

Key Factors and Applications of Cavitation Peening

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The impacts generated when cavitation bubbles collapse can be used for the mechanical treatment of surfaces in the same way as shot peening. A peening method that uses cavitation impacts is called “cavitation peening”. In the present review, the principles of cavitation peening are explained in order to illustrate the difference between cavitation peening and water jet peening. The key factors in cavitation peening, such as the type of cavitating jet, the standoff distance, the nozzle geometry, the cavitation number, the processing speed, the nozzle throat diameter, the injection pressure and the tank pressure are shown with experimental results. A semi-empirical equations to predict the peening intensity for a given nozzle and given operating conditions is proposed. The results of practical applications of cavitation peening, such as improving the fatigue strength of a material or suppressing hydrogen embrittlement, are also shown and compared with the results from shot peening.

Keywords: cavitation peening; water jet peening; shot peening; fatigue strength; residual stress; cavitating jet; pulse laser

1. INTRODUCTION

Cavitation can cause severe damage in hydraulic machinery, such as pumps, screw propellers and valves, since it produces severe impacts due to micro jets and/or shock waves generated when bubbles collapse [1]. Nevertheless, this phenomenon can be utilized for the mechanical treat-

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ment of surfaces in the same way as shot peening. A peening method that uses cavitation impacts is called “cavitation peening” [2-4] or “cavitation shotless peening” [5], as the shot normally used in shot peening is not required. In the case of cavitation peening, the treated surface is smooth compared with that after conventional shot peening, as there are no collisions between solid objects. Also, since shot is not used, there is neither contamination nor any transfer of material. Although a submerged high-speed water jet is used to produce cavitation, cavitation peening is different from “water jet peening” [6-8], in which the peening is done by the impacts of small water masses. In order to get better peening effects using cavitation peening, understanding the mechanisms of cavitation peening and the differences between cavitation peening and water jet peening is very important.

Changes in the residual stress by cavitation impact within a limited region of a cavitation tunnel has been reported [9], as have changes in the stress on the surfaces of metallic powders by ultrasonic cavitation [10]. On the other hand, in order to mitigate stress corrosion cracking in pressure vessels filled with water in nuclear power plants, methods to introduce compressive residual stress into submerged stainless steel were investigated in the late 1980's and the 1990's. Methods using pulsed laser without a coating [11] and impacts from small water masses in a submerged water jet, i.e., “water jet peening” [12] were proposed for this. Soyama et al. [13] and then Hirano et al. [14] proposed the practical use of a submerged water jet with cavitation, i.e., a cavitating jet, to introduce compressive residual stress into materials [15]. The technique using a cavitating jet has been applied to nuclear power plants to mitigate stress corrosion cracking in pressure vessels [16]. Soyama et al. succeeded in improving the fatigue strength of hard metallic materials such as silicon manganese steel [17] and carbonized chrome-molybdenum steel alloy [18] by enhancing the aggressive intensity of cavitation peening using a pressurized chamber [19]. By optimizing the nozzle geometry for a cavitating jet [20, 21], the aggressive intensity of a jet without a pressurized chamber could be enhanced by a factor of 80 compared to cavitating jets developed in the 1990's. In order to summarize and discuss cavitation peening, “The 1st International Workshop on Cavitation Peening and Related Phenomena” was held in Sendai, October 27-29, 2015. This was organized by the Society of Surface Mechanics Design, and 38 papers were presented in the workshop.

In the case of conventional cavitation peening, a high speed water jet is injected into a water filled chamber. In this case, the target to be treated is put into a water filled chamber, and large items, which cannot be placed in the chamber, cannot be treated. In order to introduce compressive residual stress into the outer surfaces of tanks, pipes and other large components without using a water filled chamber, a cavitating jet in air was

realized by injecting a high speed water jet into a low speed water jet using a concentric nozzle [22-24]. An optimized cavitating jet in air can introduce a larger compressive residual stress into the subsurface compared with a cavitating jet in water [25]. Further research on cavitating jets in air has been followed by a research group at the Georgia Institute of Technology and Boeing [26].

Although it is believed that the shock wave induced by laser abrasion has been used for submerged laser peening [27], the impact generated by collapsing bubbles developed after laser abrasion, and which behave in the same way as cavitation bubbles, was larger than that due to the laser abrasion [28]. In this review, the formation of bubbles due to laser abrasion is called laser cavitation. When the impact induced by laser cavitation is used for peening, the surface can be peened twice, i.e., by laser abrasion and laser cavitation, by a single laser pulse. Thus, understanding the mechanisms and the key factors of cavitation peening is beneficial in that this can help us improve the peening efficiency of submerged laser peening.

The cavitation peening mechanism is entirely different to the mechanism for water jet peening, and when these peening methods are confused, not only the peening effect is insufficient, but also the peened surface can be damaged [29]. As mentioned above, the impacts due to cavitation bubbles collapsing is important for cavitation peening. The cavitation impact at constant ambient pressure does not increase as the injection pressure of the cavitating jet is increased, and the peening intensity at injection pressures that are too high decreases with increasing injection pressure; thus, there is an optimum injection pressure for introducing compressive residual stress [30]. On the other hand, in the case of water jet peening, the peening intensity increases with increasing injection pressure, as the impact from the small water masses and/or shot in the water jet increases with this.

Although cavitation impacts are useful for the mechanical treatment of surfaces, as mentioned above, it should be borne in mind that cavitation erosion is still a major problem in hydraulic machinery and other systems in frontier science and technology, such as, for example, neutron sources that use mercury targets [31]. Tests on materials using a cavitating jet have been done in order to evaluate the resistance of materials to cavitation erosion [32]. Knowledge of the key factors in cavitation peening, such as the cavitation number and the scale effect, is important to enable the application of this technology and to estimate and/or reduce cavitation erosion.

In order to enable us to obtain better peening effects using cavitation peening without damage to the surface the key factors of cavitation peening are reviewed with experimental results in this paper. The effects of mechanical surface modification such as improvement in the fatigue characteristics and the suppression of hydrogen embrittlement by cavitation peening are demonstrated experimentally.

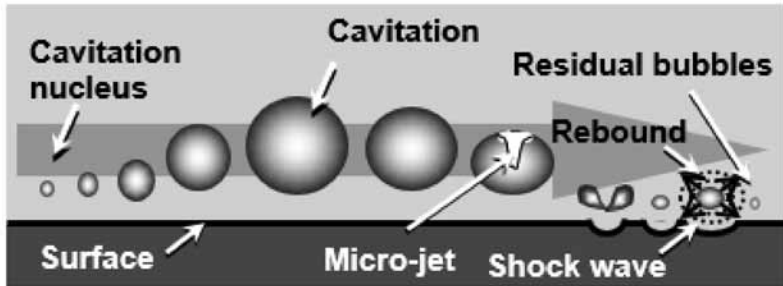
2. HOW TO PRODUCE CAVITATION

2.1. Cavitation

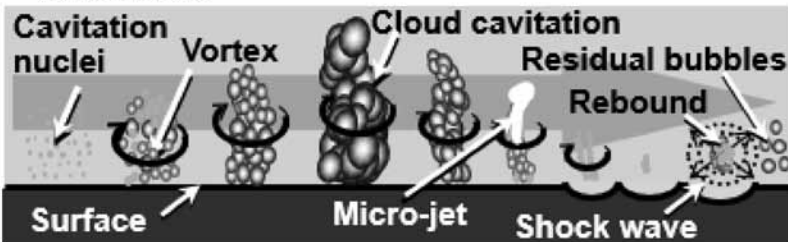
Cavitation is a hydrodynamic phenomenon from the liquid phase to the gas phase produced by increasing the flow velocity to reduce the pressure. Bernoulli's equation is

$$\frac{1}{2}\rho_L v^2 + p = \text{const.} \quad (1)$$

where, v , ρ_L and p are the flow velocity, density of the liquid and pressure. When the velocity of the liquid increases such that $p = p_v$, where p_v is the vapor pressure of the liquid, the liquid becomes vapor, i.e., the gas phase. Note that vaporous cavitation starts at $p < p_v$, and gaseous cavitation is initiated at $p > p_v$, because of the cavitation nuclei, which is explained later in this paper. Figure 1 (a) shows a schematic diagram illustrating the development and collapse of cavitation. First, a cavitation bubble is generated from a tiny bubble, which is dissolved in the liquid, the same as in nucleate boiling. These small bubbles are called cavitation nuclei. When the velocity decreases, the vapor goes back into liquid form. At this stage, the vapor bubble shrinks and collapses, and then rebounds. If it shrinks near to a solid surface, the



(a) Spherical type



(b) Cloud type

FIGURE 1
Schematic diagram of the development of the and collapse of cavitation

bubble is deformed and produces a micro-jet on the far side from the solid surface [1]. The speed of the micro-jet may reach several hundreds m/s and approach 1500 m/s, which is the speed of sound in water. This is one of the reasons why the impact due to cavitation is severe and why it results in plastic deformation and/or erosion of the metallic surface. The other reason is the shock wave produced at the rebound. As mentioned above, cavitation starts from a tiny bubble, i.e., a cavitation nucleus, and the inner pressure for cavitation bubbles is about the same as the vapor pressure, which for water at room temperature is about 3 kPa. Thus, when small amounts of air are present in cavitation bubbles, they rebound after shrinking due to the gas inside them. After collapsing, residual bubbles, which contain air and products arising from radicals, are formed in the water [33]. When the residual bubbles are entrained into the cavitating region, they act as cavitation nuclei [34]. When air is injected into the cavitating region, the cavitation and/or vaporous bubbles grow larger; however, the cavitation impact becomes weaker, as the shock wave becomes weaker. The reason for this is that the rebound speed decreases due to the large amount of gas in the cavitation bubbles. This effect is called the cushioning effect, and this aeration technique is used to reduce cavitation erosion. Note that the cavitation nuclei enhance cavitation and produce severe cavitation erosion [21, 34]. It can be concluded that cavitation nuclei enhance cavitation impacts but too many air bubbles reduce the cavitation impact due to the cushioning effect.

In the case of cavitating flow, the cavitation number σ is the most important parameter. The cavitation number is the normalized difference between the pressure p and the vapor pressure p_v [1]. The cavitation number σ through an orifice depends on the upstream pressure of the orifice p_1 , the downstream pressure of the orifice p_2 and p_v , and is defined by the following equation:

$$\sigma = \frac{p - p_v}{\frac{1}{2} \rho_L v^2} = \frac{p_2 - p_v}{p_1 - p_2} \approx \frac{p_2}{p_1} \quad (2)$$

Note that the pressures in Eq. (2) are absolute pressures. When the relationships between p_1 , p_2 and p_v are such that $p_1 \gg p_2 \gg p_v$, such as in a cavitating jet, σ can be simplified, as in Eq. (2). Cavitating flow with a small cavitation number means that the cavitating region is large, and a large cavitation number signifies that the cavitating region is reduced or has disappeared. Normally, the cavitating region and/or cavitating length are equivalent for the same cavitation number even though the flow velocity may be different.

In cavitation research, spherical bubbles have been investigated both numerically and experimentally [1, 35]. However, the type of cavitation that causes severe cavitation erosion in pumps, valves and hydrofoils is “cloud cavitation” [36-38]. As cloud cavitation consists of tiny cavitation bubbles,

and takes place in the vortex core of the cavitating flow, it is sometimes called “vortex cavitation” [36, 39-43]. A key parameter of vortex flow is the Reynolds number, which is a function of the velocity, size and kinematic viscosity coefficient; thus, the size is as important a parameter as the velocity. As is well known, the cavitation erosion rate drastically increases with the size of hydraulic machinery and hydrofoils, a phenomenon known as the scaling effect of cavitation erosion. The following power law for the rate of erosion, E_R , with respect to the size of hydraulic machinery, L , has been proposed, as well as its relationship with the velocity v in the machinery [44, 45]:

$$E_R \propto L^n \quad (3)$$

$$E_R \propto v^n \quad (4)$$

With this scaling effect, cloud cavitation, i.e., a cavitating vortex, is more remarkable [41, 46]. It has been reported that micro-jets have also been observed in a cavitating vortex [47]. Since cloud cavitation causes severe erosion in centrifugal pumps [39], numerical simulations of this have been done and the possibility of enhancing the aggressive intensity at cloud cavitation collapse has been shown [1]. The results of studies of this phenomenon suggest that micro-jets and a shock wave at rebound are the reasons why cloud cavitation causes severe cavitation erosion. Figure 1 shows a schematic diagram illustrating the development and collapse of cavitation for both spherical type cavitation and cloud type cavitation. A typical longitudinal cavitation cloud arising downstream from a butterfly valve is shown in Fig. 2 [37]. Longitudinal cavitation clouds cause severe erosion.

2.2. Methods for Generating Cavitation

For cavitation peening, aggressive cavitation such as longitudinal cloud cavitation as shown in Fig. 2 is required for practical applications. One of the powerful methods used to generate such cavitation clouds is a submerged high speed water jet with cavitation, i.e., a cavitating jet [48, 49]. Figures 3 and 4 show typical images of a cavitating jet impinging on a surface and a schematic diagram of a cavitating jet. In Fig. 3, the jet flows from left to right and the white bubbles are due to cavitation. When a high-speed water jet is injected into water through a nozzle, vortex cavitation takes place in the shear layer around the jet. The instances of vortex cavitation combine to form a large cavitation cloud, and when this hits the target, a ring vortex cavitation is formed, part of which collapses resulting in longitudinal cloud cavitation. Even with a cavitating jet, there is a potential core near the nozzle exit, and powerful impacts are produced by small water masses downstream from the



FIGURE 2
Typical image of vortex cavitation

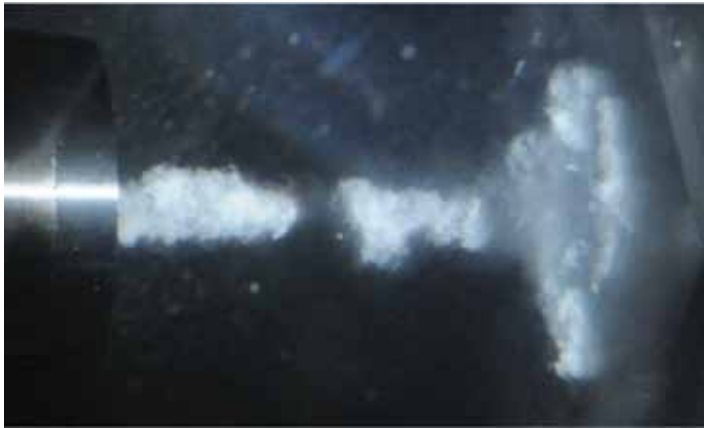


FIGURE 3
Typical image of a cavitating jet impinging on a surface

potential core. As mentioned later, the impacts from these small water masses produce water jet peening effects.

The typical area peened by a cavitating jet is shown in Fig. 5, which shows a pure soft aluminum specimen after exposure for 1 minute to a cavitating jet with a nozzle throat diameter $d = 2$ mm at $p_1 = 30$ MPa , $p_2 \approx 0.1$ MPa, $\sigma \approx 0.0033$ and standoff distance $s = 262$ mm. Plastic deformation pits can clearly be observed within an annulus of 60 mm outer diameter and 20 mm inner diameter. Thus, the cavitating jet can treat a region 30 times larger than the diameter of the throat of the nozzle in this case. As mentioned above, cavitat-

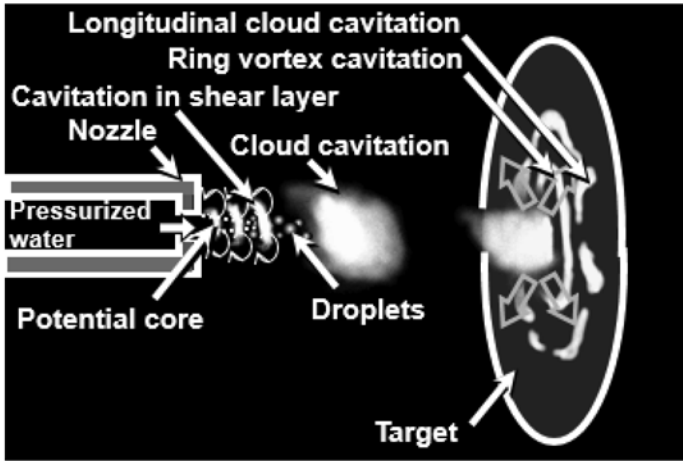


FIGURE 4
Schematic diagram of a cavitating jet

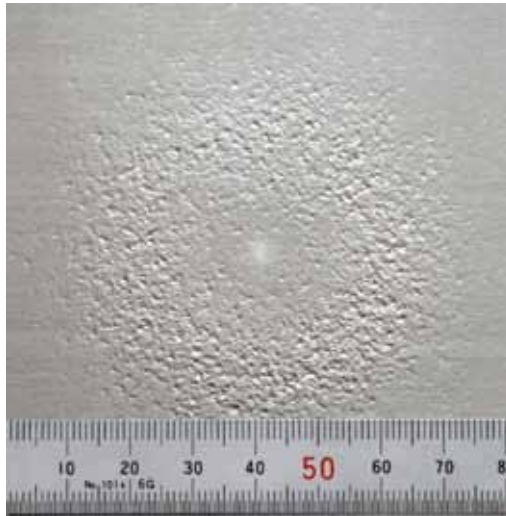


FIGURE 5
Typical area peened by a cavitating jet (pure aluminium, $d = 2$ mm, $p_1 = 30$ MPa, $p_2 = 0.1$ MPa, $s = 262$ mm, $t = 1$ min)

tion impacts are produced by bubbles collapsing in longitudinal clouds included in the ring vortex cavitation. The plastic deformation pits occur less at the jet center, but are generated at the places where the cavitation bubbles collapse. As shown in Fig. 5, the soft aluminium specimen has been slightly damaged at the jet center due to the impingement of small water masses in the jet core. In the ring region, the sizes of the plastic deformation pits are several

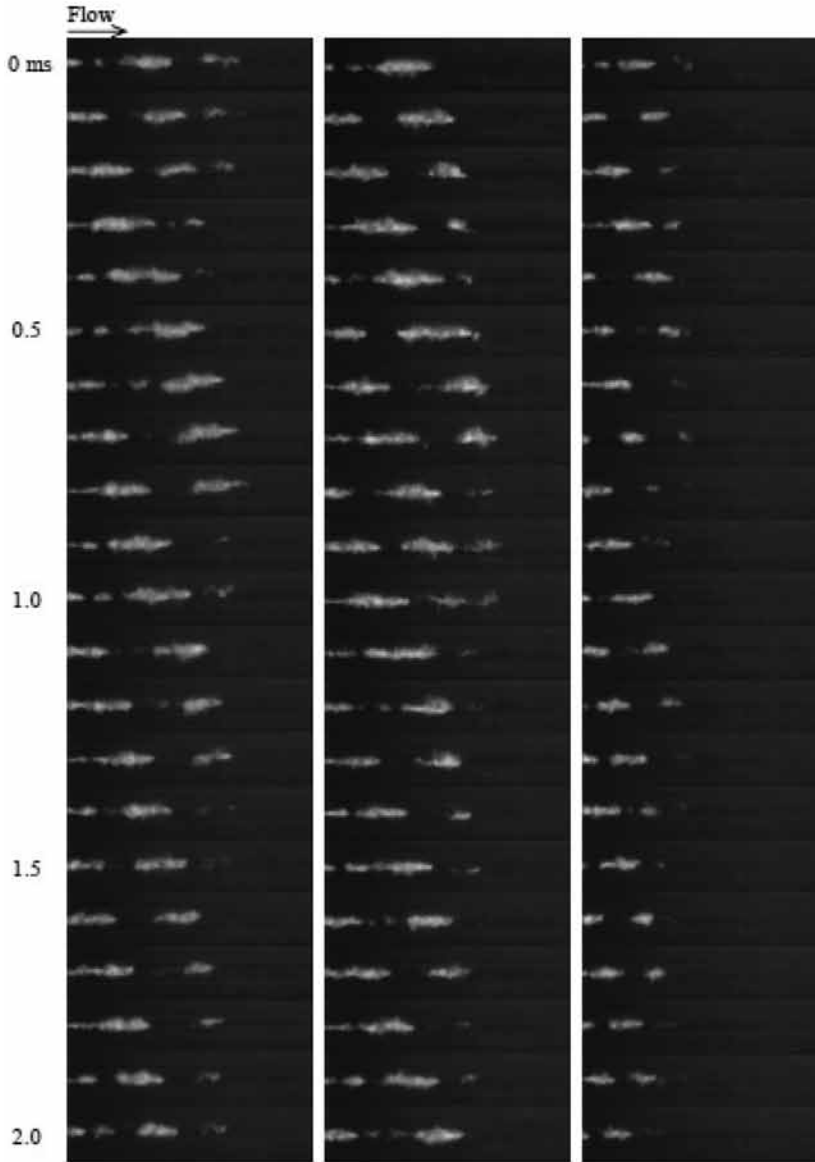
hundred micrometers in diameter and some pits are 1 or 2 mm in diameter. In order to carry out a uniform treatment of the surface with a cavitating jet, the nozzle or the target should be scanned. The optimum scanning pitch for uniform treatment can be obtained experimentally, by considering the distribution of the cavitation impacts induced by the jet [50].

A cavitation cloud, such as shown in Fig. 3, sheds periodically [49, 51, 52], as shown in Fig. 6. Figure 6 shows periodic shedding in a cavitating jet observed by a high-speed video camera. With $p_1 = 20$ MPa and $\sigma = 0.014$, the cavitation cloud is shed at 0.5, 0.9, 1.4 and 1.9 ms, thus the shedding frequency f is about 2.0 kHz. At $p_1 = 30$ MPa and $\sigma = 0.014$, the frequency is 2.4 kHz, and is 3.2 kHz with $p_1 = 20$ MPa and $\sigma = 0.02$. As the frequency changes with constant injection pressure but different cavitation number, the frequency is independent of pressure fluctuations induced by the plunger pump. Note that the shedding frequency increases with increasing injection pressure and cavitation number. This example also demonstrates that the diameter of the cavitating jet, as well as the cavitating length decreases with increasing cavitation number. The Strouhal number, S_t , which is defined by the shedding frequency, f , the maximum diameter of the cavitating jet, w , and the velocity at the nozzle exit, U , is nearly constant at 0.18 [52].

$$S_t = \frac{fw}{U} = 0.18 \quad (5)$$

When two opposing jets pressurized by two different plunger pumps are injected into the same chamber, the shedding frequency was synchronized [53]. This suggests that the pressure wave produced by the cavitation cloud collapsing propagates upstream and breaks other cavitation clouds. From the point of view of cavitation peening, the shedding frequency is closely related to the aggressive intensity of the cavitating jet [21].

As mentioned above, for conventional cavitation peening, cavitation bubbles are generated by injecting a high speed water jet into water. In the present review, this sort of conventional cavitating jet is called “a cavitating jet in water”. For these applications, the target is placed in the water filled chamber. However, the external surfaces of tanks and pipes are very difficult to treat using this apparatus. To address this, Soyama realized “a cavitating jet in air”, by injecting a high speed water jet into a low speed water jet which was injected directly into the air using a concentric nozzle [22, 23]. A typical cavitating jet in air is shown in Fig. 7. In Fig. 7, both the high and low speed water jets flow vertically down. The periodic wave pattern of the low speed water jet can be seen in Fig. 7, and this is produced by periodic shedding of the cavitation cloud induced by the high speed water jet. That is, the frequency of the wave pattern of the low speed water jet is equal to the cloud shedding frequency of the jet [23].



a) $p_1 = 20$ MPa, $\sigma = 0.014$ (b) $p_1 = 30$ MPa, $\sigma = 0.014$ (c) $p_1 = 20$ MPa, $\sigma = 0.02$

FIGURE 6

Periodic shedding of cavitation clouds arising in a free cavitating jet ($d = 2$ mm)

Note that the aggressive intensity of the jet depends appreciably on the injection pressure of the low speed water jet and the nozzle geometry [24]. Cavitating jets in air have been applied on commercial production

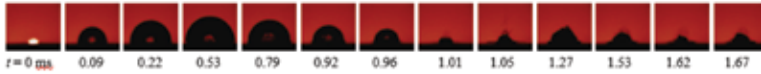


FIGURE 7
Image of a cavitating jet in air ($d = 1$ mm, $p_1 = 30$ MPa)

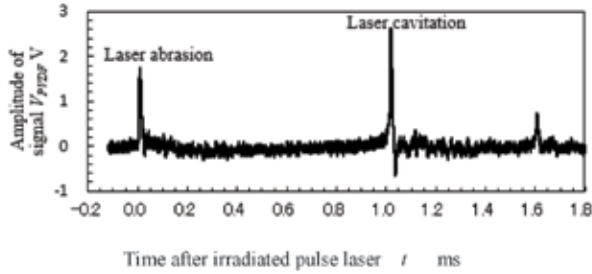
lines, for example, on a hot dip continuous galvanizing line to remove solid substances sticking to rolls [54].

For cavitating jets in water and air, the cavitation generally produced is “hydrodynamic cavitation”. On the other hand, cavitation can also be produced by ultrasonic vibrations, in which case it is called “ultrasonic cavitation”. As mentioned in the introduction, changes in the residual stress in metallic powders by ultrasonic cavitation have been reported [10]. Moreover, the introduction of residual stress into metallic materials by ultrasonic cavitation has also been demonstrated [55]. To produce ultrasonic cavitation for the mechanical treatment of a surface, a vibratory horn, which has been used for cavitation erosion tests on materials [56], is normally used. Note that a cavitating jet for materials testing has also been standardized by ASTM International as mentioned in the introduction [32]. Although optimization of the conditions for ultrasonic cavitation, such as the tip geometry, has been investigated [57], the applications are limited, as the aggressive intensity of ultrasonic cavitation changes significantly with the distance from the tip to the treated surface [58].

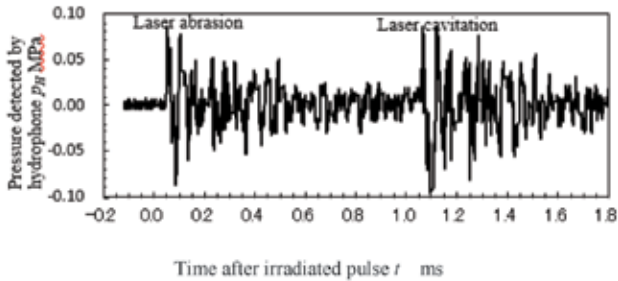
In the case of laser peening, it is believed that the shock waves induced by laser abrasion in water are concentrated in the material by the inertia of the water [27]. However, in the case of submerged laser peening, bubbles that are



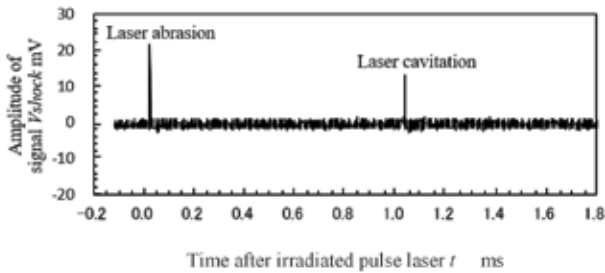
(a) Images of laser abrasion and bubbles induced by a pulsed laser



(b) Output signal from the PVDF sensor



(c) Output signal from the hydrophone



(d) Output signal from the submerged shock wave sensor

FIGURE 8
Laser abrasion and laser cavitation

produced and that develop after laser abrasion, collapse [28], as shown in Fig. 8 [59]. In this review, the development of bubbles after laser abrasion is called “laser cavitation”, as the shock wave is produced by the bubbles collapsing. For the data in Fig. 8, in order to detect the impacts induced by a laser pulse, a homemade sensor with a PVDF film used as a force sensitive material [60,

61] was placed on a metallic target material, and a hydrophone and a submerged shock wave sensor were placed in the water filled chamber. As shown in Fig. 8, when the laser pulse hits the target at $t = 0$ ms, laser cavitation is initiated, develops, and then collapses at $t = 1$ ms. After the laser cavitation has collapsed, it rebounds and collapses again at $t = 1.6$ ms. The impact at laser abrasion, and the 1st and 2nd collapses of the laser cavitation were detected by the PVDF sensor. The amplitude of the signal for the 1st collapse is about 1.5 times larger than that for the laser abrasion. In the case of the hydrophone, the signal amplitudes from laser abrasion and laser cavitation are similar [62]. On the other hand, when the pressure wave in the water was measured by the submerged shock wave sensor, the signal amplitude for laser abrasion was larger than that for laser cavitation [27]. Although the amplitude of the signal from the sensor depends on the type of sensor, the PVDF sensor measures the impact in the target material, and it detects not only the 1st collapse but also the 2nd collapse of the laser cavitation bubbles. When the impact signal was measured using an AE sensor, the ratio between the signal amplitudes for laser abrasion and for laser cavitation were found to depend on the depth of the water [63]. That is, the impact induced by laser cavitation is considered to provide a better peening effect in submerged laser peening.

Figure 9 illustrates the relationship between the time for the laser cavitation to develop, t_D , and the peening intensity in submerged laser peening. It has been shown that the peening intensity is related to the inverse of the radius of curvature, $1/\rho$, of a 5mm duralumin plate peened with 4 pulses/mm². In Fig. 9, in order to change the aggressive intensity of laser cavitation, the laser energy or standoff distance between the final convex lens and the target was changed. When a power law is assumed for the relationship between $1/\rho$ and t_D , the exponent is about 3. In the case of submerged laser peening, t_D is proportional to the maximum diameter of laser cavitation. Thus, it can be concluded that the peening intensity in submerged laser peening is proportional to the maximum volume of the bubbles, V_{Bmax} , as given by the following equation:

$$\frac{1}{\rho} \propto V_{Bmax} \quad (6)$$

3. CAVITATION PEENING AND WATER JET PEENING

3.1. Differences between Cavitation Peening and Water Jet Peening

As a submerged high-speed water jet is commonly used to generate cavitation for cavitation peening, as mentioned above, cavitation peening and water jet peening are sometimes confused. Both the Surface Enhancement Committee SEC and the Aerospace Surface Enhancement Committee ASEC of SAE

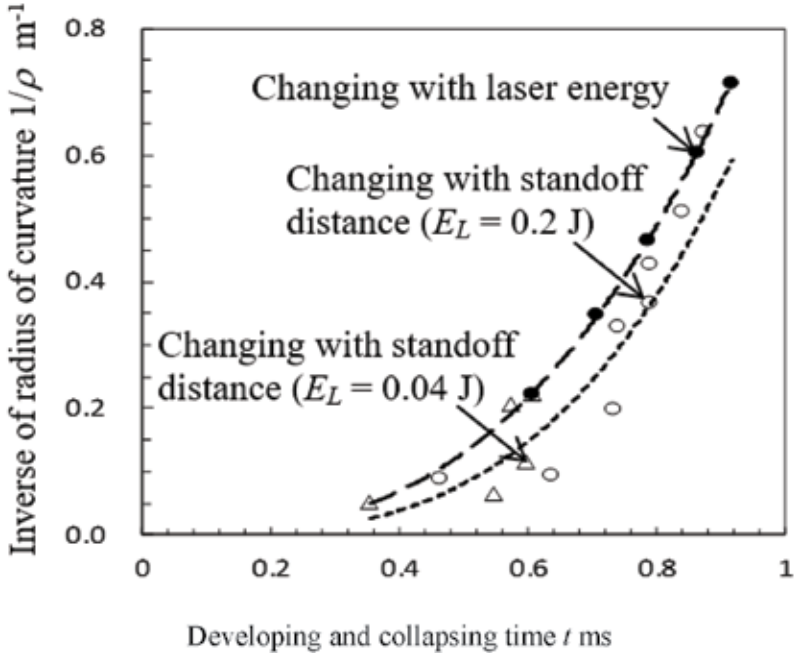


FIGURE 9
Relationship between the size of the bubbles and the peening intensity

International, in which peening methods are standardized, define the impacts generated by cavitation bubbles collapsing as “cavitation peening”. On the other hand, peening methods using the impacts of small water masses in a water jet and/or shot that are injected into the water jet [64, 65] are called “water jet peening”. When a submerged high-speed water jet is used, both cavitation peening and water jet peening can occur. In order to obtain better peening effects without damage, the mechanisms for cavitation peening and water jet peening need to be better understood and, moreover, classified.

In order to show how the aggressive intensity of a submerged high speed water jet varies with standoff distance, Fig. 10 shows the mass loss as a function of standoff distance at constant injection pressure for various cavitation numbers [66]. It is assumed that greater mass loss corresponds to higher aggressive intensity. For all three cases, two peaks were obtained. The peak close to the nozzle is called the “1st peak” and the one further from the nozzle is called the “2nd peak” [67]. The 1st peak is due to small water mass impacts, and is suitable for water jet peening and/or cutting. On the other hand, the 2nd peak is a result of cavitation impacts, and is suitable for cavitation peening. As shown in Fig. 10, the standoff distance of the 2nd peak, i.e., the optimum standoff distance, s_{opt} , increases as the cavitation number, σ , decreases, and is described by Eq. (7). A relationship between cavitation number σ and opti-

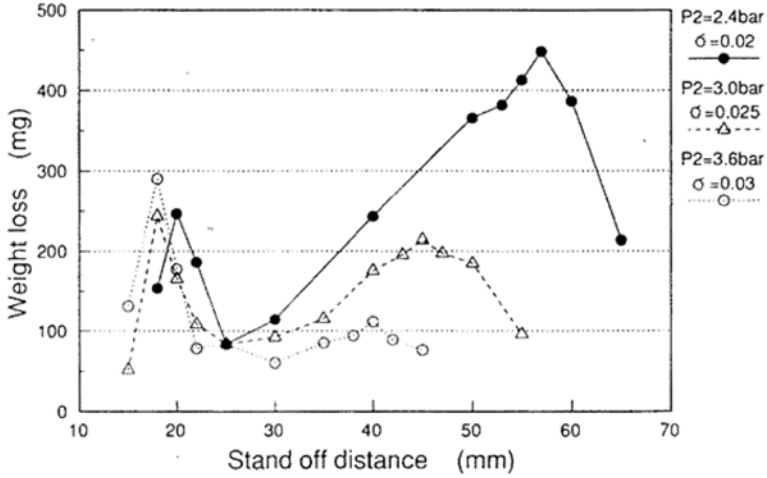


FIGURE 10

1st and 2nd peaks resulting from a submerged high-speed water jet at constant injection pressure for various cavitation number

mum standoff distance s_{opt} was found by Lichtarowicz [68], then a means of comparing cavitating jets was proposed using the following equation [69].

$$\frac{s_{opt}}{d} \propto \sigma^{-n} \quad (7)$$

where d is the diameter of the nozzle throat. Figure 11 shows the peening intensity changing with standoff distance s with $p_1 = 30$ MPa ($\sigma = 0.0033$) and $d = 2$ mm, and with $p_1 = 300$ MPa ($\sigma = 0.00033$) and $d = 0.4$ mm, at a constant downstream pressure $p_1 \approx 0.1$ MPa [70]. The jet power, which depends on the injection pressure and the flow rate, were nearly equal in these two cases. In Fig. 11, specimens made of spring steel were peened and the inverse of the radius of curvature $1/\rho$ was measured to find the peening intensity. The standoff distance is normalized by d as s/d in Fig. 11. As shown in Fig. 11, the 2nd peak with $p_1 = 30$ MPa is the largest. Although $1/\rho$ with $p_1 = 300$ MPa has a peak at $s/d \approx 140$, which is similar to that of the 2nd peak with $p_1 = 30$ MPa, this is due to impacts from small water masses, i.e., due to water jet peening. With $p_1 = 300$ MPa, there is a 2nd peak arising from cavitation impacts at $s/d \approx 280$. The peening intensity of this is very small compared with that of cavitation peening with $p_1 = 30$ MPa. Note that, not only is the peening effect of a submerged water jet with the injection pressure too high insufficient, but that it also damages the treated surface [29].

Figure 12, which is taken from reference [69], shows the normalized pressure at the center of a submerged water jet $(p_{max} - p_2)/(p_1 - p_2)$ compared with a single

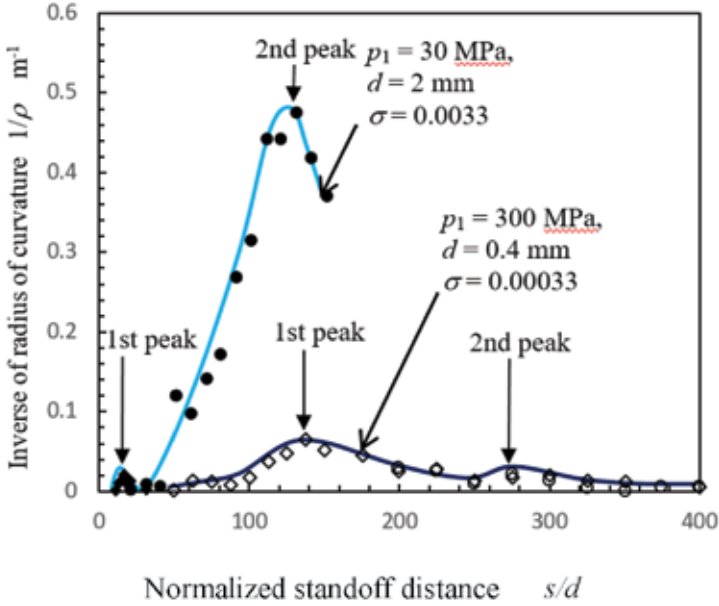


FIGURE 11

Aggressive intensity of jets at equivalent jet power as a function of standoff distance at a constant downstream pressure $p_2 = 0.1$ MPa

phase jet, such as an air jet in air [71], and a submerged water jet surrounded by an air jet [72]. The measured maximum pressure, p_{\max} , is defined as the maximum pressure at the center of a jet with an equivalent nozzle diameter, d_e , as follows [69],

$$d_e = d\sqrt{c_d} \quad (8)$$

where d is the nozzle throat diameter and c_d is the discharge coefficient. As shown in Fig. 12, after the potential core has vanished the normalized pressure at the center of the jet, $(p_{\max} - p_2)/(p_1 - p_2)$ decreases with the normalized standoff distance, revealing the following equation for single phase flow:

$$\frac{p_{\max} - p_2}{p_1 - p_2} \propto \left(\frac{s}{d_e}\right)^n \quad (9)$$

For a single-phase jet, the exponent n is -2. The distribution for a cavitating jet has a similar region; however, n for a cavitating jet is not -2 but is smaller than -2. Thus, n decreases with decreasing cavitation number. When a cavitating jet is surrounded by an air jet, it is more remarkable. Extrapolation of the straight parts of the curves in Fig. 12 to the line $(p_{\max} - p_2)/(p_1 - p_2) = 1$ gives intersects that increase with decreasing cavitation number. This suggests the

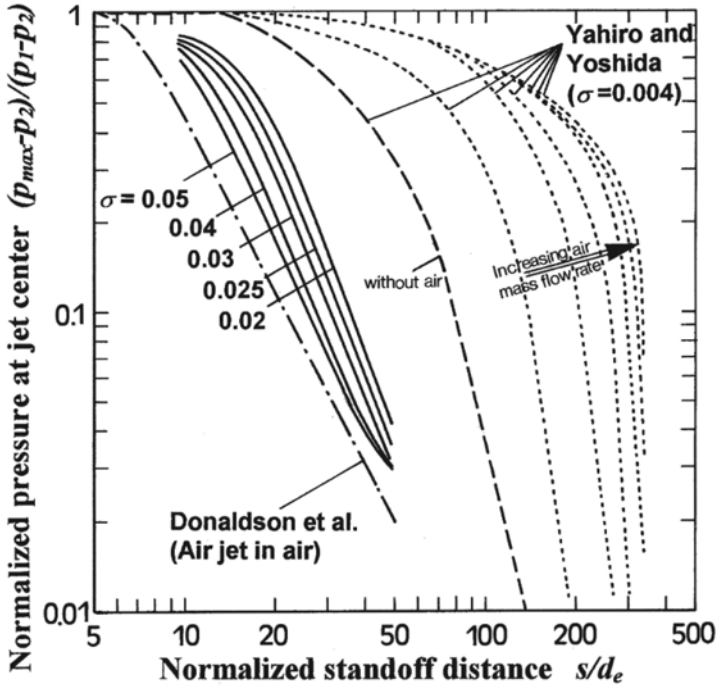


FIGURE 12

Variation of stagnation pressure with cavitation number (cylindrical nozzle, $d = 2.5$ mm, $p_1 = 8$ MPa)

potential core, where the impacts of small water masses make a significant contribution, increases with decreasing cavitation number. This is the reason why the water jet peening region changes with cavitation number, and the peak at $s/d \approx 140$ with $p_1 = 300$ MPa is caused by water jet peening. The schematic diagram of the structure of a cavitating jet was revealed by measuring the pressure distribution across a surface treated by the jet in reference [69].

3.2. Classification Map for Cavitation Peening and Water Jet Peening

As mentioned above, cavitation peening uses cavitation impacts, and water jet peening uses small water mass impacts. For cavitation peening, there is an optimum injection pressure, and if the injection pressure is too high the cavitation peening is poor. On the other hand, for water jet peening, the peening intensity increases with injection pressure. That is, the optimum jet conditions are different for cavitation peening and water jet peening. This makes it necessary to classify cavitation peening and water jet peening.

In order to classify cavitation and water jet peening, a classification map was proposed [70]. As described by Eq. (7), the optimum standoff distance for cavitation peening, i.e., the 2nd peak, varies with cavitation number, as

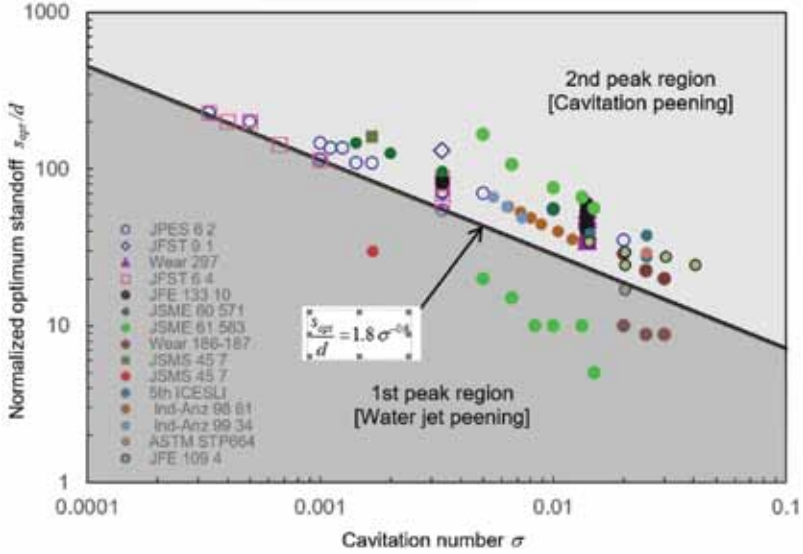


FIGURE 13

Classification map for cavitation peening and water jet peening, considering the optimum standoff distance s_{opt} , where the aggressive intensity of the jet has a maximum, as a function of cavitation number σ

shown in Fig. 10. On the other hand, the point at which the potential core ends, i.e., the 1st peak, also changes with injection pressure p_1 as shown in Figs. 11 and 12. As shown in Figs. 10 and 11, the aggressive intensity of the jet clearly has two peaks. It is easy to find the optimum standoff distances for the 1st and 2nd peaks by measuring the mass loss, the arc height (related to the inverse radius of curvature) or the residual stress as functions of standoff distance. Figure 13 illustrates a classification map for cavitation peening and water jet peening, considering the cavitation number, σ , the injection pressure, p_1 , and the optimum standoff distance, s_{opt} [70]. In Fig. 13, p_1 is considered to be one of the parameters of σ , as given by Eq. (2). The points in Fig. 13 were collected from 115 experimental data measurements from 15 references since 1976. These include the variations with standoff distance of the mass loss, the residual stress and the arc height. The details are described in reference [73]. The 1st and 2nd peak regions are divided by the line,

$$\frac{s_{opt}}{d} = 1.8 \sigma^{-0.6} \quad (10)$$

The lower region, i.e., near the nozzle, is the 1st peak region which is applicable for water jet peening. The upper region, including the line, i.e., far from the nozzle, is the 2nd peak region and is applicable for cavitation peening. If the

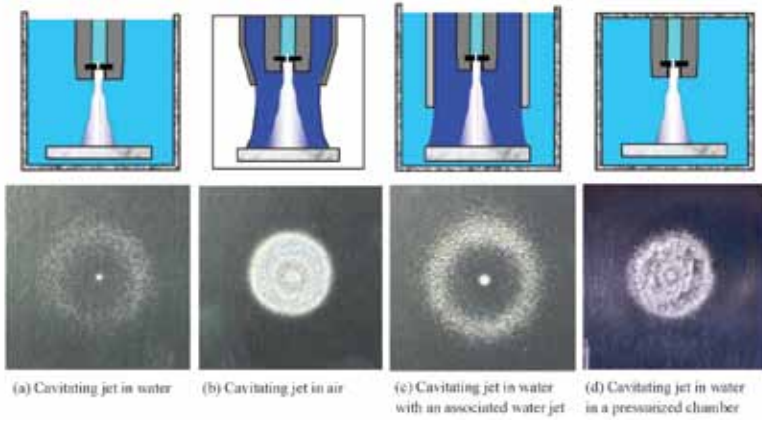


FIGURE 14

Performance and areas treated by several types of cavitating jet (pure aluminium, $d = 1$ mm, $p_1 = 20$ MPa, $t = 1$ min)

equivalent nozzle diameter d_e which is defined by Eq. (8) is considered, the difference between the 1st and 2nd peak regions is much clearer [73].

Now let's check the peaks in Fig. 11 at $s/d \approx 140$ with $p_1 = 300$ MPa ($\sigma = 0.00033$) and at $s/d \approx 140$ with $p_1 = 30$ MPa ($\sigma = 0.0033$). For $p_1 = 300$ MPa and $p_1 = 30$ MPa, the values of $1.8\sigma^{-0.6}$ are 221 and 55, respectively. As the above-mentioned value of 140 is smaller than 221, the peak with $p_1 = 300$ MPa corresponds to the 1st peak, whereas it is larger than 55, so the peak with $p_1 = 30$ MPa corresponds to the 2nd peak. Note that, with $p_1 = 300$ MPa, the peak at $s/d \approx 280$, which is greater than 221, is the 2nd peak, as expected.

4. KEY FACTORS IN CAVITATION PEENING

4.1. Types of Cavitating Jets

A submerged high-speed water jet with cavitation, i.e., a cavitating jet in water, is commonly used to generate cavitation for cavitation peening. Moreover, a cavitating jet in air was developed by Soyama et al. as mentioned above [22-24]. In order to demonstrate the performance of the various types of cavitating jet, Fig. 14 shows schematic diagrams of jets and erosion patterns on pure aluminum specimens at constant injection pressure, constant exposure time and the same nozzle throat diameter. In Fig. 14, the areas treated by the jets are clearly shown by the eroded areas, and it is assumed that larger mass loss corresponds to better performance of the jet. Figures 14 (a) and (b) show a cavitating jet in water and in air, respectively. Figure 14 (c) shows a cavitating jet in water with an associated jet and Figure 14 (d) shows a cavitating jet in a pressurized chamber in which the cavitation number can be controlled by changing the pressure of the chamber. When Figs. 14 (a) and

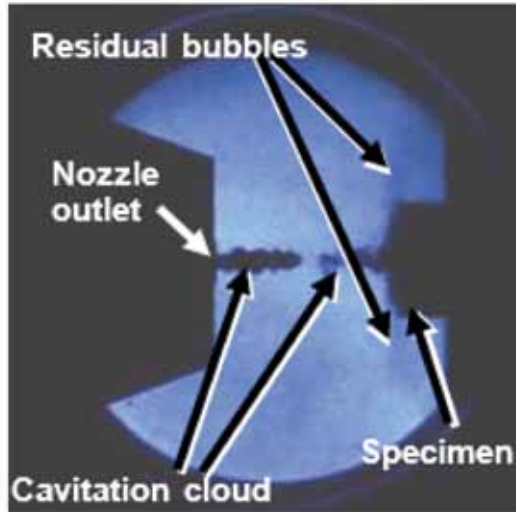


FIGURE 15
Residual bubbles induced by a cavitating jet

(b) are compared, the cavitating jet in air is more aggressive compared with the cavitating jet in water, as the mass lost from the treatment area was greater. For the cavitating jet in water with the associated water jet the plastic deformation is more remarkable compared to that for the cavitating jet in water. It can be said that the cavitating jet in water with the pressurized chamber is most powerful, as the mass loss was largest. Thus, clearly, the performance and treatment area depend on the type of cavitating jet.

One of the key factors related to the performance of the jet is the formation of residual bubbles, which are shown in the schematic diagram in Fig. 1. After cavitation collapse, tiny air bubbles are formed in the water [74]. These small bubbles act as cavitation nuclei [34] and/or provide a cushioning effect which is described above in the section on “cavitation”. Figure 15 shows residual bubbles induced by a cavitating jet [74]. As Fig. 15 is a typical instantaneous photograph taken by a CCD camera with a flash lamp with a $1\mu\text{s}$ exposure time placed on the far side of the jet from the camera, the cavitation clouds are observed as black shadows, and the residual bubbles are seen as indistinct shadows. In a normal cavitating jet in water, these residual bubbles are taken into the cavitating jet, and provide a cushioning effect, thus reducing the impact of the jet. In the case of a cavitating jet in air, fresh water without residual bubbles is fed around the high-speed water jet, so that the cushioning effect is small, since the residual bubbles are not recirculated. In addition, the vortex, which depends on the nozzle geometry and the injection conditions, around the high speed water jet also affect the performance of the jet. When an associated water jet is injected around the high speed water jet

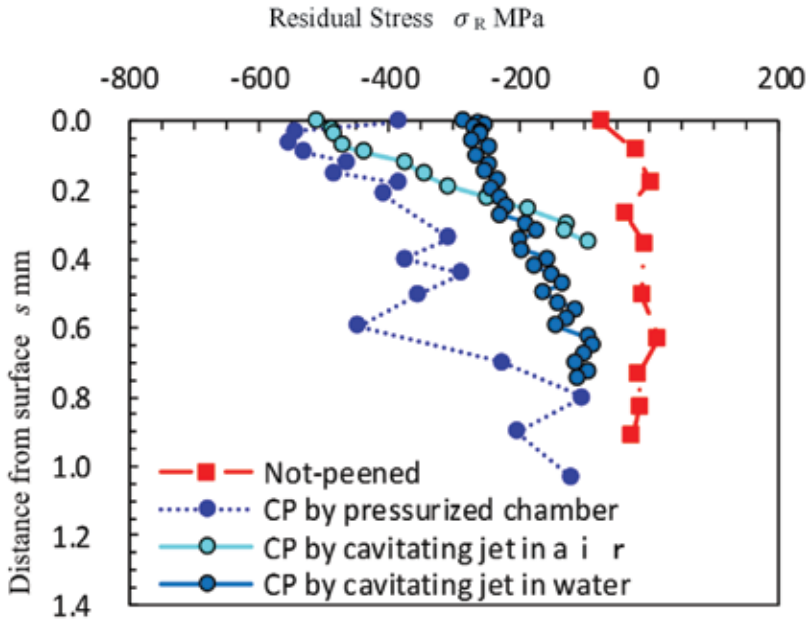


FIGURE 16 Compressive residual stress introduced by several type of cavitating jets (stainless steel).

(see Fig. 14 (c)), the recirculation of the residual bubbles is reduced, and the cushioning effect is mitigated compared with a normal cavitating jet in water (see Fig. 14 (a)). This is the main reason why a cavitating jet in water with an associated water jet produces more plastic deformation than a normal cavitating jet in water does. In the case of a cavitating jet in water in a pressurized chamber, the size of the residual bubbles is reduced by the pressure of the chamber, so that the cushioning effect is considerably less. The other reason might be that the increase in pressure of the chamber would result in an increase in the difference between the pressure outside and inside the bubbles and then in an increase in the potential energy of the vapor structures which would finally result in a more violent collapse. Thus, the performance of a jet in a pressurized chamber is the best.

Figure 16 shows the distributions of residual stress with depth in stainless steel SUS316L treated by cavitation peening (CP) using cavitating jets in water and air, and a cavitating jet in a pressurized chamber. It is obvious that all three jets can introduced compressive residual stress into stainless steel SUS316L. The cavitating jet in air can introduce large compressive residual stress in the subsurface and the cavitating jet in water can introduce compressive residual stress into a deeper region. In order to reveal the difference between cavitating jets in water and air, Fig. 17 shows plastic deformation

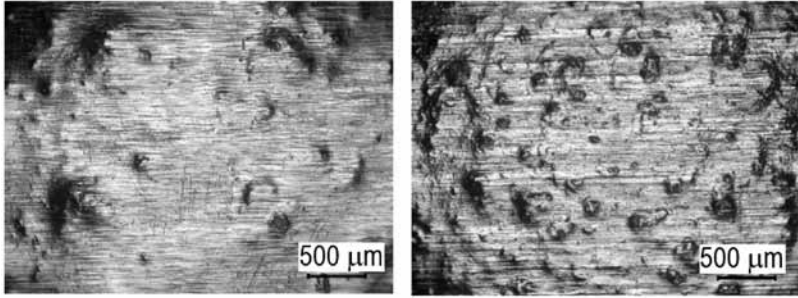
(a) Cavitating jet in water ($d = 2$ mm)(b) Cavitating jet in air ($d = 1$ mm)

FIGURE 17

Typical images of plastic deformation pits on pure aluminium.

pits on pure aluminum. The nozzle throat diameter of the cavitating jet in water was 2 mm and that of the cavitating jet in air was 1 mm in Figs. 16 and 17. Note that the diameter of the plastic deformation pit on pure aluminum is proportional to 0.6 power of nozzle throat diameter [75]. When the constant nozzle throat diameter was used [76], the tendency of the residual stress distribution was similar to that of Fig. 16. Rather larger pits of the sub-mm and/or mm order can be seen on the surface treated by the cavitating jet in water. On the other hand, higher density and deeper smaller pits can be seen in the case of the cavitating jet in air. Thus, CP using a cavitating jet in water provides an equivalent effect to shot peening with large shot, and CP using a cavitating jet in air corresponds to shot peening using small shot at high velocity. A cavitating jet in water in a pressurized chamber can introduce large compressive residual stress near the surface and also in a deeper region. As mentioned above, the pressure in the chamber reduces the residual bubbles which then enhances the performance of the jet.

When opposing cavitating jets are used for cavitation peening, a hole and/or pipe can be treated [53]. As the pressure where the opposing jets meet increases, the cavitation collapses powerfully. Even if the opposing jets are placed parallel to the surface to be treated, the cavitation collapses to the surface. The details of this phenomenon are described in reference [53].

4.2. Standoff Distance

As shown in Figs. 10 and 11, the performance of a cavitating jet varies with standoff distance, and the optimum standoff distance for the 2nd peak, s_{opt} , which depends on the nozzle diameter d and the cavitation number σ , as described by Eq. (7), is used for cavitation peening. Figure 18 shows the inverse of the radius of curvature $1/\rho$ of a 5 mm thick duralumin plate JIS A2017-T3, after exposure to a cavitating jet at various standoff distances, injection pressures and nozzle diameters, using two different types of nozzle

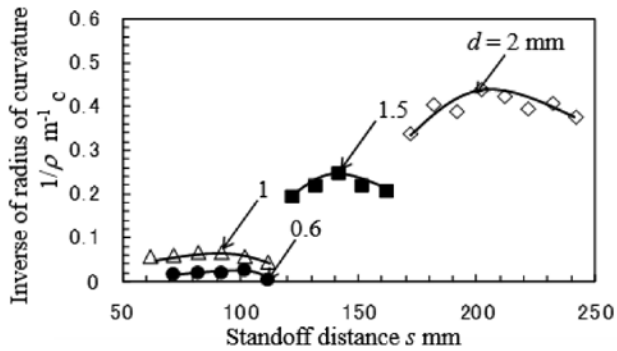
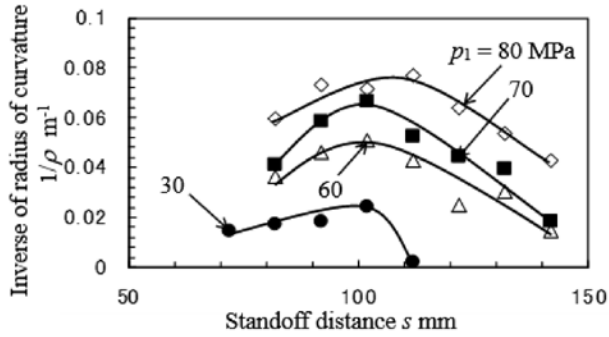
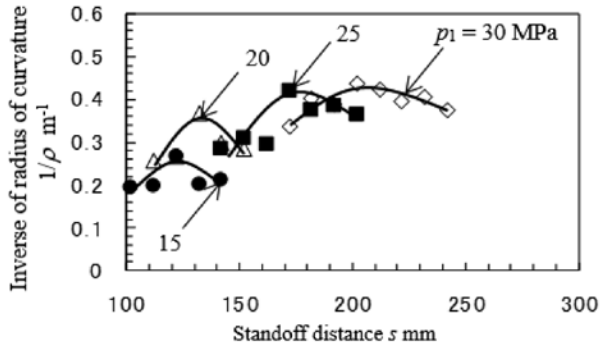


FIGURE 18

Aggressive intensity of cavitating jets as a function of standoff distance.

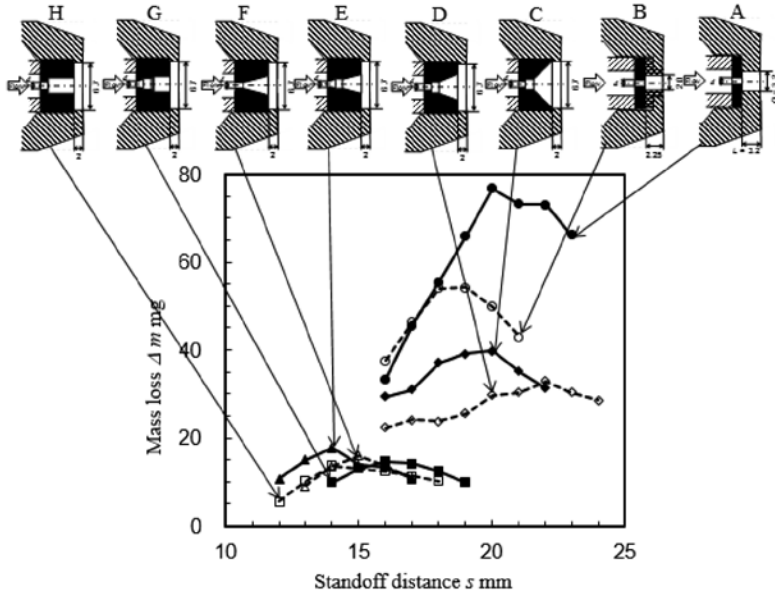


FIGURE 19

Effect of nozzle outlet geometry on the aggressive intensity of a cavitating jet ($d = 0.4$ mm, $p_1 = 30$ MPa).

N1 and N2 [77]. The $1/\rho$ has a maximum for each cavitating condition. As cavitation peening and water jet peening are classified by the relationship between the cavitation number σ and the optimum standoff distance s_{opt} as shown in Fig. 13, the peaks in Fig. 18 belong to cavitation peening. The values of s_{opt} and $1/\rho$ at the peak increase with increasing injection pressure and/or nozzle throat diameter at the present condition.

4.3. Nozzle Geometry

In order to show the relative aggressive intensities of cavitating jets through various types of nozzle, Fig. 19 shows the mass loss Δm as a function of standoff distance [78]. The specimens were made of pure aluminum to demonstrate the performance of each jet, and the exposure time in each case was 2 min. All the nozzles had the same throat diameter, i.e., 0.4 mm, with a sharp edge at the upstream end. The equivalent nozzle diameter d_e of all the nozzles was the same. However, there are large differences in Δm . For example, the maximum Δm of nozzle A is about 6 times larger than that of nozzle H. Actually, the 6 nozzles on the left hand side in Fig. 19 were used for water jets, while nozzles A and B were proposed for cavitating jets. Note that the shapes of the nozzles suitable for cavitating jets are much different to those for water jets.

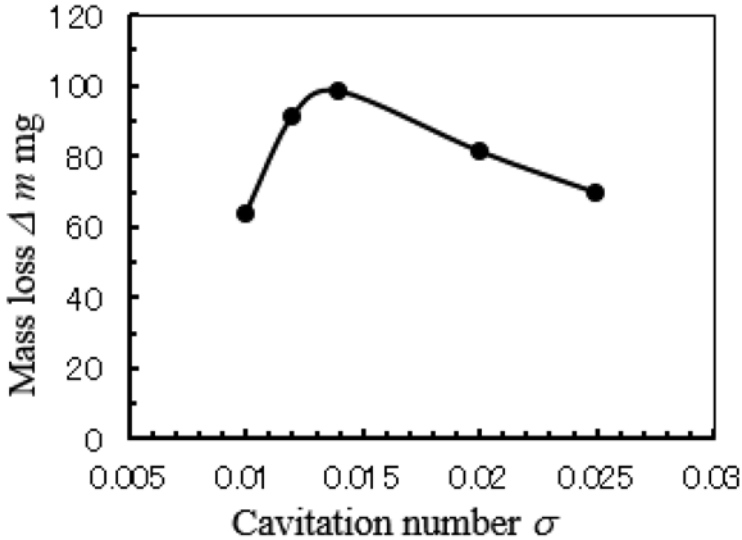


FIGURE 20

Effect of cavitation number on the aggressive intensity of a cavitating jet ($d = 0.4$ mm, $p_1 = 30$ MPa)

In order to enhance the performance of cavitating jets, resonating nozzles were proposed by Johnson et al. [79] and Chahine et al. [80]. A horn shape at the nozzle exit was also proposed [67], and an improvement in performance using a nozzle equipped with a center body as a cavitator was reported [81]. As shown in Fig. 19, a simple nozzle with an orifice plate with an outlet bore has good performance. The outlet geometry of such a nozzle was optimized by Soyama, experimentally [20], such that the aggressive intensity was increased by a factor of 20. In order to increase the aggressive intensity of the jet, a cavitator placed upstream from the orifice plate, and a guide, with which the size of the cavitation cloud was enhanced, were optimized [21]. Each of these doubled the aggressive intensity of the jet, so that the overall improvement was a factor of 4. Thus, the aggressive intensity of a jet without a pressurized chamber was improved by a factor of about 80 compared to cavitating jets in the 1990's.

4.4. Cavitation Number

In order to demonstrate the effect of cavitation number on the aggressive intensity of a cavitating jet, Fig. 20 shows the dependency of the mass loss Δm of pure aluminum on cavitation number σ [82]. The Δm was measured at the optimum standoff distance for each cavitation number. The injection pressure p_1 and exposure time of the jet were 20 MPa and 630 s, respectively. The

peak mass loss is at $\sigma = 0.014$. Previously, it had been reported that the mass loss of a cavitating jet with $p_1 = 98$ MPa peaks at $\sigma = 0.01 - 0.014$ [83]. The cavitation number at the peak, where the aggressive intensity is at its peak, is slightly different for different nozzle outlet geometries, but is in the range of $\sigma = 0.01 - 0.014$ [84].

For a cavitating jet in water in a pressurized chamber, mentioned in the section entitled “Types of Cavitating Jets”, when the cavitation collapses, it is in a relatively high-pressure region, thus, the individual impacts would be large, because the residual bubbles that normally produce the cushioning effect are reduced by the high pressure. This is why the aggressive intensity increases with cavitation number, σ , since σ increases with the higher pressure, i.e., the downstream pressure of the nozzle, p_2 , as given by Eq. (2). On the other hand, the total number of cavitation impacts decreases with cavitation number σ , so the aggressive intensity at large σ decreases with σ . This is reason why the aggressive intensity of a cavitating jet has a peak against cavitation number σ .

Regarding the experimental results of a cavitating flow through a Venturi tube [85], the aggressive intensity has a peak at a certain downstream pressure $p_{2\ opt}$, which varies with the injection pressure p_1 . When the cavitation number is considered, the cavitation number at the peak is nearly constant for various p_1 [85]. Thus, the cavitation number is one of the key factors in cavitation peening. For practical applications, it is worthwhile to set the downstream pressure at the optimum value, as the aggressive intensity of cavitation can simply be increased by controlling a valve on the downstream side without the need for additional power.

Now let's consider the aggressive intensity I_{cav} of a cavitating jet in water such as represented by the mass loss and/or the inverse of radius of curvature of the plate, i.e., the arc height, as a function of cavitation number at constant injection pressure p_1 . For constant cavitation number σ , that is, with constant p_2 , $1/\rho$, and therefore, I_{cav} , is proportional to the cavitation volume, V_{cav} , as shown in Eq. (6). Assuming that I_{cav} is proportional to the pressure difference between p_2 and p_v , then,

$$\frac{1}{\rho} \propto V_{cav} \cdot \Delta p \propto V_{cav} (p_2 - p_v) \quad (11)$$

However, the cavitation impact is reduced by the cushioning effect of residual bubbles, which reduces I_{cav} . Thus, the pseudo vapor pressure, p'_v , is used in place of p_v when residual bubbles are entrained into the cavitating region. Moreover, since the cavitating length L_{cav} is proportional to the optimum standoff distance, s_{opt} , which can be found from erosion tests [69], V_{cav} in Eq. (12) can be replaced by a term depending on s_{opt} . Thus, we have

$$I_{cav} \propto V_{cav} (p_2 - p'_v) \propto (L_{cav})^3 (p_2 - p'_v) \propto (s_{opt})^3 (p_2 - p'_v) \quad (12)$$

Since $p_v' > p_v$, I_{cav} is reduced. The relationship between σ and s_{opt} is given by Eq. (10), and that between p_2 and p_1 , σ is given by Eq. (2), so Eq. (12) can be rearranged to give

$$I_{cav} \propto (\sigma^{-0.6})^3 (p_2 - p_v') \propto \sigma^{-1.8} (p_2 - p_v') \propto \sigma^{-1.8} (p_1 \sigma - p_v') \quad (13)$$

Although in deriving Eq. (13) from Eq. (12) the cavitating length L_{cav} is given as a function of the cavitation number, σ , where the optimum standoff distance s_{opt} is used, s_{opt} depends on the nozzle geometry. Therefore, a modification to the cavitation number, s_s , should be considered. For example, L_{cav} is usually defined as the distance from the nozzle exit to the end of the cavitating region, and s_{opt} is defined as the distance from the upstream corner of the nozzle to the surface of the target. In this case Eq. (13) can be rewritten with σ - s_s replacing σ in parentheses to give

$$I_{cav} = c \sigma^{-1.8} \{ p_1 (\sigma - \sigma_s) - p_v' \} \quad (14)$$

where c is a constant of proportionality. Note that Eq. (14) gives the aggressive intensity of the jet as a function of cavitation number at constant injection pressure p_1 . Differentiating equation (14) and setting this equal to zero shows that I_{cav} has a maximum at

$$\sigma = \frac{1.8}{0.8} \left(\frac{p_v'}{p_1} + \sigma_s \right) \quad (15)$$

Figure 21 shows the normalized aggressive intensity of a cavitating jet \bar{I}_{cav} as a function of cavitation number σ . This is normalized at $\sigma = 0.014$. For Fig. 21, the experimental values of \bar{I}_{cav} were calculated from experimental data published in various reports [66, 82, 86]. The estimated values were obtained from Eq. (14) by optimizing c , s_s and p_v , respectively. As mentioned above, the maximum value of \bar{I}_{cav} is taken to be at $\sigma \approx 0.014$. The estimated values of \bar{I}_{cav} have maxima in the range $\sigma = 0.01 - 0.014$. Thus, Eq. (14) shows the effect of cavitation number on the aggressive intensity of a cavitating jet.

4.5. Processing Speed (Processing Time per Unit Length)

In order to discover the effect of processing speed, i.e., processing time per unit length, Fig. 22 shows the arc height produced in an Almen gauge as a function of processing time per unit length t_p [87]. The t_p is defined by the processing speed v and the number of scans n as follows

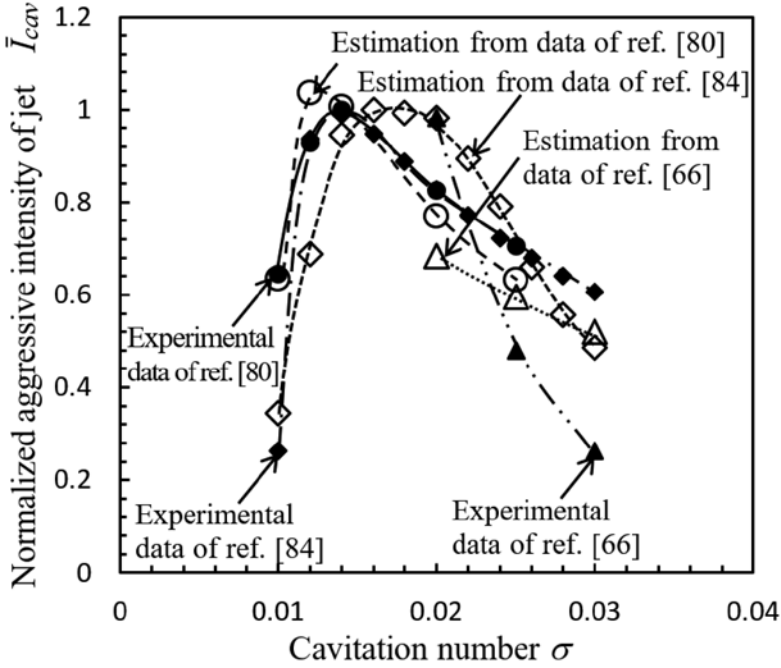


FIGURE 21
Normalized aggressive intensity of a jet I_{cav} as a function of cavitation number

$$t_p = \frac{n}{v} \quad (16)$$

The cavitation peening conditions were as follows. For the cavitating jet in water in a pressurized chamber, the nozzle throat diameter d was 2 mm, the injection pressure p_1 was 30 MPa, the standoff distance s was 80 mm, and the cavitation number σ was 0.014. For the cavitating jet in water in an open chamber, the cavitating conditions were $d = 2$ mm, $p_1 = 30$ MPa, $s = 262$ mm and $\sigma = 0.0033$. For the cavitating jet in air, the conditions were $d = 1$ mm, $p_1 = 30$ MPa and $s = 56$ mm. In all three cases, the arc height of the Almen gage increased with t_p and saturated at a certain t_p . The arc height reached 0.2 mm with $t_p = 1$ mm/s, when the cavitating jet in water in the pressurized chamber was used. According to a previous report [24], the distribution of the intensity and the frequency of cavitation impact are stochastic phenomena. Moreover, the frequency of intense cavitation impacts is less than 1/10 the frequency of weak impacts, and the arc height can be expressed by the following equation:

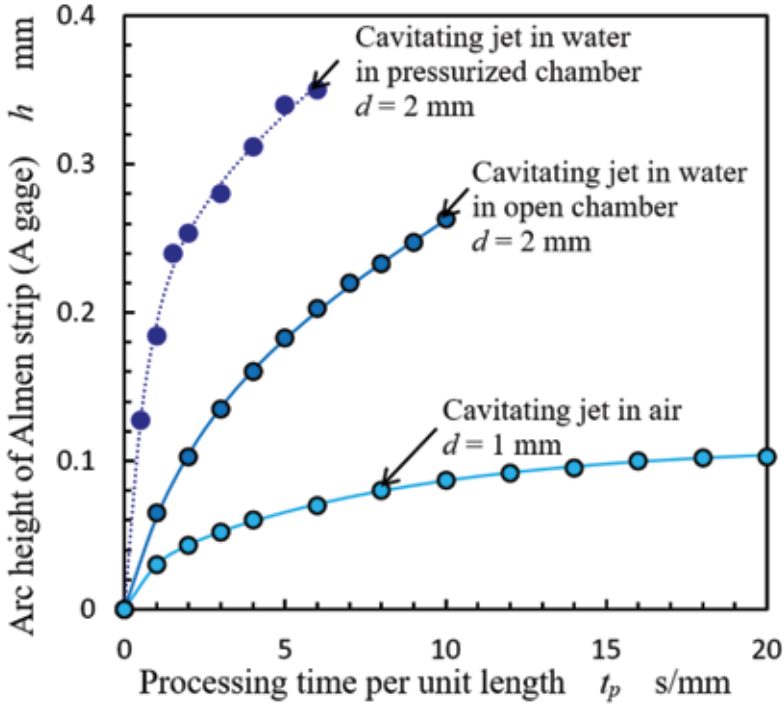


FIGURE 22
Normalized aggressive intensity of a jet J_{cav} as a function of cavitation number

$$h = h_{sat1} \left(1 - e^{-c_1 t_p} \right) + h_{sat2} \left(1 - e^{-c_1 \frac{t_p}{c_2}} \right) \quad (17)$$

where, h_{sat1} and h_{sat2} are the saturation arc height caused by weak impacts and the saturation arc height caused by intense impacts, respectively. c_1 is a constant that ensures h_{sat1} is reached, and c_2 is the ratio of the frequency of weak impacts to that of intense impacts. Note that when the relation between intensity and frequency of impact was assumed as Poisson distribution law [24], the impact force of weak impacts was 79 N and that of intense impacts was 112 N.

In Fig. 22, the symbols are experimental data and the approximate curves were obtained from Eq. (17). As the symbols lie on the curves, it can be concluded that the arc height expressed by Eq. (17) is valid. Note that it has been shown that the compressive residual stress introduced by cavitation peening can be described by a similar equation to Eq. (17) [24].

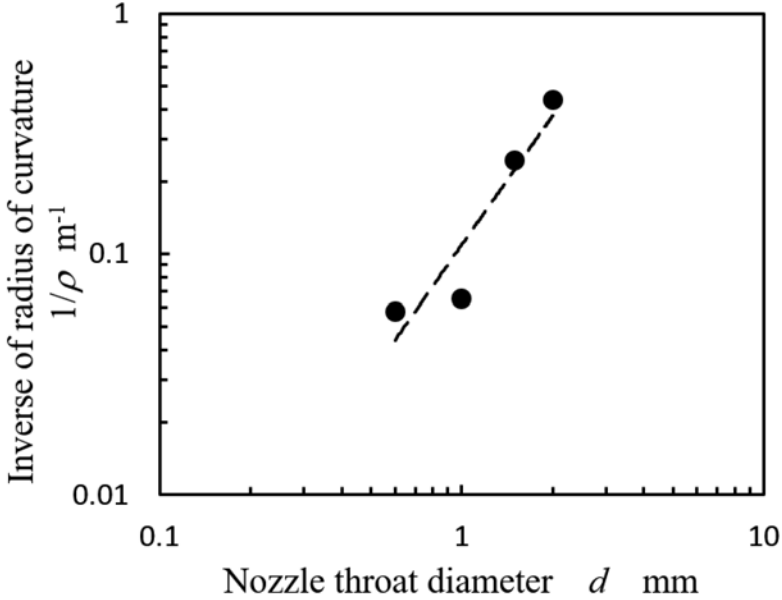


FIGURE 23
Effect of nozzle throat diameter on the peening intensity ($p_f = 30$ MPa)

As the optimum processing time of cavitation peening is about 1/25 to 1/5 of the incubation period for both stainless steel and copper [88], cavitation peening does not make damage with material loss on the treated surface.

4.6. Nozzle Throat Diameter

In order to illustrate the relationship between the nozzle throat diameter and the peening intensity, Fig. 23 shows the inverse of the radius of curvature $1/\rho$ as a function of nozzle throat diameter d . In Fig. 23, $1/\rho$ at the optimum standoff distance, where $1/\rho$ has its maximum value, is plotted from the data points in Fig. 18 (c). When a power law is assumed by considering the scaling effect on cavitation erosion, i.e., Eq. (3), the relationship between d and $1/\rho$ can be expressed by the following equation:

$$\frac{1}{\rho} \propto d^{n_d} \quad (18)$$

where, n_d is the exponent of the power law. In Fig. 23, n_d is 1.8 ± 0.4 . When the erosion rate is measured with various values of d , n_d depends on cavitation number σ , with $n_d = 1.56 \pm 0.03$ at $\sigma = 0.01$, $n_d = 1.97 \pm 0.03$ at $\sigma = 0.014$ and $n_d = 2.49 \pm 0.02$ at $\sigma = 0.02$ [89]. These results suggest that

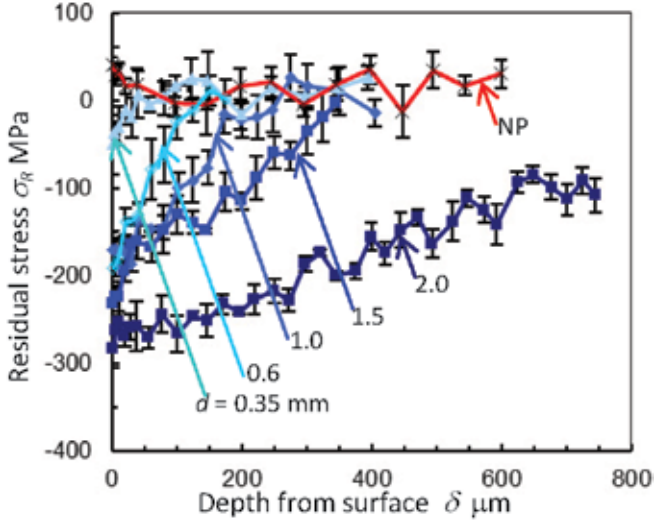


FIGURE 24

Effect of nozzle throat diameter on the introduction of compressive residual stress into stainless steel ($p_1 = 30$ MPa, $p_2 = 0.1$ MPa, $\sigma = 0.003$, $t_p = 1$ s/mm)

n_d is roughly about 2. Thus, it can be concluded that the aggressive intensity of the cavitating jet is roughly proportional to the flow rate of the jet, as the flow rate is proportional to the square of d at constant injection pressure.

In order to understand the effect of the nozzle throat diameter d on the thickness of the surface modification layer, δ , Fig. 24 shows the variation in the distribution of residual stress, s_R , with d for SUS316L stainless steel treated by cavitation peening with $p_1 = 30$ MPa, $p_2 = 0.1$ MPa, $\sigma = 0.003$, and $t_p = 1$ s/mm [29]. At $d = 0.35$ mm, the residual stress at the surface is about -40 MPa and the thickness of the compressive layer is about 60 mm. On the other hand, at $d = 2$ mm, the residual stress at the surface is about -270 MPa and the thickness of compressive layer is about 1 mm. Thus, a cavitating jet using a large nozzle can introduce greater compressive residual stress up to greater depth.

4.7. Injection Pressure

Figure 25 shows the relationship between the inverse of the radius of curvature $1/\rho$ and the injection pressure p_1 from the data points for the optimum standoff distances in Fig. 18 (a) and (b). By considering Bernoulli's equation (Eq. (1)) and the power law dependency on flow velocity given in Eq. (4), the following power law for the relationship between peening intensity, represented by $1/\rho$, and injection pressure is derived,

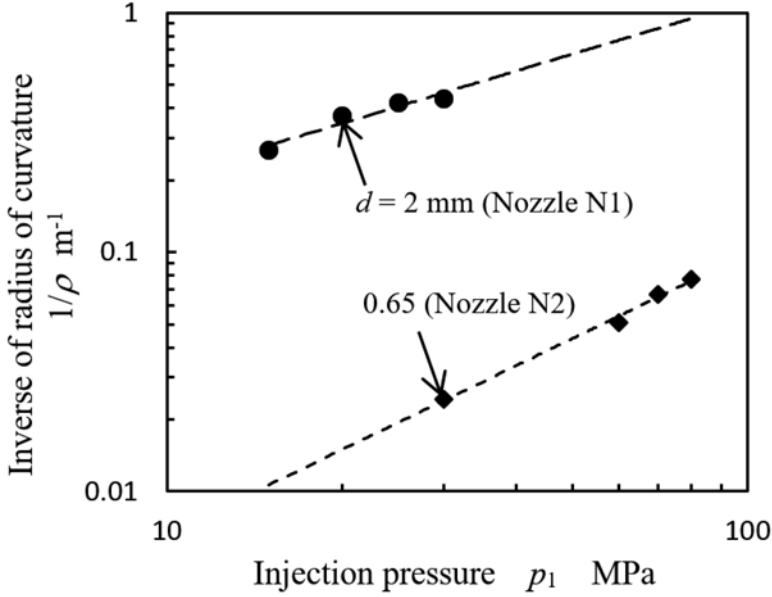


FIGURE 25
Effect of injection pressure on the peening intensity

$$\frac{1}{\rho} \propto p_1^{n_p} \quad (19)$$

where n_p is the exponent of the power law. The values of n_p in Fig. 25 are 1.17 ± 0.06 at $d = 0.65$ mm and 0.73 ± 0.12 at $d = 2$ mm. Note that the values of $1/\rho$ in Fig. 18 (a) and (b) were evaluated at constant downstream pressure. This means that the cavitation number changes with changes in injection pressure. The above-mentioned n_p includes the effect of cavitation number. As mentioned in the section on “cavitation number”, the aggressive intensity of the jet decreases with decreasing cavitation number σ for $\sigma < 0.01$. Regarding a previous report, the values of n_p at constant cavitation numbers were as follows; $n_p = 2.25 \pm 0.05$ at $\sigma = 0.01$, $n_p = 2.42 \pm 0.02$ at $\sigma = 0.014$ and $n_p = 2.82 \pm 0.01$ at $\sigma = 0.02$ [89], suggesting that n_p changes with σ . Furthermore, n_p decreases with decreasing σ ($= p_2/p_1$), i.e., increasing p_1 at constant tank pressure. That is, if the injection pressure is too high at a constant tank pressure p_2 , the peening intensity hardly increases with p_1 .

In order to illustrate the effect of injection pressure at relatively high injection pressures on the introduction of compressive residual stress at a constant tank pressure p_2 , Fig. 26 shows the distribution of the residual stress as a func-

tion of depth from the surface δ [29]. The material under test was stainless steel and this is the same material used for the data in Fig. 24. The cavitating conditions were $d = 0.35$ mm, $p_2 = 0.1$ MPa, and $t_p = 1$ s/mm. With p_1 in the range from 100 to 300 MPa, the residual stress at the surface is in the range from -170 to -200 MPa, while the thickness of the compressive layer is about 0.2 mm – 0.38 mm, neither of which varies very much with p_1 at constant p_2 .

A comparison between the distributions with $p_1 = 30$ MPa, $d_2 = 2$ mm in Fig. 24 and $p_1 = 300$ MPa, $d_2 = 0.35$ mm in Fig. 26 shows the former introduces large compressive residual stress into a deeper region. Note that the jet powers, which is defined by the pressure difference and the flow rate, in these two cases are nearly equal to each other. That is, when cavitation peening is applied at a constant tank pressure, a cavitating jet with low injection pressure and a large nozzle is better for introducing compressive residual stress than high injection pressure with a small nozzle. This is one of the reasons why a cavitating jet for which the injection pressure is too high cannot introduce large compressive residual stress [90]. Clearly, from the point of view of practical applications, a jet with low injection pressure and a large nozzle is better than one with high injection pressure and a small nozzle, as the initial and running costs of low injection pressure pumps are much less than those of high injection pressure pumps.

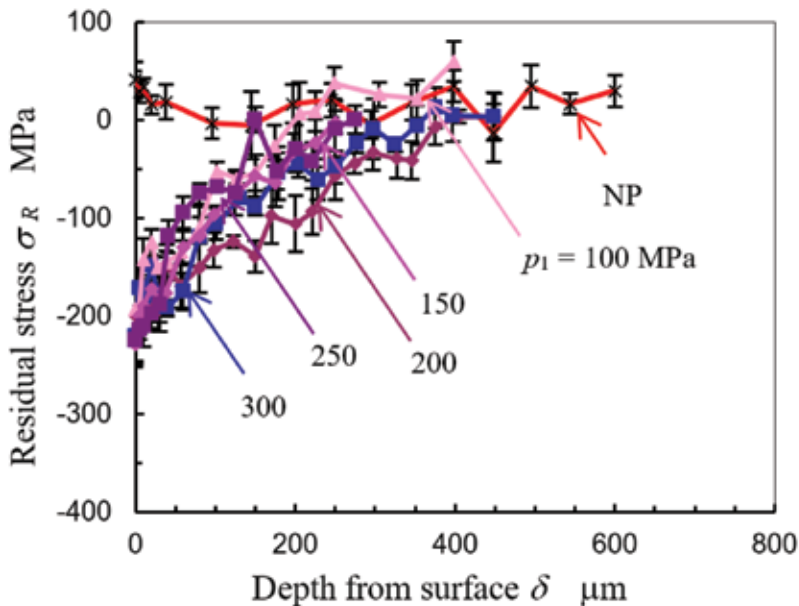


FIGURE 26

Effect of injection pressure on the introduction of compressive residual stress into stainless steel ($d = 0.35$ mm, $p_2 = 0.1$ MPa, $t_p = 1$ s/mm)

4.8. Downstream Pressure (Tank Pressure)

When the effect of the pressure downstream from the nozzle throat p_2 , i.e., the tank pressure, on the aggressive intensity of the cavitating jet was examined, a peak was found at a certain p_2 [85, 91]. Although the value of p_2 , where the maximum occurred, depended on the injection pressure p_1 , the cavitation number σ ($= p_2/p_1$) at the peak was almost constant [85], signifying that the cavitation number is a key parameter. If the optimum downstream pressure is required, it is easy to obtain it by considering the cavitation number and the injection pressure. In the case of a cavitating jet, the optimum cavitation number is 0.01 – 0.014 as mentioned in the section on “cavitation number”.

4.9. Water Temperature and Other Parameters

As cavitation is a phase change phenomenon from the liquid phase to the gas phase, similar to boiling, the water temperature T_w is one of the key parameters. The water temperature affects the vapor pressure, the dissolved gas content, the viscosity, the surface tension and the density. The effect of temperature on the aggressive intensity of cavitation peening, such as the erosion rate has been investigated by carrying out vibratory erosion tests [92-96] and cavitating jet erosion tests [97]. The various reports concluded that the maximum erosion rate occurred at 40 – 50 °C [92, 95], 60 – 70 °C [94], about 30 °C [93], or 21 °C [96]. In the case of a cavitating jet, the erosion rate had a maximum at about 40 °C, and the peak became indistinct at relative low cavitation numbers [97]. Therefore, the effect of the water temperature on the aggressive intensity of a cavitating jet is not clear.

Figure 27 shows the inverse of the radius of curvature $1/\rho$ of a 5 mm thick duralumin plate JIS A2017-T3 as a function of processing time per unit length t_p at various water temperatures, T_w . The curve for $T_w = 5$ °C is slightly lower than the other curves. At $T_w = 15, 25$ and 35 °C, $1/\rho$ is independent of water temperature. That is, the peening intensity is nearly constant in the range $T_w = 15 - 35$ °C under the conditions used here.

Next, let's consider the effect of the depth of the nozzle in the water on cavitation peening. As mentioned in the sections on “Cavitation” and “Types of Cavitating Jets”, residual bubbles and/or air bubbles in the water around the jet are a very important factor, as they provide a cushioning effect. When the position of the nozzle is in a shallow open chamber in which the water surface has a free surface, a suction vortex around the jet feeds air bubbles from the surface into the jet. These air bubbles potentially provide a cushioning effect, thus reducing the peening intensity of the jet. Thus, the water depth d_w , i.e., the distance from the water surface to the nozzle should be considered. Figure 28 shows the inverse of the radius of curvature $1/\rho$ as a function of processing time per unit length t_p for various water depths d_w . The plate used was 5 mm thick duralumin, the same as that used for the experiments carried out for the data presented in Figs. 18 and 27. As shown in Fig. 28, $1/\rho$ with $d_w = 0.12$ m is about two thirds of that with $d_w = 0.24$ m. In these exper-

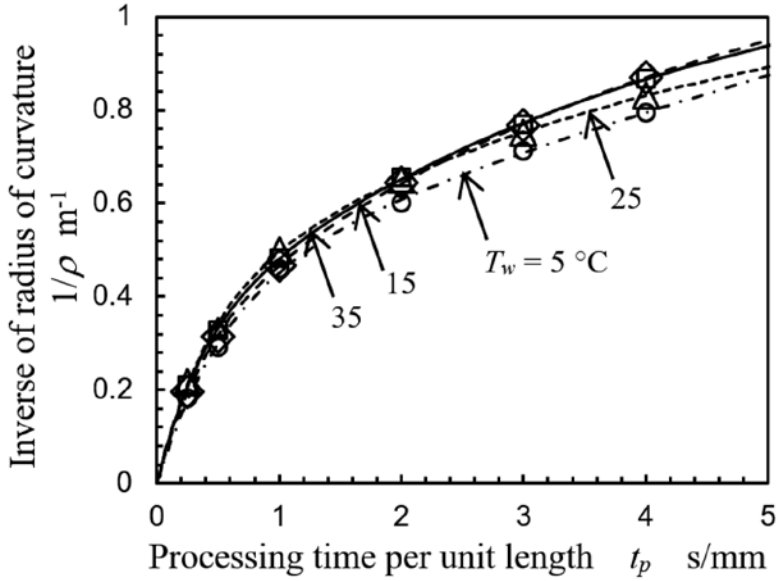


FIGURE 27
Effect of water temperature ($d = 2$ mm, $p_1 = 30$ MPa, $p_2 = 0.1$ MPa)

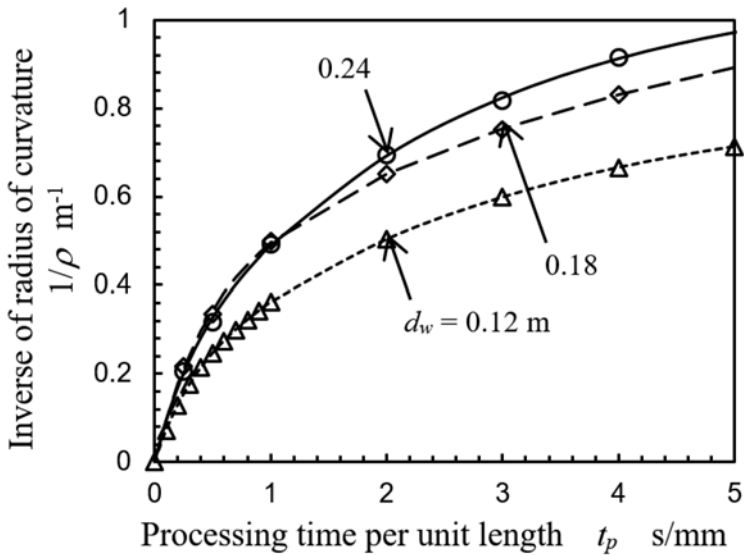


FIGURE 28
Effect of the depth of water ($d = 2$ mm, $p_1 = 30$ MPa, $p_2 = 0.1$ MPa)

iments, the plate was placed horizontally and the nozzle was set vertically above the plate. Actually, the pressure difference between $d_w = 0.12$ m and $d_w = 0.24$ m was only about 1.2 kPa, and the difference in cavitation number was only 0.00004 at $p_1 = 30$ MPa. Thus, the difference in $1/\rho$ between $d_w = 0.12$ m and $d_w = 0.24$ m was not caused by the differences in pressure and/or cavitation number, but might be due to air bubbles, which are entrained into the jet. Thus, the water depth needs to be considered in order to mitigate the cushioning effect caused by air bubbles.

4.10. Experimental Formula to Estimate the Aggressive Intensity of Cavitation

As mentioned above, the peening intensity using a cavitating jet in water depends on the nozzle geometry, the nozzle throat diameter d , the cavitation number σ and the injection pressure p_1 . The optimum standoff distance s_{opt} can be roughly estimated using Eq. (10), and it should be experimentally verified by measuring the peening intensity as a function of standoff distance. The peening effect of processing time per unit length and/or processing speed can be expressed by Eq. (17). Thus, in this section, the aggressive intensity of a cavitating jet in water I_{cav} at s_{opt} is discussed considering the nozzle geometry, the nozzle throat diameter d , the cavitation number σ and the injection pressure p_1 . Here, the aggressive intensity I_{cav} is found from arc height measurements and/or erosion tests, as cavitation impacts cause plastic deformation and/or erosion of a material. Considering the power law dependencies of the intensity on the nozzle throat diameter d and the injection pressure p_1 as expressed by Eqs. (18) and (19), an experimental formula was proposed to estimate the aggressive intensity $I_{cav\ est}$ from a reference aggressive intensity $I_{cav\ ref}$ as follows [89].

$$I_{cav\ est} = I_{cav\ ref} K_n \frac{f(\sigma)}{f(\sigma_{ref})} \left(\frac{d}{d_{ref}} \right)^{n_d} \left(\frac{p_1}{p_{1ref}} \right)^{n_p} \quad (20)$$

where the parameters with the subscript $_{ref}$ are those for the reference conditions. Here, K_n depends on the geometry of the nozzle and/or the test section, and n_d and n_p are the exponents of the power laws in Eqs. (18) and (19). Considering Eq. (14), the function $f(\sigma)$ is given by the following equation:

$$f(\sigma) = \sigma^{-1.8} \{ p_1 (\sigma - \sigma_s) - p'_v \} \quad (21)$$

As mentioned in the sections on “nozzle throat diameter” and “injection pressure”, the values n_d and n_p depends on the cavitating condition. Example of values in the reference to estimate the aggressive intensity of cavitation are shown in Table 1.

TABLE 1

Example values of experimental formula to estimate the aggressive intensity of cavitation

(a) Power law exponents for nozzle throat diameter and injection pressure

Parameter	Value	Range	Cavitating condition	Reference
n_d	1.8 ± 0.4	$d = 1 \text{ mm} - 2.5 \text{ mm}$	$p_1 = 30 \text{ MPa}, p_2 = 0.1 \text{ MPa}, \sigma = 0.0033$	[75]
	1.56 ± 0.03	$d = 1 \text{ mm} - 2.5 \text{ mm}$	$p_1 = 10 \text{ MPa}, p_2 = 0.1 \text{ MPa}, \sigma = 0.01$	[86]
	1.97 ± 0.03	$d = 1 \text{ mm} - 2.5 \text{ mm}$	$p_1 = 10 \text{ MPa}, p_2 = 0.14 \text{ MPa}, \sigma = 0.014$	[86]
	2.49 ± 0.02	$d = 1 \text{ mm} - 2.5 \text{ mm}$	$p_1 = 10 \text{ MPa}, p_2 = 0.2 \text{ MPa}, \sigma = 0.02$	[86]
n_p	1.17 ± 0.06	$p_1 = 30 \text{ MPa} - 80 \text{ MPa}$	$d = 0.65 \text{ mm}, p_2 = 0.1 \text{ MPa}$	[75]
	0.73 ± 0.12	$p_1 = 15 \text{ MPa} - 30 \text{ MPa}$	$d = 2 \text{ mm}, p_2 = 0.1 \text{ MPa}$	[75]
	1.56 ± 0.03	$p_1 = 10 \text{ MPa} - 30 \text{ MPa}$	$d = 1 \text{ mm}, \sigma = 0.01$	[86]
	1.97 ± 0.03	$p_1 = 10 \text{ MPa} - 30 \text{ MPa}$	$d = 1 \text{ mm}, \sigma = 0.014$	[86]
	2.49 ± 0.02	$p_1 = 10 \text{ MPa} - 20 \text{ MPa}$	$d = 1 \text{ mm}, \sigma = 0.02$	[86]

(b) Function depending on the shape of the nozzle

Parameter	Value	Nozzle type	Cavitating condition	Reference
K_n	1	$d : D : L = 1 : 6 : 8$ (see Ref. [20])	$p_1 = 30 \text{ MPa}$	[20]
	22	$d : D : L = 1 : 8 : 8$ (ditto)	$p_2 = 0.42 \text{ MPa}$	
	12	$d : D : L = 1 : 10 : 8$ (ditto)	$\sigma = 0.014$	
	10	$d : D : L = 1 : 8 : 6$ (ditto)	$d = 2$	
	10	$d : D : L = 1 : 8 : 10$ (ditto)		
K_n	1	Without cavitator and guide pipe (see Ref. [20])	$p_1 = 30 \text{ MPa}$	[21]
	1.8	Without cavitator with guide pipe (ditto)	$p_2 = 0.1 \text{ MPa}$	
	2.3	With cavitator and without guide pipe (ditto)	$\sigma = 0.0033$	
	4.2	With cavitator and guide pipe (ditto)	$d = 2$	
K_n	1.48 ± 0.06	Nozzle A (see Fig. 19)	$p_1 = 30 \text{ MPa}$	[76]
	1.00 ± 0.03	Nozzle B (ditto)	$p_2 = 0.42 \text{ MPa}$	
	0.66 ± 0.07	Nozzle C (ditto)	$\sigma = 0.014$	
	0.54 ± 0.03	Nozzle D (ditto)	$d = 0.4$	
	0.38 ± 0.03	Nozzle E (ditto)		
	0.36 ± 0.03	Nozzle F (ditto)		
	0.23 ± 0.01	Nozzle G (ditto)		
	0.23 ± 0.01	Nozzle H (ditto)		

(c) Values to estimate relative aggressive intensity of cavitating jet

p_v'	c	σ_s	Reference (experimental data)
0.05 MPa	0.00261	0.00301	[66]
	0.00148	0.00171	[80]
	0.00236	0.00270	[84]

Now, let's check the validity of Eq. (20). For example, when $d_{ref} = 1$ mm, $p_{1\ ref} = 10$ MPa, and $s_{ref} = 0.014$, $I_{cav\ ref}$ is 0.022 g/min, so that if $d = 2$ mm, $p_1 = 30$ MPa, and $\sigma = 0.014$, $I_{cav\ est}$ is 1.231 g/min as shown by Eq. (22) below. The experimentally measured mass loss rate for these latter parameters was 1.428 g/min [89]. The difference between the estimated and experimental values is 16% at constant σ . Thus, Eq. (20) is useful for estimating the relative aggressive intensity of a cavitating jet in water.

$$I_{cav\ est} = 0.022 \times 1 \times 1 \times \left(\frac{2}{1}\right)^{1.97} \times \left(\frac{30}{10}\right)^{2.42} \quad (22)$$

5. PEENING EFFECTS

5.1. Introduction of Compressive Residual Stress

As mentioned in the introduction, in order to mitigate stress corrosion cracking in nuclear power plants, the introduction of compressive residual stress by "water jet peening" was proposed [12]. Soyama et al. found the cavitation impacts around a submerged water jet introduced compressive residual stress into stainless steel [13], and this was then confirmed by Hirano et al. [14]. Now, this method is applied to nuclear power plants [16]. Typical examples of the introduction of compressive residual stress into stainless steel by cavitation peening are shown in Figs. 16, 24 and 26. With the optimum cavitation conditions, i.e. $d = 2$ mm and $p_1 = 30$ MPa, cavitation peening can introduce compressive residual stress up to a depth of about 1 mm.

The introduction of compressive residual stress by cavitation peening in order to extend the lifetime of a die for hot forging has been done. The lifetime of a die was increased by 50 % [98], as a result of the compressive residual stress, which mitigates cracking of the die, and the work hardening, which suppresses deformation of the die. Figure 29 shows the variation in the distribution of residual stress with processing time per unit length t_p [99]. The material under test was heat treated alloy tool steel JIS SKD61 with a Vickers hardness of 710 ± 30 before peening. After cavitation peening at $t_p = 10$ s/mm, the Vickers hardness had increased by 17 % to 830 ± 30 . Under the conditions used in that work, cavitation peening introduced compressive residual stress up to a depth 400 μm [99]. Note that the full width at half maximum of X-ray diffraction measurements on the material decreased after cavitation peening [99, 100]. Analysis of the micro strain using X-ray diffraction showed that the micro strain, introduced by heat treatments, such as quenching, and/or mechanical surface finishing, decreased after cavitation peening [100]. As cavitation peening is a kind of shotless peening, and can introduce compressive residual stress without collisions between solid materials, there is very

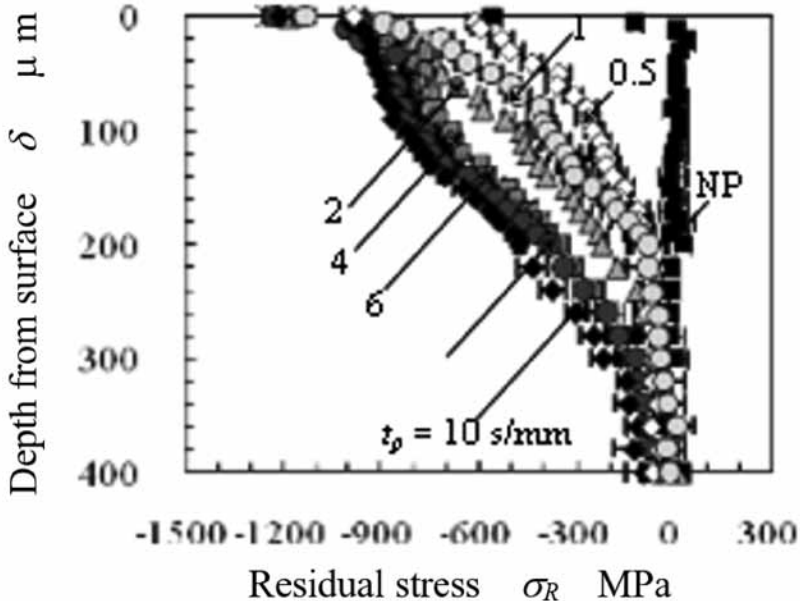


FIGURE 29

Introduction of compressive residual stress into tool alloy steel JIS SKD61 ($d = 2$ mm, $p_1 = 30$ MPa, $p_2 = 0.42$ MPa)

little change in the surface roughness. On the other hand, the shock wave induced by cavitation bubbles collapsing can move dislocations in a polycrystalline metal. This was confirmed by observation with a transmission electron microscopy [101]. Thus, cavitation peening can introduce compressive residual stress, i.e., macro strain, while relieving micro strain.

Cavitation peening can also introduce compressive residual stress into Ti-6Al-4V titanium alloy [102]. When the surface residual stress s_R and the surface roughness R_a of cavitation peening and shot peening were compared, these were -988 ± 18 MPa and 0.53 mm, respectively, for a cavitation peened specimen, and -541 ± 141 MPa and 2.44 mm, respectively, for a shot peened specimen. Therefore, cavitation peening is capable of introducing compressive residual stress into titanium alloy with considerably less surface roughness compared to that from the widely used shot peening.

As shown in Figs. 16, 24, 26 and 29, the compressive residual stress introduced by cavitation peening has a maximum at the surface. There are two reasons why this is so. In the case of shot peening, in order to introduce compressive residual stress near the surface, small shot are applied after large shot, a process called two-stage shot peening. In the case of cavitation peening, the cavitating jet produces both small and large impacts at the same time [24, 60]. As the small impacts behave like small shot and the large impacts

ing jets in air and water, respectively. In both cases, the nozzle throat diameter d was 1 mm and the injection pressure of the jet p_1 was 30 MPa. In the case of the cavitating jet in water, the 1st and 2nd peaks were obtained by measuring the variation of residual stress with the standoff distance. As mentioned in the section on “Cavitation Peening and Water Jet Peening”, the 1st peak corresponds to water jet peening (WJP) and the 2nd peak corresponds to cavitation peening (CP). The fatigue strength after $N_f = 10^7$ cycles obtained by Little’s method [112] were 279 MPa for the non-peened specimen, 292 MPa for WJP by CJW, 327 MPa for CP by CJW and 360 MPa for CP by CJA. Although water jet peening can improve the fatigue strength, improvement in the fatigue strength by cavitation peening is better than that by water jet peening. From this test, it was found that the fatigue strength of the specimen treated by cavitation peening using the cavitating jet in air was best.

As is well known, the improvement in fatigue strength depends on crack initiation and crack propagation. A method for measuring fatigue crack growth rates using a compact tension specimen has been standardized by ASTM E647-13 [113]; however, it is very difficult to evaluate crack propagation in a modified layer at the surface using the standard test method, as the thickness of the layer is too thin compared with the base material. Therefore, a load-controlled plate bending fatigue tester was developed, and it was shown that the relationship between the threshold stress intensity factor range ΔK_{th} and the crack propagation rate da/dN of the peened material can be evaluated using this tester [114, 115]. Examining the mechanisms by which the fatigue strength can be improved by peening can be very beneficial, and can help check whether crack initiation and/or crack propagation are suppressed by cavitation peening. With ΔK_{th} defined as the stress intensity factor range ΔK at $da/dN = 10^{-10}$ m/cycle, ΔK_{th} of a non-peened stainless steel specimen, which was 3.75 MPa, became 7.35 MPa after cavitation peening [115]. The crack propagation rate was also reduced by cavitation peening [114]. Thus, cavitation peening can suppress crack initiation and crack propagation.

There are many practical applications of cavitation peening to mechanical components. Improvements to the fatigue strengths of the elements of a steel belt for CVT [116], a roller [117], gears [118], an elastic ring for a planetary traction drive unit [119] have all been demonstrated. Figure 31 shows the relationship between torque D_n and the number of cycles to failure N_f . The gears tested were made of chromium molybdenum steel JIS SCM420H and were treated by cavitation peening with $d = 2$ mm, $p_1 = 30$ MPa, and $p_2 = 0.42$ MPa, and examined by a power circulating-type gear tester. The fatigue torque at $N_f = 10^7$ determined by Little’s method [112] was 337 Nm for the non-peened gear, 376 Nm for the shot-peened gear and 418 Nm for the cavitation peened gear. Thus, it is clear that a greater improvement in fatigue torque was achieved with cavitation peening compared to shot peening.

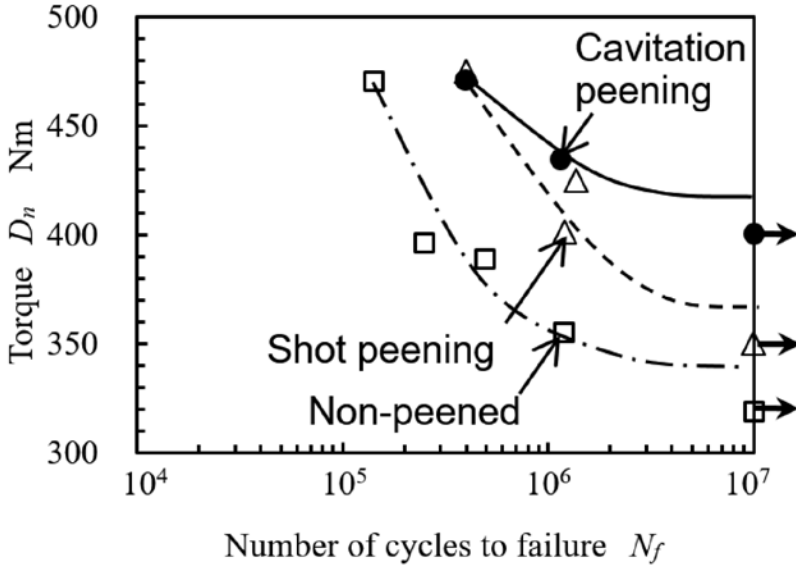


FIGURE 31

Improvement in fatigue strength demonstrated by a power circulating_type gear tester ($d = 2$ mm, $p_1 = 30$ MPa, $p_2 = 0.42$ MPa)

5.3. Improvement in Fretting Fatigue Strength

Cavitation peening also suppresses fretting fatigue by introducing compressive residual stress [120, 121]. A spinal implant rod and its holding fixture can suffer from severe fretting fatigue, so it would be valuable if the fretting fatigue properties of these could be enhanced. Figure 32 illustrates the results of fretting fatigue tests on a 5 mm diameter spinal implant made of Ti-6Al-4V ELI (Extra-Low Interstitial) [122], [121]. As the diameter of the implant rod is relatively small, the cavitation peening conditions chosen were $d = 0.64$ mm, $p_1 = 80$ MPa, and $p_2 = 0.8$ MPa. The test rod was evaluated by a fretting fatigue test in accordance with the ASTM F1717 standard [123]. As shown in Fig. 32, at an applied load $P = 350$ N, the number of cycles to failure N_f of the non-peened specimen is 5.86×10^4 , and that of the cavitation peened specimen is 2.05×10^6 . The number of cycle to failure is 40 times more after cavitation peening. When the applied loads for $N_f > 5 \times 10^6$ are compared, the non-peened specimen is 150 N and the cavitation peened specimen is 350 N. Thus, the fretting fatigue strength of the spinal implant rod was enhanced by a factor of 2.2 by cavitation peening. This improvement in the fretting fatigue properties is due to hardening and the introduction of compressive residual stress [124, 125]. The Vickers hardness and

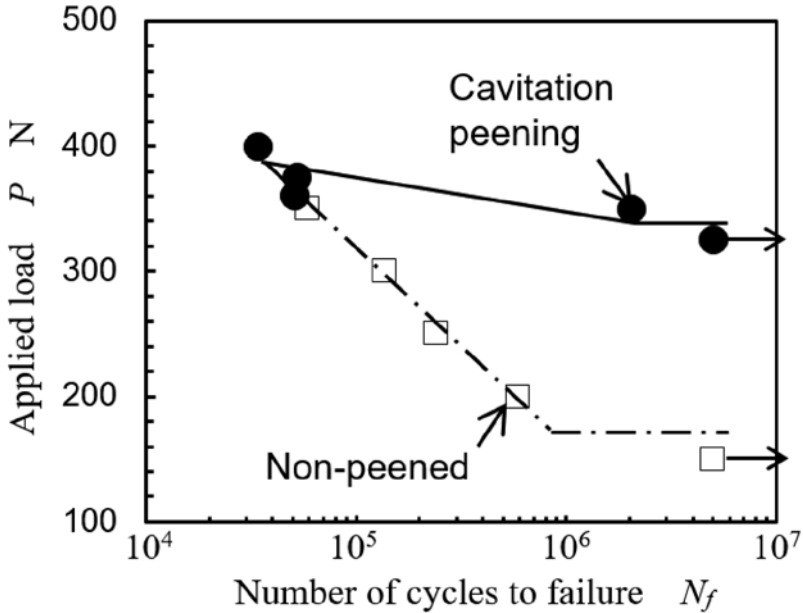


FIGURE 32

Improvement in the fretting fatigue strength of a spinel implant evaluated by the ASTM F1717 Standard ($d = 0.64$ mm, $p_1 = 80$ MPa, $p_2 = 0.8$ MPa)

residual stress were 5.0 GPa and -116 ± 20 MPa, respectively, for the non-peened specimen, and -554 ± 20 MPa and 9.6 GPa, respectively, for the cavitation peened specimen. Thus, cavitation peening can drastically improve the fretting fatigue properties by work hardening and introducing compressive residual stress.

5.4. Improvement in Yield Strength

Mechanical surface treatments can improve yield strength by work hardening. Improvements in the yield stress of electrical sheet steel by cavitation peening has also been demonstrated [126]. Electrical sheet steel is used in the IPM motors [127] of electric and hybrid vehicles. In order to obtain better electromagnetic properties, an increase in the permissible speed of rotation is required, without changing the chemical composition of the sheet steel. In one report [126], cavitation peening was proposed as a technique to partially strengthen the steel to increase the speed of rotation. Figure 33 shows the relationship between tensile stress s_t and displacement δ_D [126]. The tensile test was conducted using a tensile test specimen. The thickness and width of the test section of the specimen made of non-oriented electrical sheet steel were 0.35 mm and 1 mm to simulate the component of an IPM motor. The yield stress σ_y of the sheet steel without peening was 372

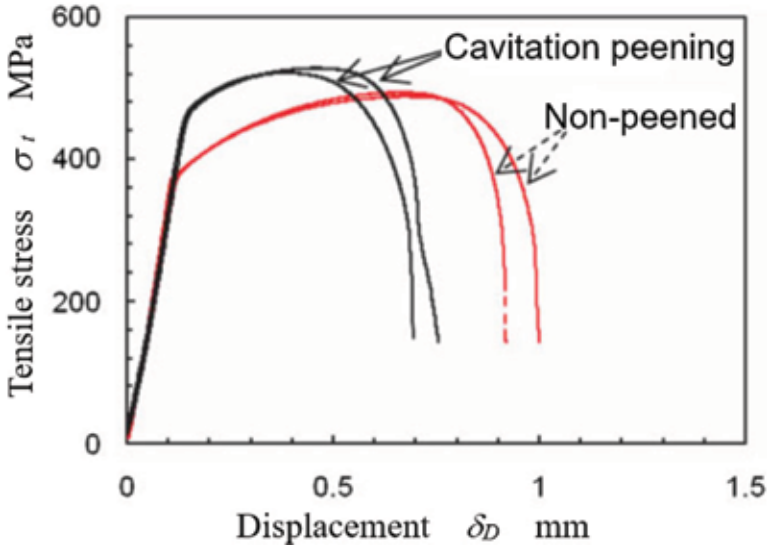


FIGURE 33 Improvement in the yield stress of electrical sheet ($d = 2$ mm, $p_1 = 30$ MPa, $p_2 = 0.42$ MPa)

MPa, and it increased to 453 MPa after cavitation peening. Thus, an improvement in yield stress of the sheet steel by about 22 % was obtained by cavitation peening.

In the test mentioned above the cross-sectional area was relatively small, thus, the improvement in yield stress was verified by a conventional tensile test. It is difficult, however, to demonstrate improvements in the yield stress of mechanically treated surfaces, such as those treated by shot peening, laser peening, cavitation peening, etc., as the thickness of the modified layer is relatively thin compared with the bulk material. Also, the effect of the compressive residual stress in a specimen with a small test area is difficult using a conventional tensile test. In this case, inverse analysis of the yield stress using an indentation test is very useful, as mechanical properties, such as the yield stress, Young's modulus, the residual stress, and the work hardening coefficient in a local area can all be evaluated [128-138]. For example, in order to investigate the mechanism for the improvement in the fatigue strength of stainless steel by cavitation peening, the yield stress of a cavitation peened layer was investigated using inverse analysis and an indentation test. This showed that the yield stress could be improved from 300 MPa to 500 ± 60 MPa by cavitation peening [139]. This is reasonable, considering the relationship between the yield stress and the fatigue strength of medium strength steels [139]. It can be concluded that cavitation peening improves the yield stress of metallic materials and that inverse analysis and

an indentation test can be used to investigate the yield stress of a modified layer at the surface.

5.5. Suppression of Hydrogen Embrittlement

Since Johnson [140] found that hydrogen has a remarkable effect in iron, many researchers have been investigating hydrogen embrittlement [141-143]. In order to use hydrogen for one of our basic energy sources, we need to be able to suppress hydrogen embrittlement. It has been shown that hydrogen concentrates around crack tips where the hydrostatic stress is a maximum [144, 145]; thus, the introduction of compressive residual stress might reduce hydrogen embrittlement. However, it has been reported that the conventional way to introduce compressive residual stress, i.e., shot peening, did not suppress hydrogen embrittlement and, moreover, was detrimental [146]. Another report revealed that shot peening plays a dual role in hydrogen embrittlement [147], in that shot peening reduces the hydrogen diffusion coefficient and also enhances hydrogen induced cracking. These effects might be due to increases in the surface roughness and/or the dislocation density induced by shot peening. In the case of cavitation peening, the surface roughness scarcely increases, as there are no collisions between solid materials. Cavitation peening can introduce compressive residual stress while relieving the micro strain as mentioned above [100]. Therefore, cavitation peening can suppress hydrogen embrittlement.

In order to demonstrate the suppression of hydrogen embrittlement by cavitation peening, Fig. 34 shows the crack length $2a$ as a function of the number of cycles N for non-peened and cavitation peened specimens with and without hydrogen charging [148]. Test specimens made of stainless steel SUS316L with a precrack were tested using a plate bending fatigue tester with bending stress $\sigma_a = 300$ MPa. The specimens were treated using a cavitating jet in air with $d = 1$ mm and $p_1 = 30$ MPa. The number of cycles to failure N_f of the non-peened specimen was 4.11×10^4 for the specimen charged with hydrogen and 6.70×10^4 for the specimen not charged with hydrogen. Thus, N_f of the non-peened specimen charged with hydrogen was considerably reduced, as the secondary cracks of the specimen combined, as shown in the figure on the upper left-hand side of Fig. 34. On the other hand, N_f of the cavitation peened specimen was 1.23×10^5 for the specimen charged with hydrogen and 1.20×10^5 for the specimen not charged with hydrogen. For both cavitation peened specimens, the cracks grew stably as shown in the figure on the upper right-hand side of Fig. 34, and N_f of the specimens with and without hydrogen are nearly equal. The N_f of the specimen charged with hydrogen increased by a factor of about three after cavitation peening. Consequently, cavitation peening can suppress hydrogen embrittlement in stainless steel SUS316L.

In order to investigate the mechanism for the suppression of hydrogen embrittlement by cavitation peening, hydrogen invasion of a specimen was measured by thermal desorption analysis (TDA) using gas chromatography [149] and secondary ion mass spectrometry (SIMS) [150]. In both these

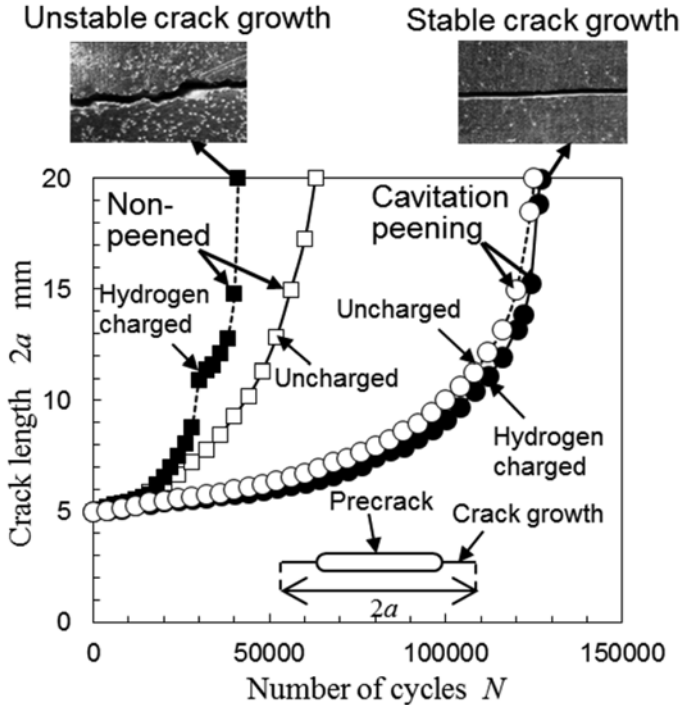


FIGURE 34
Suppression of hydrogen embrittlement in stainless steel by cavitating in AIR ($d = 1$ mm, $p_1 = 30$ MPa)

reports, the material under test was stainless steel SUS316L, the same as the material used for the data in Fig. 34. Cavitation peened and non-peened specimens were charged with hydrogen by cathodic electro-charging. By evaluating hydrogen invasion by both TDA and SIMS, suppression of hydrogen invasion by cavitation peening was found to be proportional to the amount of compressive residual stress with respect to depth introduced by cavitation peening [149, 150]. As is well known, compressive residual stress causes crack closure which mitigates the stress concentration around the crack tip [151, 152], that is, the main mechanism for the suppression of hydrogen embrittlement by cavitation peening is the mitigation of hydrogen invasion by introducing compressive residual stress.

5.6. Improvement of Resistance to Delayed Fracture

Delayed fracture [153] is also a big problem for safety and the reliability of high strength steel [154]. Since a key factor in delayed fracture is the presence of hydrogen [155-157], cavitation peening can improve the resistance to delayed fracture. Figure 35 shows the relationship between the tensile stress

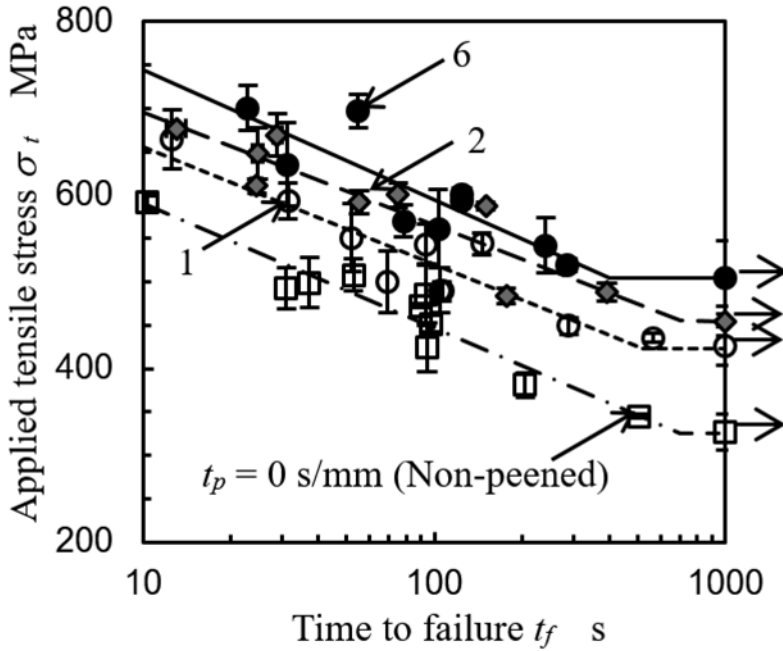


FIGURE 35

Improvement in the delayed fracture resistance on chrome molybdenum steel bolt ($d = 2$ mm, $p_1 = 30$ MPa, $p_2 = 0.42$ MPa)

s_t applied to a steel bolt and the time to failure t_f [158]. The bolt under test was a commercially available M8 with a 1.25 mm pitch screw made of chrome molybdenum steel. In order to examine the delayed fracture of a bolt associated with hydrogen, a delayed fracture test was conducted under a constant load after hydrogen charging. In order to concentrate the cavitation peening on the bolt surface, the cavitation conditions chosen were $d = 2$ mm, $p_1 = 30$ MPa, and $p_2 = 0.42$ MPa. The threshold stress for delayed fracture s_{th} is defined as the tensile stress σ_t at which the bolt had not fractured within 24 hours. Without hydrogen charging, the bolt fractured at $\sigma_t \approx 910$ MPa. On the other hand, σ_{th} of a non-peened bolt with hydrogen charging was 327 ± 22 MPa. When the bolt was treated by cavitation peening, σ_{th} with hydrogen charging was 426 ± 21 MPa for $t_p = 1$ s/mm, 455 ± 11 MPa for $t_p = 2$ s/mm and 505 ± 42 MPa for $t_p = 6$ s/mm, demonstrating that the threshold stress increases with increasing processing time per unit length. The residual stress at the bottom of the thread was -269 ± 55 MPa for the non-peened bolt, -205 ± 2 MPa for $t_p = 1$ s/mm, -187 ± 6 MPa for $t_p = 2$ s/mm and -198 ± 6 MPa for $t_p = 6$ s/mm, showing that cavitation peening improves the resistance to delayed fracture by introducing compressive residual stress.

6. CONCLUSIONS

In order to obtain better peening effects without damage to the surface by cavitation peening, the principal and key factors of cavitation peening were reviewed, especially in order to understand the differences between cavitation peening and water jet peening. In this review, cavitation peening refers to peening methods that use cavitation impacts, and water jet peening refers to peening methods using impacts due to small water masses and/or shot in the water jet. The key points can be summarized as follows:

1. For cavitation peening at a constant downstream pressure, a cavitating jet with a relatively low injection pressure and a large nozzle is better than that with high injection pressure and a small nozzle.
2. Cavitation peening and water jet peening can be classified according to Eq. (23) which is modified from Eq. (10).

$$s_{opt} = 1.8d\sigma^{-0.6} \quad (23)$$

3. Here, s_{opt} is the distance from the nozzle to the treated surface, d is the nozzle diameter and σ is the cavitation number. When the distance is smaller than s_{opt} in Eq. (23), the peening mechanism is water jet peening, while if it is larger it is cavitation peening.
4. The key factors in cavitation peening, which affect the aggressive intensity of the cavitating jet, are the type of cavitating jet, the standoff distance, the nozzle geometry, the cavitation number, the processing speed, the nozzle throat diameter, the injection pressure, the tank pressure, the water temperature and the depth of water above the nozzle.
5. The relative aggressive intensity of a cavitating jet can be estimated from a reference intensity by substituting the cavitation number, nozzle throat diameter and injection pressure in Eq. (20).
6. Cavitation peening is beneficial for the mechanical treatment of surfaces in order to improve the fatigue strength, the fretting fatigue strength, and the yield strength, and for suppressing hydrogen embrittlement and improving the resistance to delayed fracture.

NOMENCLATURES

- | | |
|-----|-----------------------|
| a | crack length |
| c | proportional constant |

c_1	constant
c_2	ratio of frequency of weak impacts to intense impacts
c_d	discharge coefficient
d	nozzle throat diameter
D_n	torque
da/dN	crack propagation rate
d_e	equivalent nozzle diameter
d_w	water depth
E_R	erosion rate
f	shedding frequency of cavitation cloud
$f(\sigma)$	function of cavitation number
h	arc height
h_{sat1}	saturation arc height caused by weak impacts
h_{sat2}	saturation arc height caused by intense impacts
I_{cav}	aggressive intensity of cavitating jet
$I_{cav\ est}$	estimated value of aggressive intensity of cavitating jet
$I_{cav\ ref}$	aggressive intensity of cavitating jet at reference condition
K_n	function depending on the shape of the nozzle and/or test section
L	size
L_{cav}	cavitating length
N	number of cycles
N_f	number of cycles to failure
n	power law exponent
n_d	power law exponent for nozzle throat diameter
n_p	power law exponent for injection pressure
P	applied load
p	pressure
p_1	upstream pressure of nozzle, injection pressure
p_2	downstream pressure of nozzle
$p_{2\ opt}$	optimum downstream pressure of nozzle
p_{max}	maximum pressure at jet center
p_v	vapor pressure
p_v'	pseudo vapor pressure
ref	subscript for reference conditions
s	standoff distance from nozzle to target surface
S_t	Strouhal number
s_{opt}	optimum standoff distance
t	exposure time to the jet
t_D	development time of a bubble
t_f	time to failure
t_p	processing time per unit length
T_w	water temperature
U	velocity at nozzle exit
V_{cav}	volume of cavitation

$V_{B\ max}$	maximum volume of the bubble
v	flow velocity
w	maximum diameter of cavitating jet
ΔK	stress intensity factor range
ΔK_{th}	threshold stress intensity factor range
Δm	mass loss
Δp	pressure difference
δ	depth from surface
δ_D	displacement
σ	cavitation number
σ_a	amplitude of bending stress
σ_R	residual stress
σ_s	shift of cavitation number
σ_t	tensile stress
σ_{th}	threshold stress of delayed fracture
σ_y	yield stress
ρ	radius of curvature
ρ_L	density of liquid

7. ACKNOWLEDGEMENTS

The author's work on cavitation peening was partly supported by the Japanese Society for the Promotion of Science 17H03138, Ministry of Economy, Trade and Industry, and the Osawa Scientific Studies Grants Foundation.

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