Cavitation Peening Using a Submerged Water Jet and a Pulsed Laser Comparing with Shot Peening

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Abstract
Improvement of fatigue strength treated by cavitation peening, in which cavitation impact at bubble collapse is utilized for peening, was demonstrated by using a plane bending fatigue test comparing with shot peening and non-peened. In the present paper, a submerged water jet and a pulsed laser were used for cavitation peening. Stainless steel SUS316L, aluminum alloy A2024-T3 and magnesium alloy AZ31B were treated by cavitation peening and shot peening. It was revealed that the best improvement of the fatigue strength comparing with non-peened was 25% for SUS316L by cavitation peening using the jet, 42% for A2024-T3 by cavitation peening using the laser and 55% for AZ31B by cavitation peening using the laser.

Keywords cavitation peening, submerged jet, pulsed laser, fatigue strength.

Introduction
Cavitation normally causes severe damage in hydraulic machineries such as pumps and valves because of intense impacts at bubble collapse. However, the impact at bubble collapse can be utilized for mechanical surface treatment in the same way of shot peening. A peening method using cavitation impact is named as “cavitation peening” [1-3].
At conventional cavitation peening, cavitation is produced by injecting a high-speed water jet into a water filled chamber through a nozzle, and cavitation is generated in a shear layer around the jet. The submerged high-speed jet with cavitation is called as “cavitating jet” [4]. Note that peening mechanism of cavitation peening is different from that of water jet peening, in which water column impacts in jet center are used. It was reported that efficiency of optimized cavitation peening was 3.2 times better than that of water jet peening [5]. In the case of cavitation peening using the submerged water jet, the optimum injection pressure is 40 MPa [5], then an expensive plunger pump is not required.
In the case of submerged laser peening, a bubble, which behaves like a cavitation bubble, is generated after laser ablation [6-8]. In the present paper, the bubble after the laser ablation was named as “laser cavitation”. When amplitude of pressure wave in water was measured by a submerged shock wave sensor, the amplitude at laser ablation was larger than that of laser cavitation collapse [6-8]. On the other hand, when impact which propagated in the target metal was measured by a PVDF sensor, the impact of laser cavitation collapse was larger than that of laser ablation [7,8]. Namely, the submerged laser peening is a kind of cavitation peening using the pulsed laser.
When the fatigue poperies of stainless steel treated by cavitation peening were compared with that of shot peening, the fatigue strength of cavitation peening was larger than that of shot peening, and the relief of compressive residual stress introduced by cavitation peening during the fatigue test was smaller than that of shot peening [9]. At the equivalent peening intensity condition for stainless steel, the summation of compressive residual stress was nearly equivalent for cavitation peening and shot peening, however, the dislocation density of the sub-surface treated by cavitation peening was smaller than that of shot peening [10]. These differences might be caused by the impact characteristics such as strain speed and applied stress distribution of the impact [3]. Then, these effects would cause the differences on the fatigue properties.

In the present paper, in order to make clear the difference on improvement of fatigue properties by cavitation peening comparing with shot peening, stainless steel Japanese Industrial Standards JIS SUS316L, aluminum alloy JIS A2024-T3 and magnesium alloy JIS AZ31B were treated by cavitation peening using the submerged water jet and the pulsed laser and shot peening, then tested by a displacement-controlled plane bending fatigue test.

Experimental Methods

Figure 1 illustrates geometry of specimen. The thickness of specimen was 2 mm for SUS316L, 3 mm for A2024-T3 and 4 mm for AZ31B, respectively.

Figure 2 shows a schematic diagram of cavitation peening system using the submerged water jet. The water pressurized by a plunger pump was injected to the specimen, which was set in the recess, through a nozzle. The nozzle throat diameter d was 2 mm and it had an optimized outlet bore whose diameter D was 16 mm and the length L was 16 mm. It also had a cavitator whose diameter d_c was 3 mm and a guide pipe to enhance aggressive intensity of the cavitation impacts. The injection pressure was 30 MPa and the standoff distance was 222 mm.

Figure 3 reveals a schematic diagram of cavitation peening system using a pulsed laser. The used pulse laser source was a Q-switched Nd:YAG laser. The wave length was 1,064 nm, as laser cavitation impact was used for the peening at the present test to utilize heat effect caused by the pulse laser, as the laser cavitation is a kind of sub-cool boiling. Note that conventional submerged laser peening uses 2nd harmonics of Nd:YAG laser, i.e., 532 nm, to mitigate attenuation of the pulse energy due to water, and 40 % of source energy was lost at the wavelength conversion from 1,064 nm to 532 nm. The used pulsed laser energy was 0.35 J, the pulse width was 6ns, the beam diameter was 6 mm, the repetition frequency was 10 Hz. The pulsed laser was reflected by the mirrors, and expanded by a concave lens, then focused on the specimen, which was placed in a water filled glass chamber, by a convex lens to avoid the damage of the glass chamber. The standoff distances in air s_a and water s_w were optimized by measuring the peening intensity. The specimen was placed on the stage which was controlled by stepping motors.

Figure 4 shows the schematic diagram of shot peening system. In the preset experiment, a recirculating shot peening system accelerated by a water jet was used. Stainless steel shots, whose diameter were 3.2 mm were installed in the chamber. The number of shots was 500.

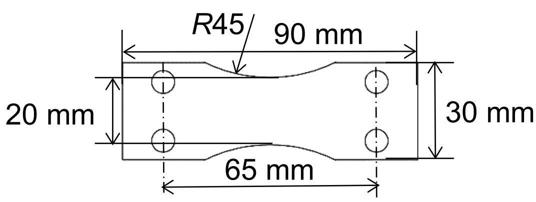


Fig. 1 Geometry of specimen

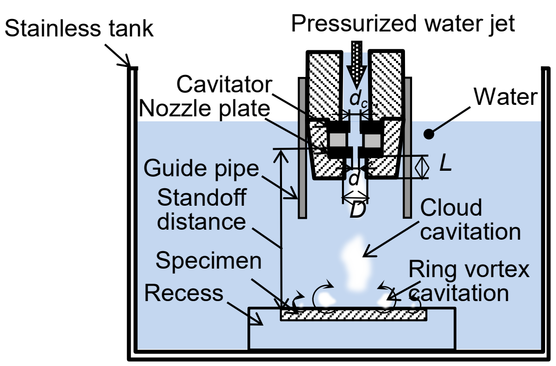


Fig. 2 Schematic diagram of cavitation peening system using submerged water jet

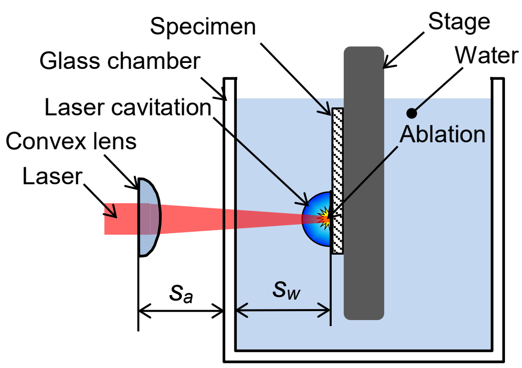


Fig. 3 Schematic diagram of cavitation peening system using pulsed laser

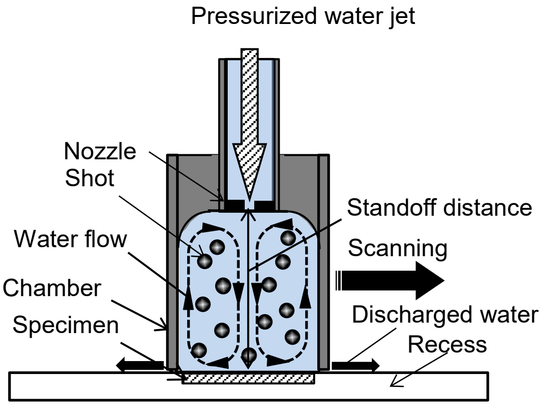


Fig. 4 Schematic diagram of shot peening system accelerated by water jet

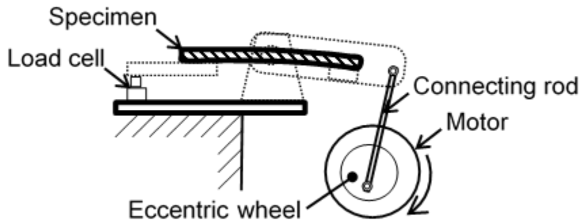


Fig. 5 Schematic diagram of a Schenk-type displacement-controlled plate bending fatigue tester

The standoff distance from the nozzle to the specimen surface was 50 mm. The water jet was injected into the chamber through three holes with a diameter of 0.8 mm. The injection pressure was 12-15 MPa. At the present condition, the water jet without shots did not introduce compressive residual stress into metallic surface.

Figure 5 illustrates a schematic diagram of a Schenk-type displacement-controlled plate bending fatigue tester. The fatigue properties of tested materials were evaluated at stress ratio R =-1. The test frequency was 12 Hz. In order to investigate mechanical properties of peened surface, the residual stress on the surface was evaluated by 2D method using X-ray diffraction [11]. The surface roughness and the surface hardness were also measured.

Experimental Results

In order to reveal effect of impact at laser cavitation collapse comparing with laser ablation, Fig. 6 shows the aspect of laser ablation and laser cavitation observed by a high-speed video, and Fig. 7 reveals signal from the PVDF sensor and the submerged shock wave sensor [7]. After the laser ablation, laser cavitation was developed and it was collapsed at t = 1 ms. The amplitude of laser ablation was larger than that of laser cavitation, when the amplitude of pressure was measured by the submerged shock wave sensor. On the other hand, when the impact passing through the target metal was measured by the PVDF sensor, the impact at

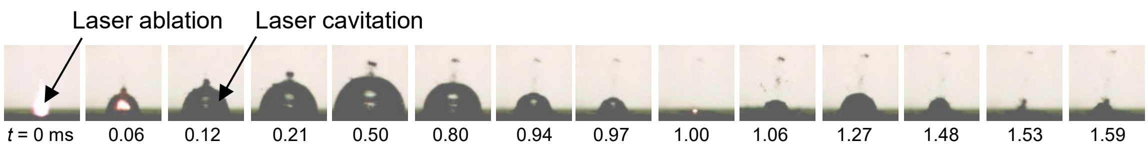
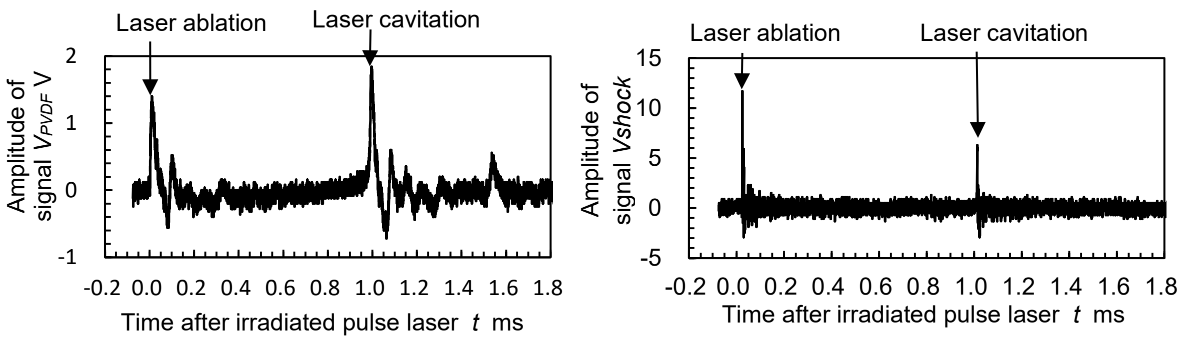


Fig. 6 Aspect of laser ablation and laser cavitation



(a) Signal from PVDF sensor (b) Signal from submerged shockwave sensor

Fig. 7 Signals of laser ablation and laser cavitation the laser cavitation collapse was larger than that of the laser ablation. Namely, the laser cavitation impact can be utilized for the peening.

In order to find optimum coverage for cavitation peening and shot peening, Fig. 8 shows the number of cycles to failure at constant amplitude of bending stress as a function of coverage *Cov* for (a) SUS 316L, (b) A2024-T3 and (c) AZ31B. The used pulse density or processing time per unit length to calculate coverage for each materials and peening method are shown in Table 1. As shown in Fig. 8, the number of failures at constant applied stress N_f was increased with *Cov*, and then saturated, except AZ31B treated by CP by laser. Although AZ31B was relatively soft material, the fatigue life was still increasing at 14 pulse/mm^2.

In order to demonstrate the improvement of fatigue properties of metallic materials by cavitation peening using the laser and the jet comparing with shot peening, Figs. 9 -11 reveal the *S-N* curves for SUS316L, A2024-T3 and AZ31B obtained by the plane bending fatigue test. Table 2 shows hardness of non-peed one and fatigue strength obtained by Little's method [12]. In Figs.9-11, the amplitude of bending stress was normalized by the fatigue strength of non-peened which was shown in Table 2.

As shown in Fig. 9, at bending stress σ_a = 400 MPa, the fatigue life of shot peening was better than that of cavitation peening using the jet. However, the fatigue strength of cavitation peening using the jet was larger than that of shot peening. In the case of AZ31B, $\sigma_a \approx$ 140 MPa, the fatigue life of shot peening was better than that of cavitation peening using the jet, and the fatigue strength of cavitation peening using the jet was slightly larger than that of shot peening, as shown in Fig. 11. In the case of A2024-T3, the fatigue life of shot peening at $\sigma_a \approx$ 280 MPa was better than cavitation peening using the laser, but the fatigue strength of cavitation peening using the laser was larger than that of shot peening. These might be caused by the difference on the increase of surface roughness by the peening methods.

In the case of the fatigue strength of SUS316L, cavitation peening using the jet was best, and it improved 25% comparing with non-peened. In the case of A2024-T3 and AZ31B, the improvement by cavitation peening using the laser was best, and it improved 42% for A2024-T3 and 55% for AZ31B.

Table 1. Used Pulse Density or Processing Time per Unit Length to Calculate Coverage.

Material	Peening method			
	Cavitation peening by laser	Cavitation peening by jet	Water jet peening	Shot peening
SUS316L	4 pulse/mm^2	8 s/mm	8 s/mm	0.88 s/mm
A2024-T3	10 pulse/mm^2	8 s/mm	—	0.9 s/mm
AZ31B	14 pulse/mm^2	16 s/mm	—	1 s/mm

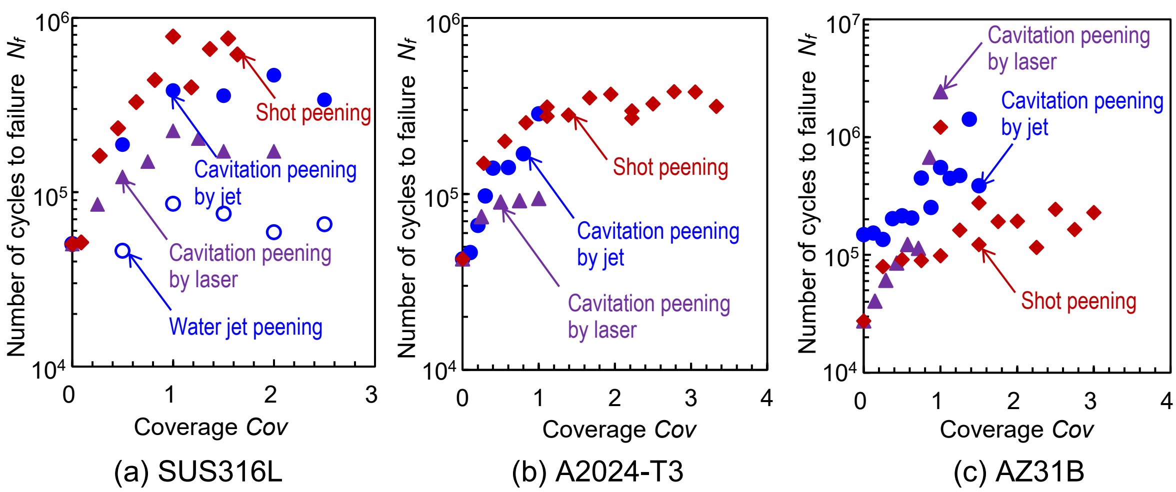


Fig. 8 Fatigue life as a function of coverage

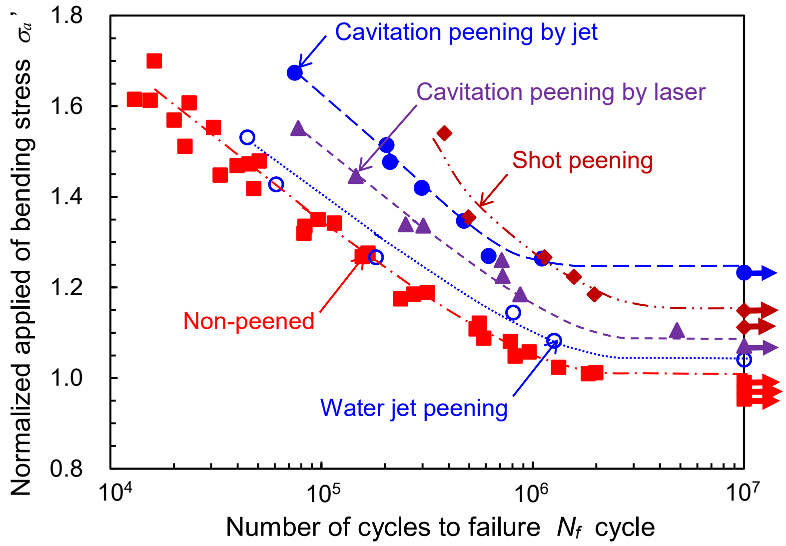


Fig. 9 *S-N* curves (SUS316L)

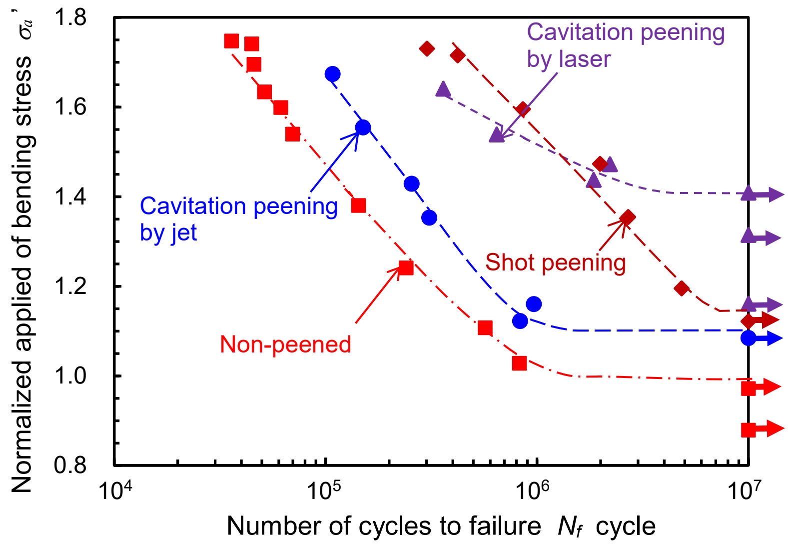


Fig. 10 *S-N* curves (A2024-T3)

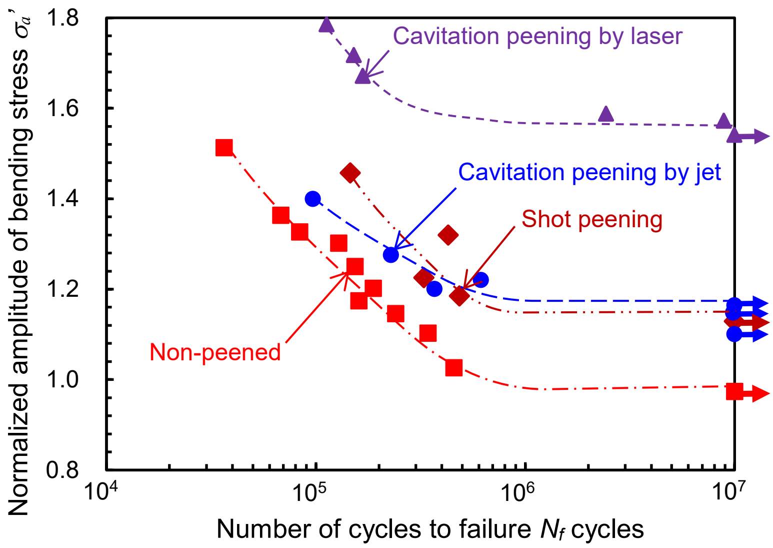


Fig. 11 *S-N* curves (AZ31B)

Table 2. Improvement of Fatigue Strength of Tested Materials.

Material	Yield strength [MPa]	Hardness		Fatigue strength [MPa]			
		HR15N	HR15T	NP	CP by laser	CP by jet	SP
AZ31B	-	38.6±0.6	74.3±0.4	97±3	151±2	115±2	112±3
A2024-T3	311	63.3±0.3	87.0±0.2	175±5	248±3	193±3	202±6
SUS316L	216	63.2±0.7	86.6±0.2	279±3	303±5	348±5	325±5

Conclusions

In order to investigate the fatigue properties of metallic materials treated by cavitation peening using the pulsed laser and the submerged water jet comparing with shot peening, stainless steel SUS316L, aluminum alloy A2024-T3 and magnesium alloy AZ31B were treated, and tested by the plane bending fatigue test. It was revealed that the fatigue strength of AZ31B and A2024-T3 treated by cavitation peening by the laser was better than shot peened one, and that of SUS316L treated by the jet was better than shot peened one.

Acknowledgments

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