Sustainability of compressive residual stress on the processing time of water jet peening using ultrasonic power

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Abstract

Water jet peening (WJP) is used as a stress improvement method and a countermeasure against stress corrosion cracking (SCC) in the internal structures of reactors in nuclear power plants. However, when residual stress is converted to compressive stress and applied to the specimen surface as a countermeasure against SCC, voids and cracks can easily form inside the specimen because of the increase in the pressure applied to the surface during WJP processing. Recently, multifunction cavitation (MFC), which is WJP using ultrasonic power, has been developed as an alternative to WJP. In MFC-processed low-alloy steel, when the residual stress is converted to compressive stress as an SCC countermeasure, voids and cracks do not form inside the specimen. In this study, to further improve current MFC techniques, the surface modification of low-alloy steel (Cr–Mo steel) was further investigated using 1200 W ultrasonic power. In MFC using 1200 W ultrasonic power, the corrosion resistance, compressive residual stress, and strength of the specimens were improved when the processing time was 10 min; however, decarburization occurred at longer processing times, causing these characteristics to worsen. The decarburization that occurs at high ultrasonic outputs may be caused by an increase in the water temperature and of the heating of the specimen surface. The evaluation of the surfaces of specimens processed for 30 min at ultrasonic powers of up to 1200 W revealed that
decarburization does not occur on the specimen surface as long as the power does not exceed 720 W.

Keywords: Materials science, Mechanical engineering

1. Introduction

Water jet peening (WJP) [1, 2, 3, 4, 5] is commonly used as a countermeasure against stress corrosion cracking (SCC) in the internal structure of furnaces in nuclear power plants and as a stress improvement technique to preserve these structures. Cavitation jets occur in the WJP process when high-pressure water containing fine microscopic cavitation bubbles is injected. Cavitation bubbles are repeatedly produced in a turbulent flow within the surrounding water and generates an extremely large impact force together with sound. The cavitation bubbles shrink at high speed due to the surrounding pressure, generate large shock waves and microjets, and then disappear. WJP is a processing method that induces a small amount of plastic deformation of a material surface by this impact pressure. When a minute portion on the material surface is stretched and plastically deformed, the deformed portion is elastically restrained from the surroundings, so that compressive residual stress is imparted to the impacted region. Therefore, when WJP is applied to a material surface where tensile residual stress remains, it is possible to change from tensile residual stress to compressive residual stress. Three factors are commonly considered to be causes of SCC: the material, the environment, and stress. As a countermeasure against stress, this technology prevents the generation of SCC by converting the tensile residual stress generated by welding and surface grinding to compressive residual stress [2]. However, it has been reported that when the residual stress is converted to compressive stress, voids and cracks tend to form inside the specimen because of the increase in the pressure applied to the surface with WJP [3, 4, 5].

Recently, Yoshimura et al. developed multifunction cavitation (MFC) [6, 7, 8] processing, which is a cavitation technique that applies ultrasonic waves to WJP. It is possible to reform a material surface with MFC in the same way as with WJP. However, the cavitation bubble temperature with MFC is different; the sound pressure due to ultrasonication exceeds the breaking threshold before the bubbles from the WJ nozzle collide with the material surface. Therefore, high-temperature, high-pressure cavitation that produces hot spots occurs by repeated isothermal expansion and adiabatic compression. If a cavitation bubble begins to collapse when it is approaching the specimen surface, the volume of the bubble decreases, and a microjet is formed that impacts the surface of the object. The impact force is large because of the high temperature (several thousand degrees Celsius) and high pressure (about 1000 MPa) inside the bubble.
In contrast to WJP processing, previous studies have shown that when MFC processing is applied to low-alloy steel with the compressive residual stress converted as an SCC countermeasure, voids and cracks do not form inside the specimen [4, 5]. In addition to improving the strength of the specimen surface, MFC has also been reported to improve the corrosion resistance [9]. Various properties of MFC-processed materials [6, 7, 8] have been reported to date [4, 5, 7, 8, 9, 10]. In this study, to further improve current MFC techniques, the surface modification of low-alloy (Cr–Mo) steel was investigated using an ultrasonic power of 1200 W, which is higher than the value of 225 W used in a similar previous report [4].

2. Experimental

The material used for these tests was Cr-Mo steel (SCM435), which is a structural machine steel with the chemical composition shown in Table 1.

Round bar (rod) specimens were heated at 860 °C as a solution treatment, followed by quenching. Tempering was performed at 600 °C. The specimens were subsequently cut into rectangular specimens with dimensions of 100 × 100 × 3 mm³.

Fig. 1 shows the MFC processing equipment, in which an ultrasonic transducer (WD-1200-28T, Honda Electronics Co., Ltd) irradiates the water jet as it emerges from the nozzle.

A swirl flow nozzle [10] was used at the tip of the WJ nozzle to increase the number and size of cavitation bubbles. The discharge pressure of the pump was about 35 MPa, the nozzle diameter was 0.8 mm, and the distance between the nozzle and the specimen was assumed to be 65 mm, which is considered as the second peak [11] with the highest cavitation-bubble density. Processing was performed in a tank (JIS-SUS310S) with dimensions of 41 × 44 × 60 cm³. The output of the ultrasonic transducer was varied from 240 to 1200 W, and the nominal drive frequency was 28 kHz. The considered processing times were 2, 10, 20, and 30 min.

Residual stress was measured using an X-ray stress analyzer (MSF-3M, Rigaku Co., Ltd) with the peak top method after measurement of the (211) strain between lattice planes with the Cr Kα line generated at 30 kV-10 mA. A region of 1 × 1 cm² was measured. Tensile residual stress was taken to be positive and compressive residual stress was taken to be negative. The corrosion resistance was evaluated by measuring the surface potential using a Kelvin probe force microscopy (KFM) system equipped

| Table 1. Chemical composition of the Cr-Mo steel. |
|-----------------------------------------------|
| C     | Si  | Mn | P    | Ni  | Cr   | Mo  | Cu   | Fe  |
| 0.37  | 0.32| 0.81| 0.014| 0.012| 0.95 | 0.15| 0.14 | Bal. |

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with a multi-compatible miniature probe microscope (AFM5200S Hitachi High-Tech Sciences Co., Ltd). The measurement area was 100 × 100 μm². Micro Vickers hardness tests were performed at room temperature under a load of 1.96 N for a loading duration of 10 s. The hardness measurements were averaged for eight values after the minimum and maximum of ten measurements were removed. In addition, hardness measurements near the surface after processing were performed after slight mechanical polishing to remove oxide film and peening marks formed during processing. Measurement of residual stress and KFM, hardness was performed in the area where peening was most performed in cavitation bubbles. The amount of dissolved oxygen (DO) in the water where cavitation occurred was measured 30 min after cavitation had begun using a portable DO meter (OM-71, Horiba, Ltd.).

3. Results and discussion

Photographs of the specimen surface after MFC processing (Ultrasonic output: 1200 W) are shown in Fig. 2. To specify the position being peened, oil-based ink was applied to the specimen surface prior to processing. Observation of the peeling state of the ink after processing indicated that the ink peeling range was expanded by ultrasonic irradiation and the peening distribution was affected. Grinding scratches were observed on the surface of specimens with a processing time of 2 min, but such grinding flaws were nearly absent for specimens processed for longer than 10 min. Furthermore, the specimen surface became bright yellow after processing for longer than 20 min, and 30 min of processing generated a large amount of the bright yellow color products on the specimen surface. This phenomenon indicates
that rust abnormally formed on the specimen surface when processing was applied for longer than 20 min.

To evaluate the effectiveness of the MFC processing (Ultrasonic output: 1200 W), the residual stress was measured, and the results are shown in Fig. 3. Residual stress measurements were made in the dashed box, of which part is highly peening, shown

![Fig. 2. Change in surface morphology of (a) an abraded specimen and specimens treated by MFC for (b) 2 min, (c) 10 min, (d) 20 min, and (e) 30 min.](image)

![Fig. 3. Residual stress plotted against processing time.](image)

-400  -300  -200  -100   0   100   200   300

Residual stress [MPa]  Processing time [min]

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in Fig. 2. To ascertain the effects of MFC processing, high tensile residual stress was imparted to the specimen surface by applying grinding before processing. Tensile residual stress (179 MPa) was applied to the abraded material in the direction parallel to grinding, and it was confirmed that a nonzero compressive residual stress (−158 MPa) was present in the direction perpendicular to grinding. After each specimen was processed by MFC, the residual stress was measured in the direction to which the tensile residual stress was applied. The tensile residual stress was improved to compressive residual stress when MFC processing was applied 2 min. Furthermore, when the processing time was extended to 30 min, the compressive residual stress gradually decreased with increasing processing time after reaching a maximum value of −358 MPa at 10 min. Compressive residual stress occurs when the surface is compressed by the cavitation collapse pressure and deformation in the lateral direction is elastically constrained by the surroundings. The improvement to the compressive residual stress with MFC processing was similar to that obtained with WJP processing; however, in the case of MFC, the stress began to decrease at a processing time of 20 min.

The KFM results, which give an indication of the surface condition of the specimens, are shown in Fig. 4. KFM measurements were made in the dashed box shown in Fig. 2. Because KFM involves the detection of the displacement of a cantilever due to the electrostatic attractive force on the specimen surface, it is possible to obtain the work function difference (contact potential difference) between the needle and the specimen surface.

![Graph showing surface potential plotted against processing time.](https://doi.org/10.1016/j.heliyon.2018.e00747)

Fig. 4. Surface potential plotted against processing time.
The electrostatic force received by the probe from the fixed charge distributed on the specimen surface can be detected using KFM to obtain the surface potential. The surface potential measurement is affected by surface roughness, so the surface of each measured specimen was mirror polished before processing. The surface potential of the abraded specimen prior to MFC treatment was 234 mV. The surface potential of the specimens increased with increasing processing time until reaching a maximum value of 648 mV at 10 min and subsequently decreased with further increases to the processing time. At the longest considered processing time of 30 min, the surface potential of the treated specimen was lower than that of the abraded untreated specimen. It has been reported that because selective oxidation occurs during MFC processing, it is likely that an oxide film forms on the specimen surface [9]. This surface potential increase is related to the formation of the oxide film on the surface. However, it is not known why the surface potential and compressive residual stress decrease with increasing processing time beyond a certain point. To clarify this cause, the microstructure of the specimen cross section was observed.

Fig. 5 shows optical microscopy (OM) images of the cross section of specimens after abrasion and after MFC treatment for each considered processing time.

The grain size in the depth direction from the surface after processing at each considered processing duration did not change greatly from case to case. However, in the vicinity of the surface, when the processing time was prolonged, it was observed that the color of the surface became white, with the color change progressing from the surface inward. Regarding the color of the crystal grains in the OM photograph, black grains are pearlite, and white grains are ferrite. Thus, the whitening of the specimens shows that MFC processing causes pearlite existing near the processed surface to disappear.

Fig. 6 shows scanning electron microscopy (SEM) images of the specimen surface after MFC processing for 30 min. As shown in Fig. 6(a), the shape of the ferrite grains did not change, but the lamellar structure of the pearlite became bent and kinked bands formed; this structure is very similar to the cold-rolled texture.
Moreover, many other flat surfaces, such as ferrite, were observed in other parts of the pearlite. The SEM image shown in Fig. 6(b) is an enlarged image of a flat surface observed in the pearlite on the specimen surface. Among such flat surfaces, cementite was present in slightly lower concentrations after processing than before. Furthermore, in the vicinity of the grain boundary, the small amount of remaining cementite indicates that more cementite disappears when the processing time is prolonged. Similar phenomena have been confirmed by the observation of other regions. The likely cause of this is considered to be diffusion decarburization. In general decarburization, oxygen in the atmosphere and carbon in the steel combine on the steel surface during heating. This is caused by carbon scattering from the steel in the form of carbon monoxide and carbon dioxide gas. The occurrence of decarburization affects the hardness of the specimen surface.

To confirm the occurrence of decarburization, the hardness of the processed specimen surface after MFC treatment at each considered processing time was measured. The hardness of the abraded surface before MFC treatment was 246 HV. The hardness after processing for 2, 10, 20, and 30 min was 264, 266, 244, and 215 HV, respectively. The increase in the hardness of the specimens after processing for 2 and 10 min is considered to be due to the plastic deformation amount that the surface is compressed by the cavitation collapse pressure and stretched in the lateral direction. The contrasting decrease in the hardness after 20 and 30 min of processing time is considered to be due to the decrease in the amount of cementite contained in the pearlite.

In decarburization, when iron is oxidized by heating in an oxygen atmosphere, the carbon content in the material decreases. Fig. 7 shows the measured water temperature and DO concentrations in the water tank during MFC processing at 1200 W along with the corresponding results at 225 W obtained in a previous study [5]. When the ultrasonic output was high, the water temperature increased, and the
DO concentration decreased, as shown in Fig. 7(a) and (b), respectively. The increase in the water temperature is attributable to the pressurization of the water by a high-pressure pump, which produces energy in the water flow that is partially converted into thermal energy. Regarding the reduction of the DO concentration in the water, selective oxidation occurs because of the increase in the surface temperature that occurred after 2 or 10 min of processing, causing the Cr concentration on the specimen surface to increase. It is considered that the DO concentration decreased because the Cr combined with the DO and formed an oxide film. After MFC processing for at least 20 min, the oxidized film was destroyed by cavitation bubbles, and the surface became deficient in Cr. It is thus considered that the concentration of iron oxide (rust) on the surface increased as a result of the binding of DO and iron due to the Cr deficiency on the surface.

The reason for the decrease in the carbon concentration on the surface after processing is considered to be as follows. As shown in Fig. 5, the color of the surface of the specimen processed for 2 min was slightly whiter than that of the unprocessed abraded specimen. It is considered that the DO and carbon on the specimen surface combined and escaped in the form of carbon monoxide or carbon dioxide gas, causing a reduction in the amount of cementite and an increase in the amount of ferrite on the surface.

When diffusion decarburization occurs, the surface hardness decreases, and change fatigue strength or property; thus, the relationship between the output power of the ultrasonic waves and the occurrence of decarburization was examined by measuring the residual stress at different ultrasonic powers.

Fig. 8 shows the residual stress measurement results of specimens processed for 2 and 30 min at various ultrasonic outputs. The residual stress of each specimen after processing was measured in the grinding direction along which the tensile residual stress was applied. After 2 min of MFC treatment at various ultrasonic powers, the residual stress was approximately −335 MPa regardless of the ultrasonic power. The residual stresses after 30 min of processing at ultrasonic powers of 240–480 W were
the same as those for the specimens processed for 2 min. However, for 30 min of processing at 720 W, the residual stress peaked at $-375$ MPa. When the ultrasonic power was increased to 960 W or more, the residual stress after 30 min of processing decreased. The reason for this behavior is considered to be the impact of the ultrasonic power on the occurrence of decarburization. At a low ultrasonic power, the occurrence of decarburization is low, which causes a low residual stress.

General decarburization occurs at the steel surface when the steel is at a temperature of approximately 727–1227 °C, which is the two-phase temperature range of ferrite and austenite. Additionally, within the decarburization temperature range, the decarburized layer grows most rapidly at approximately 800 °C [12], and the heating or cooling rate is also affected. In MFC processing, the increase in surface temperature during processing depends on the magnitude of the ultrasonic output. Furthermore, diffusion decarburization occurs after MFC processing, so it is considered that the temperature inside the bubbles is above approximately 727 °C. Because there are various factors in the MFC processing conditions that can affect these results, further factors must be investigated in future studies to fully elucidate the mechanisms at play here. Finally, when MFC is used as a countermeasure against SCC, decarburization occurs on the specimen surface, necessitating the consideration of the ultrasonic conditions.

For the Cr–Mo steel used in this study, it was revealed that when MFC treatment was performed, if the ultrasonic power was 720 W or less, decarburization did not occur and the specimen experienced compressive residual stress. When applying...
MFC processing to various materials, it is necessary to evaluate the surface condition of the specimens after processing.

4. Conclusions

When applying MFC at an ultrasonic output of 1200 W, it was found that the corrosion resistance, compressive residual stress, and strength of Cr–Mo steel specimens were optimized by using a processing time of 10 min. However, all three of these factors decreased with increased processing time beyond this point. The reason for the deterioration of these characteristics is the occurrence of decarburization on the specimen surface. When the output power of the ultrasonic waves is high, the DO concentration decreases, the water temperature increases, and the temperature of the specimen surface increases, and these factors are thought to contribute to the occurrence of decarburization. Through the evaluation of the surfaces of specimens processed for 30 min at ultrasonic outputs of up to 1200 W, it was revealed that decarburization did not occur at powers of 720 W or less. When MFC technology is used, the amount of DO in the water, the water temperature, and the temperature of the specimen surface are affected by MFC processing, necessitating the evaluation of the specimen surface after MFC processing.

Declarations

Author contribution statement

Masataka Ijiri: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Toshihiko Yoshimura: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.
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