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Surface Modification of Al by a New Technology Using High Speed Jet in Water under ultrasonic Irradiation

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***Abstract*—Al has been widely used in many common products, such as household items, industrial products, and accessories. To respond to the increasing demand for its use, the enhancement of various properties of Al by adding different elements has been explored. As a result, numerous types of aluminum alloys have been developed, the addition of elements is a complex process, and the recycling of such alloys is difficult. In this study, the improvement of the residual stress of the surface of pure Al specimens by the multifunction cavitation (MFC) processing was investigated. In the MFC-processed pure Al, water jet peening always suppressed the erosion generated in the center part of the specimen surface and improved the residual stress applied to the specimen surface.**

***Index Terms*—pure Al, cavitation erosion, water jet peening, multifunction cavitation**

I. INTRODUCTION

Al is widely used in many common products, including household items, industrial products, and accessories. To respond to the increasing demand for its use, various desirable properties of Al have been enhanced by adding various elements. As a result, numerous types of aluminum alloys have been developed, the addition of elements to create these alloys is a complicated process, and they are difficult to recycle [1].

One technique for improving the fatigue strength and stress corrosion cracking resistance of metal parts is peening. Peening involves subjecting the material surface to high mechanical forces to induce the work hardening and plastic deformation of the surface layer. One notable peening technique is water jet peening (WJP) [2, 3], which involves the impingement of a high-pressure water jet on the surface of the material. When WJP is conducted underwater, cavitation occurs, resulting in the injection of a high-speed water jet containing fine microscopic cavitation bubbles. These cavitation bubbles repeatedly appear and disappear in turbulent flows containing the surrounding water and generate an extremely large impact force along with sound. Additionally, with the stress improvement effect of this technique, the produced cavitation bubbles shrink at high speeds as a result of the surrounding pressure, generate large shock waves and microjets (MJ), and disappear. This impact pressure results in the slight plastic deformation of the material surface. When a minute portion of the material surface is stretched and plastically deformed, the deformed portion is elastically restrained from the surroundings, causing compressive residual stress to be imparted to the portion to which the pressure is applied. Therefore, when WJP is applied to a material surface with tensile residual stress, it is possible to improve this residual stress by converting it from tensile to compressive stress.

In a previous report [4], erosion was shown to occur in the central portion of a pure Al surface subjected to fixed-point injection with WJP. It is clear that this erosion is not caused by cavitation bubbles and that erosive bubbles generated in the central part of the material during WJP processing cause erosion. It is possible to increase the number of cavitation bubbles and their size by attaching a swirling flow nozzle (SFN) to the outlet of the water jet (WJ) nozzle. Furthermore, WJP with an SFN has the effect of suppressing erosive bubbles.

Recently, Yoshimura et al. developed multifunction cavitation (MFC) [5-7] processing, which is a cavitation technique that applies ultrasonic waves to WJP. It is possible to reform a material surface with MFC in the same way as with WJP. However, the cavitation bubble temperature with MFC is different; the sound pressure due to ultrasonication exceeds the breaking threshold before the bubbles from the WJ nozzle collapse with the material surface. Therefore, high-temperature, high-pressure cavitation that produces hot spots occurs by repeated isothermal expansion and adiabatic compression. If a cavitation bubble begins to collapse when it is approaching the specimen surface, the volume of the bubble decreases, and a MJ is formed that impacts the surface of the object. The impact force is large because of the high temperature (several thousand degrees Celsius) and high pressure (about 1000 MPa) inside the bubble. In contrast to WJP processing, previous studies have shown that when MFC processing is applied to low-alloy steel with the compressive residual stress, voids and cracks do not form inside the specimen [3, 8]. In addition to

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improving the strength of the specimen surface, MFC has also been reported to improve the corrosion resistance [9]. Various properties of MFC-processed materials have been reported to date [6, 7].

In this study, the improvement of the residual stress of the surface of pure Al by MFC processing was investigated.

II. EXPERIMENTAL METHODS

The materials used for the tested specimens were pure Al (Nippon Light Metal Co., Ltd.), the chemical compositions of which are given in Table I.

TABLE I. CHEMICAL COMPOSITION OF THE PURE AL.

	Si	Fe	Cu	Mn	Mg	Zn	Ti	V	Al
Pure Al	0.06	0.31	0.03	0.01	0.01	0.01	0.03	0.01	Bal.

The Al was cut into square specimens with dimensions of 60 × 60 × 10 mm. To remove the surface roughness and improve workability, the pure Al surfaces were ground uniformly to average roughnesses *Ra* of 0.193.

Fig. 1 shows a diagram of the equipment used for MFC processing. This equipment was similar to a conventional WJP apparatus, in that a jet of room temperature tap water was discharged from a nozzle at 35 MPa. The nozzle diameter was 0.8 mm, the distance between the nozzle and the specimen was 65 mm, and the reactor dimensions (JIS-SUS310S) were 41 cm×44 cm×60 cm. The depth of the water in the reactor was about 37 cm, and the nozzle was installed about 28 cm from the reactor bottom. The conduit of the WJ nozzle in Fig. 1 was processed in a closed state. During the MFC treatment, an ultrasonic transducer (WD-1200-28T, Honda Electronics Co., Ltd.) was positioned orthogonal to the water jet nozzle and ultrasonic waves was irradiated to the water jet. The output of the ultrasonic transducer was 800 W and the nominal drive frequency was 28 kHz.

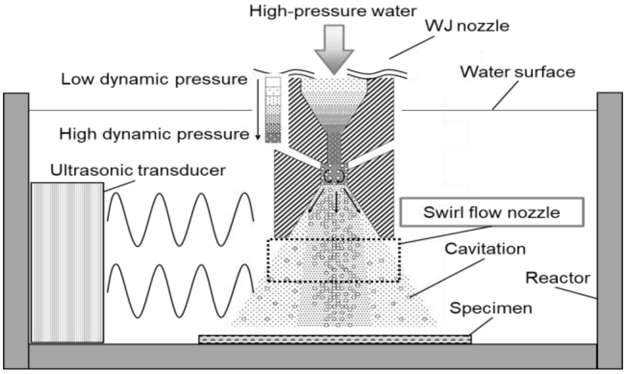

Figure 1. Equipment for surface processing by MFC.

As shown in Fig. 2, bubbles from water jet caviation isothermally expand when the sonic pressure due to ultrasonic irradiation exceeds the Blake threshold, and after the bubbles expand to a certain size, Rayleigh shrinkage occurs rapidly (adiabatic compression). The flow cavitation, including the hot spot, becomes MFC by the repetition of isothermal expansion and adiabatic compression. At the same time that the MFC begins to collapse, it approaches the specimen surface.

Fig. 3 shows the bubble shape change from photographs taken by a high-speed camera during bubble collapse into an aspheric shape [10]. As the volume of the bubble decreases, a microjet (MJ) with a columnar shape is formed and impinges on the specimen surface. This phenomenon is referred to as micro-forging because the MJ provides high-temperature and high-pressure processing in a microscopic area. Conventional WJP produces large high-pressure bubbles (diameter of several hundred micrometers at approximately 1,000 MPa), whereas bubbles produced with conventional ultrasonic waves are small (several micrometers) with high temperature (several thousand degrees Celsius). In contrast, the MJ that occurs in a bubble during MFC is a deforming liquid-phase body similar to a liquid jet (column) at the terminal stage of bubble collapse, and the interior temperature and pressure of the bubble become high (several thousand degrees Celsius and approximately 1,000 MPa, respectively).

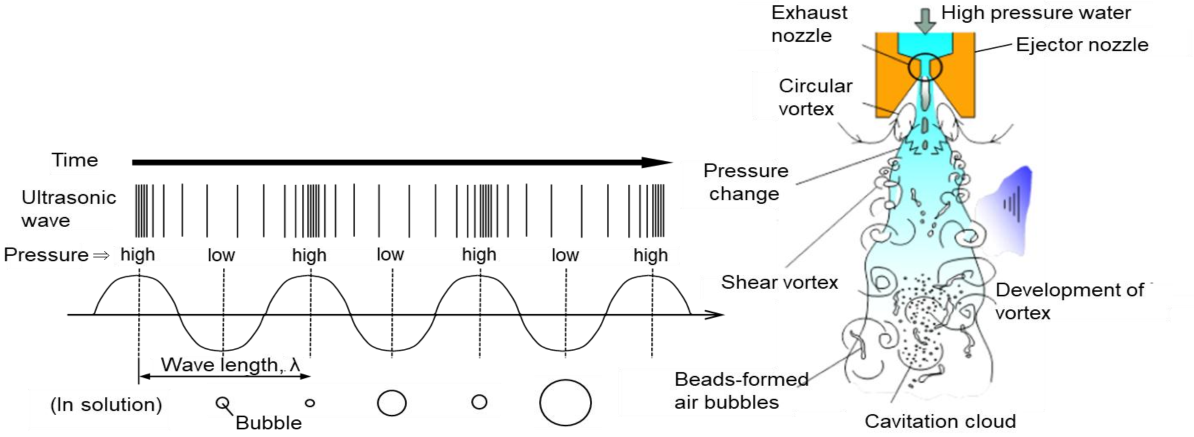

Figure 2. Mechanism for MFC

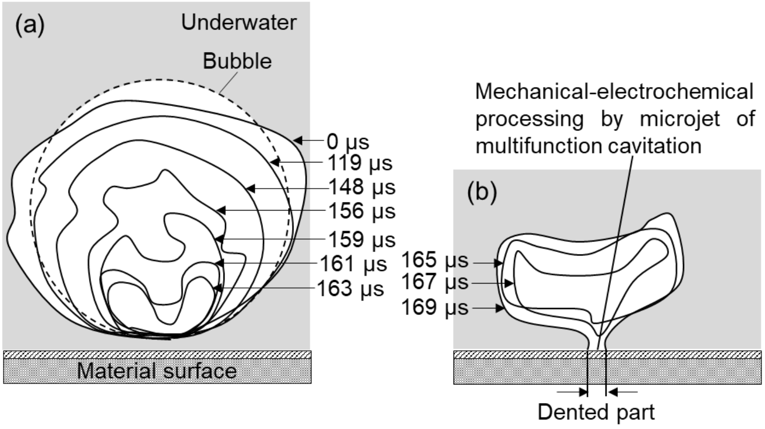

Figure 3. A state of non-spherical collapse of bubbles. (a) 0-163 μs, (b) 165μs~.

A swirl flow nozzle (SFN) [4] was used at the tip of the WJ nozzle to increase the number of cavitation bubbles and their size. In this research MFC and WJP using SFN are abbreviated SFN–MFC and SFN–WJP respectively. Processing times were 2, 10, 20, and 30 min.

Residual stress was measured using an X–ray stress analyzer (MSF–3M, Rigaku Corporation) with the peak top method after measurement of the (211) strain between lattice planes with the Cr Kα line generated at 30 kV–10 mA.

III. RESULTS AND DISCUSSION

Photographs of the resultant processed surfaces are shown in Figure 4. The photographs of the surfaces processed by WJP and SFN-WJP show the results reported previously [4] for comparison. The surface of each specimen was painted with an oil-based ink prior to processing to identify the peening position. The area of ink removal (peening range) on the specimen surface processed with WJP had a diameter of 56.0 mm, SFN-WJP had a diameter of 43.7 mm and SFN-MFC had a diameter of 45.1 mm. SFN-WJP has a smaller peening range than WJP because of the size of the SFN injection port. The peening range of SFN-MFC was found to be slightly larger than that of SFN-WJP. This is considered to be a result of the cavitation bubbles generated by the WJ nozzle growing by repeated isothermal expansion and adiabatic compression by the ultrasonic waves, thereby increasing the processing region of SFN–MFC as a result of the slight increase in the cross-sectional area of the bubble. In the erosion trace region formed by the erosive air bubble, as indicated by the dashed box labeled A in Figure 4, the erosion marks were smallest after SFN-MFC processing.

Figure 5 shows SEM images of the regions labeled A in Figure 4. After WJP processing, dropped particles, voids, cracks, scrapes, and raised regions were observed on the specimen surface (Fig. 3(a)), and dropped particles, voids, and cracks were observed after SFN-WJP processing (Fig. 3(b)). However, after SFN-MFC processing, only voids and dropped particles were observed (Fig. 3(c)). These results indicate that SFN-MFC provided the most suppression of erosive air bubble generation. It is thought that the formation of erosion marks was suppressed by the addition of an SFN and the resulting increase in the number and size of cavitation bubbles. The reason almost no erosion traces were formed during SFN-MFC processing is that the ultrasonication caused the repeated isothermal expansion and adiabatic compression of the erosive air bubbles. When these bubbles collide with the surface, they have a broader impact area than in WJP, which is thought to suppress the formation of erosion traces.

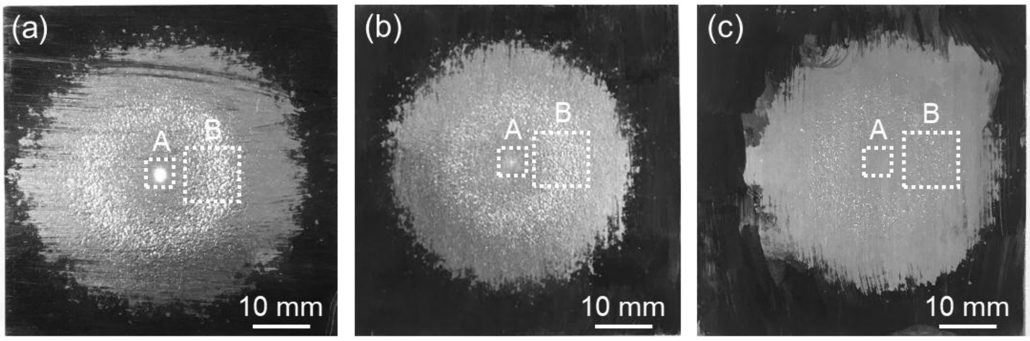

Figure 4. Change in surface morphology by (a) WJP treatment, (b) SFN-WJP treatment, (c) SFN-MFC treatment for 2 min.

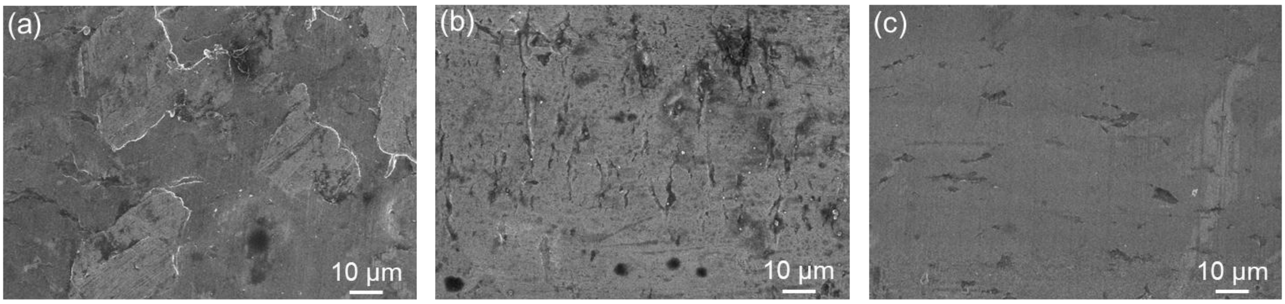

Figure 5. SEM images of specimen surface after (a) WJP, (b) SFN-WJP and (c) SFN-MFC for 2 min. Enlargement of the dashed box region in Fig. 2.

Table 2 gives the residual stress and *Ra* measurement results to demonstrate the effect of each processing method. These measurements were carried out in the area of the dashed box labeled B in Figure 4 after each processing method. To ascertain the effects of processing, tensile residual stress was imparted to the surface of each specimen by grinding the specimen before processing. The compressive residual stress is considered to increase after processing as the result of a shakedown effect. Tensile residual stress was applied to the abraded specimens in the direction parallel to grinding, and it was confirmed that compressive residual stress was applied in the direction perpendicular to grinding. The residual stress in the grinding direction was measured after each of the different processing methods. After the processing of each specimen, the tensile residual stress was improved to compressive residual stress, and SFN-MFC yielded the greatest improvement to the residual stress. Compressive residual stress occurs when the surface is compressed by the cavitation collapse pressure and deformation in the lateral direction is elastically constrained by the surroundings.

The *Ra* measurement results revealed that the surface roughness after SFN-MFC processing was small. The likely cause of the suppression of the surface roughness was considered to be the exposure of the surface to high temperatures. Regarding the temperature applied to the surface, the temperature at which pearlite cementite is spheroidized has been reported to be approximately 727 ℃ or more [3]. However, although the approximate surface temperature was confirmed by the structural change of the material surface at the present stage, it is not possible to determine the accurate surface temperature, because there are various disturbances to the temperature in the cavitation bubbles; thus, this remains as a task for future study.

TABLE II. RESIDUAL STRESS AND SURFACE ROUGHNESS OF PURE ALS AFTER VARIOUS TREATMENTS.

		Residual stress [MPa]	*Ra* [μm]
As-received after grinding	Parallel direction	+7.08	0.110
	Vertical direction	−15.44	0.124
WJP		−26.75	2.464
SFN-WJP		−27.33	2.367
SFN-MFC		−38.01	1.974

Fig. 6 shows the measurement results of the mass loss due to erosion plotted against the processing time. These results indicate that the amount of cavitation erosion generally does not increase linearly with processing time but shows more complex changes and undergoes latent, acceleration, stationary, and deceleration periods [11]. If the amount of erosion is large, the risk of material breakage is high. WJP showed the largest amount of erosion, and erosion was comparatively suppressed in SFN-WJP and SFN-MFC. This is considered to be due to the formation of cavitation clouds and the increase in the number and size of cavitation bubbles, which is a feature of SFN. From these results, it was clarified that the erosion of pure Al, which is a problem in WJP processing, is suppressed by SFN-WJP and SFN-MFC. Furthermore, in comparison with WJP, SFN-MFC was shown to reduce the surface roughness and the residual stress after processing.

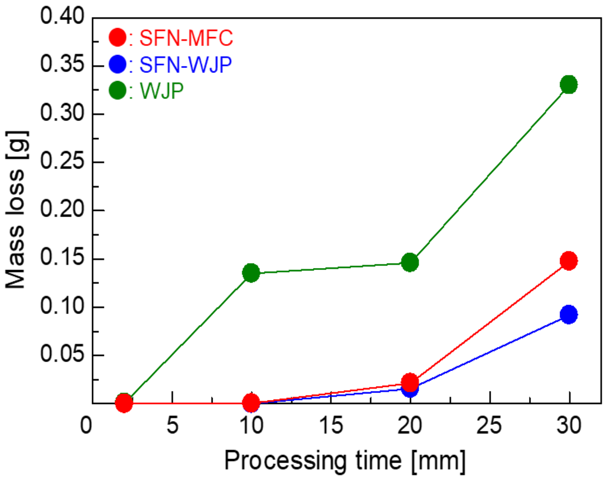

Figure 6. Mass loss due to erosion plotted against processing time.

IV. CONCLUSION

In pure Al processed by SFN-MFC, the erosion in the central part of the WJP-processed surface was suppressed, and the surface residual stress was improved. Additionally, after SFN-MFC processing, the roughness of the surface was reduced, and processing for a long time was confirmed to suppress the erosion of the surface.

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