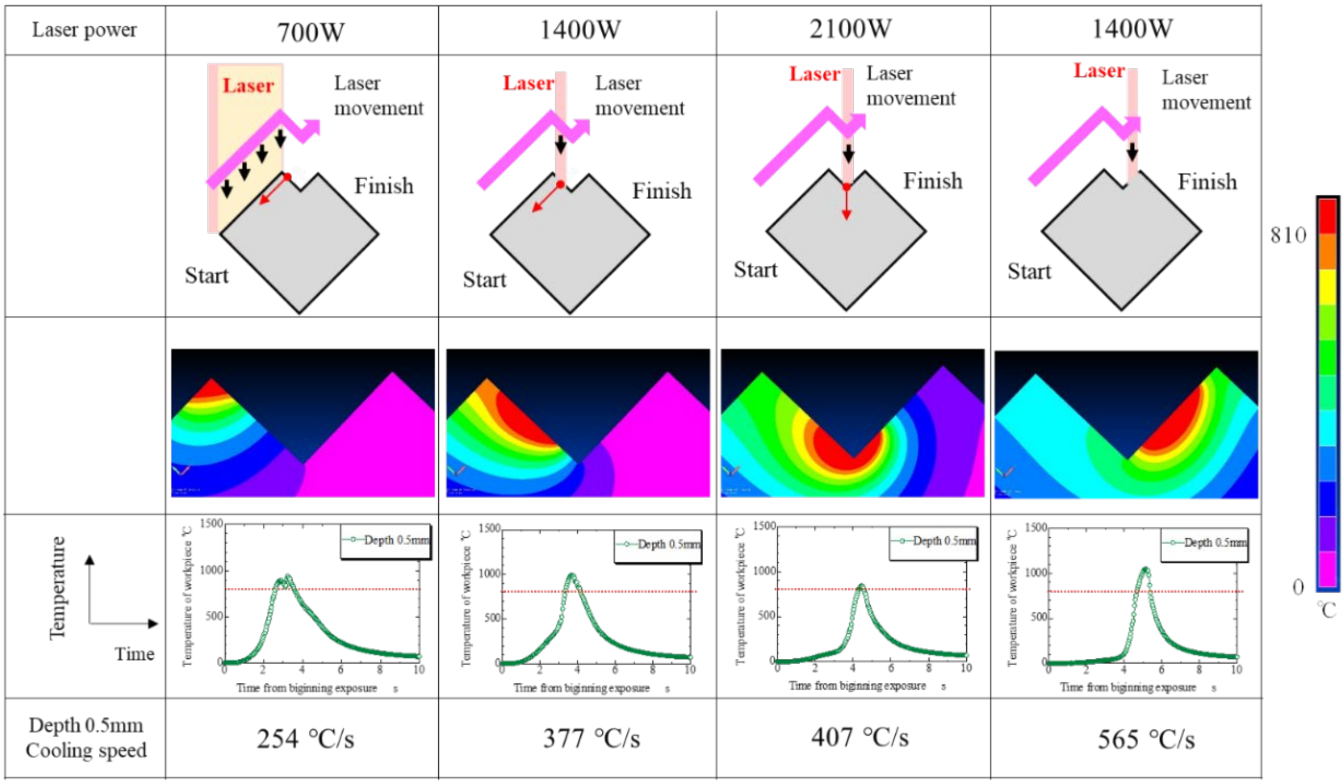


Fig. 9 Results of FEM analysis

temperature changes at the surface and at a depth of 0.5 mm were investigated. Consequently, it was estimated that melting occurred on the surface of the workpiece when the laser irradiation was P = 800 W because there were regions where temperature increases of more than 1400°C could be observed on the workpiece surface. For P = 600 W, the temperature distribution at a depth of 0.5 mm at the concave corner (point A) did not show an increase in the hardening temperature (800°C). However, in the case of P = 700 W, neither melting in the surface layer nor insufficient heat input at any position was observed. Figure 9 shows the results of this analysis. The maximum temperature exceeded the hardening temperature (800°C) at all locations and a cooling rate above the critical cooling rate (250°C/s) was observed. This result suggests that a uniform hardening zone can be formed over the entire region, including the concave and convex corners.

4. Conclusions

To establish a laser-hardening technique for uniformly hardening the entire surface of stepped shafts, a method for changing the laser irradiation conditions according to the difference in the heat capacity of the laser-irradiated part was proposed. The effectiveness of this method was indicated using laser irradiation experiments and finite-element method (FEM) analysis.

ACKNOWLEDGEMENT

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