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New water jet cavitation technology to increase number and size of cavitation bubbles and its effect on pure Al surface

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A B S T R A C T

Currently, a wide variety of alloying elements are added to Al to strengthen it, which complicates the recycling process at the end of the product life. In this study, we focused on water jet cavitation (WJC) as a means to harden pure Al. When this treatment is performed, a peening effect can improve the hardness near the surface and apply a compressive residual stress, thus improving the fatigue strength. However, WJC processing requires a high-water pressure, which generally means the use of large, expensive pumps. In this study, we developed a supplemental nozzle that increases the number and size of cavitation bubbles in the discharge from a water jet nozzle. In addition, we evaluated the effect of longer WJC processing time on the pure Al surface. Conventional WJC nozzles produced erosion-forming air bubbles at the jet center. When WJC processing was performed with the new swirling flow nozzle, the increased cavitation weakened the influence of the erosion-forming bubbles. In fixed-point processing of pure Al with the new nozzle, the specimen surface underwent various cavitation erosion processes that formed a sponge-like structure, a surrounding layered structure, and detached particles. When the processing time was increased, the affected area was extended and it had more of a peened appearance.

1. Introduction

Al and Al alloys have excellent physical and chemical properties, and they have many applications, from household goods to aircraft and automobiles. To respond to the increasing demand for new applications, the properties of Al have been enhanced by alloying with various elements. Thus, the current variety of Al alloys is enormous, the elements added to Al are also complicated, and the recycling process is difficult [1]. If the mechanical properties of pure Al could be improved without needing to form Al alloys, recycling would be simplified. In recent years, various methods have been extensively studied for improving mechanical properties without adding alloying elements.

Water jet technology is a type of cold working method, and it has been used in many fields, including civil engineering, architecture, and machinery. In this technique, water is discharged from nozzles immersed in water, and it has been used to study water jet flows and develop new applications.

Available water jet processing methods include water jet cavitation (WJC) [2–5], multifunction cavitation [3,4,6–9], and cavitating jet in air [10–12]. Here, we focus on WJC technology, in which a workpiece surface is processed using a high-speed underwater cavitation jet in a water-filled tank. The resulting impact pressure slightly deforms the material surface layer plastically and produces a peening effect that improves the hardness near the surface and applies compressive residual stress by inducing a restraining force between the lower layers and the surface. The overall effect is to improve the fatigue strength [5,13,14]. For that reason, if WJC treatment is applied to an industrial product made from Al or an Al alloy, it is possible to increase the hardness near the surface, prolong the life of the metal while using no or fewer alloying elements, and improve its recyclability.

However, WJC generally requires high pressure, and the specimen surface is difficult to process if the water pressure discharged from the nozzle is too low. Thus, WJC technology generally requires a large pump having a high discharge pressure to improve processing, which is disadvantageous from the viewpoints of apparatus size, equipment cost, and noise. Therefore, it is necessary to further develop WJC technology. In addition, many studies on WJC technology relate to improvement of the durability of compressive residual stress and stress corrosion cracking resistance

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characteristics, and few detailed reports exist on the influence of WJC on the surface of pure Al after long-term processing.

In this study, we developed a supplemental nozzle that increases the number and size of cavitation bubbles in the discharge from a water jet nozzle (WJ nozzle). Moreover, the effect of WJC on a pure Al surface processed for a long time was investigated.

2. Material and methods

The material used in this study was pure Al made by Nippon Light Metal Co., Ltd., the chemical composition of which is shown in Table 1. The Al sample was cut into square specimens with dimensions of 60 × 60 × 10 mm. To remove the surface roughness and improve workability, the specimen surface was ground uniformly to an average roughness (Ra) of 0.193 μm.

Fig. 1 is a schematic diagram of the equipment used for WJC processing. The setup was similar to a conventional WJC apparatus, with the nozzle fixed in water at room temperature and the water pumped at a discharge pressure of 35 MPa. The nozzle diameter was 0.8 mm, and the distance between the nozzle and specimen was 65 mm. A pressure gauge was attached to the WJ nozzle at the inflow hole. The processing was performed in a stainless-steel tank measuring 60 × 45 × 37 cm for durations of 2 min, 10 min, 20 min, and 30 min. As shown in Fig. 2, a swirling flow nozzle (SFN) was installed at the tip of the WJ nozzle. Fig. 2(a) is a photograph of the nozzle used in the experiment, Fig. 2(b) shows the SFN operating mechanism, and Fig. 2(c) shows a front view of the SFN nozzle. The SFN uses on offset inflow pipe to impart a swirling motion to air bubbles blown out from the WJC, which increases the number and size of cavitation bubbles in the discharge from the WJ nozzle. The inlet angle was 7°. For each processing duration, the post-processing microstructure of the specimen was observed using scanning electron microscopy (SEM; S-4800, Hitachi).

Table 1
Chemical composition of pure Al specimens (mass%).

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

3. Results and discussion

3.1. Mechanism for increasing the number and size of cavitation bubbles

This section provides an experimental and theoretical explanation of how the SFN attached to the WJ nozzle generates ultrahigh-pressure cavitation bubbles. We measured the static pressure at the nozzle inlet, and it decreased as the dynamic pressure at the nozzle outlet increased. The static pressure was −8.5 kPa (gauge) for the WJ nozzle alone and −36.5 kPa (gauge) for the WJC nozzle with the SFN attached. In the SFN, the flow velocity at the WJ nozzle discharge is fast, but decreases due to the decreased static pressure, which is caused by the swirling flow that surrounds the WJ nozzle. The discharge pressure and flow rate of the high-pressure pump used in this experiment were 35 MPa and 15 L/min, respectively; however, with a WJ nozzle diameter of 0.8 mm, the flow rate was reduced to 6.9 L/min. The flow velocity of the WJ nozzle discharge obtained from the nozzle sectional area was 229 m/s. To determine the flow velocity at the nozzle exit, the nozzle cross-sectional area (S) was obtained from the nozzle diameter (d), and the measured flow rate (Q) was divided by S. The swirling flow in the nozzle increased the amount of cavitation and provided the pressure required for bubble expansion. If the internal pressure (p_n) of the swirling nozzle becomes negative, the flow velocity in the inflow hole (v_i) can be obtained by Eq. (1). This negative pressure is the force that pulls on the water flow to cause swirling. However, in practice, it is necessary to consider the inflow pipe loss and pipe friction pressure loss,

$$p_n = p_i - \frac{\rho}{2} v_i^2 \quad (1)$$

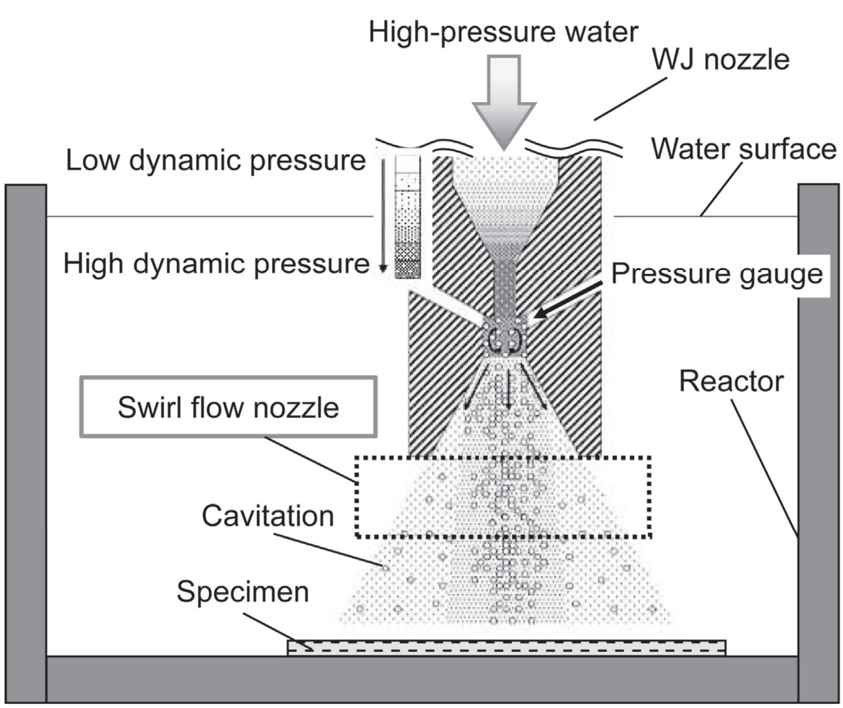

Fig. 1. Equipment for surface processing by water jet cavitation.

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