Original Article
ISSN (Online): 2456-8651

International Journal of Engineering Science Technologies
March-April 2024 8(2), 31–44

PRECISE PEENING OF NI-CR-MO STEEL BY ENERGY-INTENSIVE MULTIFUNCTION CAVITATION IN CONJUNCTION WITH POSITRON IRRADIATION

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Received 03 March 2024
Accepted 05 April 2024
Published 19 April 2024

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DOI 10.29121/IJOEST.v8.i2.2024.589

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

The peening characteristics of Ni-Cr-Mo steel were investigated using energy-intensive multifunction cavitation using positron irradiation (PMEI-MFC). It was found that PMEI-MFC in a high magnetic field, multifunction cavitation in a high magnetic field (MEI-MFC), laser irradiation ultrasonic cavitation (LMEI-UC), and a combination of positron and laser irradiation ultrasonic cavitation in a high magnetic field (PLMEI-UC) could reduce the surface roughness of unprocessed metal specimens by approximately one-fourth. Furthermore, the PMEI-MFC method greatly improved the residual stress at the metal surface by up to 1155 MPa. Each of these technologies was found to increase the surface hardness although the PLM-WJC and PMEI-MFC processes, which generated high temperatures, produced smaller increases than were obtained using the LMEI-MFC technique. This difference is attributed to recrystallization, which eliminated work hardening at the outermost metal surface during processing using positrons. The data also indicate that the PMEI-MFC method was able to both smooth and flatten the metal surface. This research demonstrates an approach to precision peening that can reduce surface roughness while imparting high compressive residual stress.

Keywords: Positron Excitation High Magnetic Field Energy-Intensive Multifunction Cavitation, Precise Peening, Ni-Cr-Mo Steel

1. INTRODUCTION

Cavitation is a physical phenomenon in which bubbles appear and disappear in a short period of time due to pressure differences in a liquid flow. Originally, cavitation was observed in fluid processing machinery such as pumps, as well as in valves and piping in hydraulic systems, and was thought to be an undesirable process that could lead to erosion. More recently, the effective utilization of

How to cite this article (APA): Yoshimura, T., Yamamoto, S., and Watanabe, H. (2024). Precise Peening of Ni-Cr-Mo Steel by Energy-Intensive Multifunction Cavitation in Conjunction with Positron Irradiation. *International Journal of Engineering Science Technologies, 8*(2), 31–44. doi: 10.29121/IJOEST.v8.i2.2024.589

cavitation has been examined. An example is ultrasonic cavitation (UC), in which ultrasonic vibrations are transmitted through water or organic solvents such that variations in sound pressure induce the isothermal expansion and adiabatic compression of bubble nuclei originally present in the liquid and having diameters of several micrometers. Upon compression, the internal temperatures of these bubble can increase to over 2000 K, creating hot spots that promote chemical reactions Gompf et al. (1997). UC technology has a wide range of potential applications in surface treatment processes and more generally in the fields of chemistry, biotechnology, and medicine Gendanken (2004), Suslick et al. (1991), Nagata et al. (1992), Yeung et al. (1993).

Water jet cavitation (WJC) is a related process that can impart compressive residual stress to the surfaces of various materials. During WJC, very high pressures (more than 10,000 atm) are generated on the basis of microjet collapse near the material surface and can produce residual stresses that increase the mechanical strength of the specimen being treated Yoshimura et al. (2007). The WJC technique has been used as a countermeasure against stress corrosion cracking in nuclear power plants Saitou et al. (2003). However, the surface area that can be treated using a WJC system is limited to that corresponding to the jet position of the nozzle. Therefore, even if the nozzle is moved while applying the compressive residual stress, the processing speed will be relatively slow.

Multifunction cavitation (MFC) techniques that combine the properties of both WJC and UC have also been developed Yoshimura et al. (2016), Yoshimura et al. (2018), Yoshimura (2020), and the concept of combining a magnetic field with MFC (M-MFC) while using narrow nozzles has additionally been demonstrated in previous studies Yoshimura et al. (2022). In the latter process, a magnetic field is applied to the MFC system, leading to the generation of electrically charged gas bubbles. This process has been found to change the molecular structure of polyamide 11 specimens. In the MFC process, the thermal decomposition of water vapor produces electrically charged bubbles containing ions such as O^+, H^+ and OH^+. In the case that a magnetic field is applied to these bubbles, the Lorentz force acts in the liquid flow direction, promoting collisions between the bubbles Yoshimura et al. (2022a) that generate new bubbles so as to improve the material processing ability of the system. The authors also previously developed an energy-intensive MFC (EI-MFC) technology Yoshimura et al. (2021a) that concentrates the ultrasonic irradiation generated in the vicinity of WJC bubbles, together with an MEI-MFC apparatus that applies a magnetic field to the EI-MFC process Yoshimura et al. (2021a). A new metal processing technique referred to as laser-assisted EI-MFC (LMEI-MFC) was also demonstrated in prior studies Yoshimura et al. (2021b), Yoshimura et al. (2022b). This system combines an MFC system with irradiation by laser light in conjunction with the application of a strong magnetic field to promote multiphoton ionization within bubbles Yoshimura (2023a), Yoshimura et al. (2023b).

The positron (e^+) is the antiparticle to the electron, having the same mass and absolute value of charge but opposite sign. Radioactive isotopes such as ^{22}Na and ^{58}Co are commonly used as positron sources in the laboratory. Because positrons have a positive charge, they move away from the positive ions that make up metal crystals. Therefore, positrons (also known as Bloch positrons) moving through crystals containing conduction electrons serve as the primary annihilation partners for ions. Positrons that reach sites lacking cations, such as atomic vacancies, microvoids (three-dimensional vacancy clusters less than 1 nm in size), voids or surfaces, are captured and annihilated. Various applications utilizing this positron annihilation phenomenon have been proposed Ishii (1993), Puska & Mieminen (1994), Asoka-Kumar et al. (1994), Dupasquier & Mills (1995).

On this basis, a new technique has been developed in which small cavitation bubbles generated by a narrow nozzle are irradiated with positrons, referred to as positron excitation LMEI-MFC (PLMEI-MFC) Yoshimura et al. (2023c). As positrons pass through the walls of the bubbles in this apparatus, they react with the electrons in the bubbles, resulting in annihilation events between the electron-positron pairs that generate gamma rays. This process increases the concentration of energy inside the bubbles.

In the present study, PLMEI-MFC, PMEI-MFC (comprising positron/laser excitation concentrated energy MFC under a strong magnetic field), PLMEI-UC or LMEI-UC (positron/laser excitation with UC under a strong magnetic field) were applied to Ni-Cr-Mo steel (SNCM420) in an attempt to obtain precision peening and increase the strength of the material while reducing surface roughness.

2. MATERIALS AND METHODS

Figure 1 shows a diagram of the PLMEI-MFC apparatus, in which five ultrasonic transducers are installed in a tapered heptagonal tank with a WJ nozzle situated in the center of the tank. The diameter of the nozzle used in this work was 0.2 mm, the WJ pressure was 22 MPa and the flow rate was 195 mL/min. The instrumentation employed in previous work Yoshimura et al. (2021a), Yoshimura et al. (2022b) incorporated a nozzle having a diameter of 0.8 mm along with a flow rate of 7 L/min to generate a swirling flow based on the inflow of surrounding water Yoshimura et al. (2018). The use of a nozzle diameter of 0.8 mm and a flow rate of 7 L/min increased both the WJ bubble diameter and the microjet impact pressure. These conditions improved the material handling properties of the system but required pure water to be drained from the bottom of the water tank through a large diameter hole. Because this rapid flow of pure water had to be replenished, the system was modified so that tap water was continuously fed into the apparatus using a high-pressure pump. As a result of these changes, the pump noise level increased and the effect of impurities in the untreated tap water became an issue. In contrast, employing a nozzle diameter of 0.2 mm and a flow rate on the order of 195 mL/min allowed the continuous application of ultrasound, magnetic and laser energy to the bubbles over long periods of time.

A magnetic field was obtained by incorporating a total of 34 highly powerful neodymium permanent magnets (NS167, Sangyo Supply Co., Ltd., 20 mm × 7 mm × 20 mm) into the apparatus Yoshimura et al. (2022b), Yoshimura et al. (2023b). These were installed both inside and outside the upper water tank containing the ultrasonic transducer, near the nozzle outlet. An additional 38 magnets were placed inside and outside the lower water tank, near the base. This apparatus was used to carry out LMEI-UC (that is, to impart concentrated ultrasound irradiation to bubble nuclei in a magnetic field together with laser excitation), PLMEI-UC (the same technique as above but with the addition of positron irradiation), PLM-WJC (WJC in a magnetic field with excitation by both positrons and a laser), LMEI-MFC (using laser irradiation with MFC in a magnetic field) and PLMEI-MFC (MFC in a magnetic field with excitation by positrons and a laser). It should be noted that the so-called EI technique employed herein involved the concentration of ultrasound energy around the WJ. The purpose of conducting the present LMEI-UC and PLMEI-UC tests was to investigate the extent to which bubble nuclei having sizes of several micrometers originally present in pure water could be activated.

Figure 1

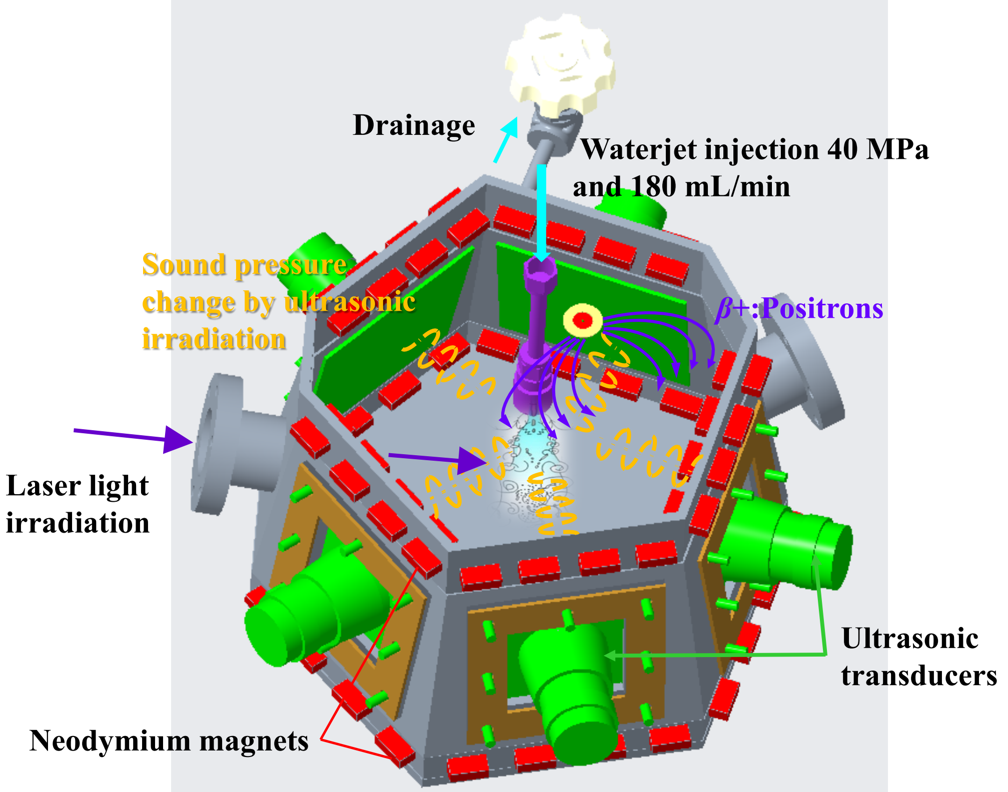


Figure 1 Diagram of the Apparatus Used for Energy-Intensive Multifunction Cavitation in a Strong Magnetic Field with Laser Light and Positron Excitation.

Figure 2 presents a photographic image of the entire apparatus. In this system, pure water (having a specific resistance of 15 MΩ) stored in a container was dispensed via a high-pressure pump (maximum pump pressure: 40 MPa, maximum pump flow rate: 200 mL/min, L.TEX8731, L. TEX Co., Ltd.). The resulting high-pressure water was ejected from a 0.2 mm nozzle installed in the center of the tank. The jet pressure was measured using a pressure gauge while the flow rate was confirmed with a flow meter attached to the pump. During the PLMEI-MFC, PLM-WJC and PLMEI-UC trials, a ^{22}Na source was placed above the water tank so that positrons traveled from the top of the water tank to the water surface. Those magnets immersed in the pure water were covered with a waterproof film to prevent the nickel plating on the magnet surfaces from peeling off.

Table 1 summarizes the chemical composition of the Ni-Cr-Mo steel used in this research. During these experiments, the surface temperature of each specimen was increased due to the heat generated by the large number of ultra-high temperature bubbles applied to the surface during the collapse of the microjet. The extent to which the temperature was increased was determined by the balance between heat release to the surrounding water and heat transfer into the interior of the specimen. Therefore, as the heat capacity or thermal conductivity of the specimen was decreased, the surface temperature was increased and thinner specimens would therefore exhibit a greater rise in surface temperature. Furthermore, as the thermal resistance values of the back and side surfaces of the specimen were increased, the surface temperatures also increased. For this reason, two pieces of double-sided tape (NytacTM, adhesive strength: 02, NW-50, Nichiban Co., Ltd.) were attached to the backs and sides of the test pieces to increase the thermal resistance and suppress heat dissipation.

Figure 2

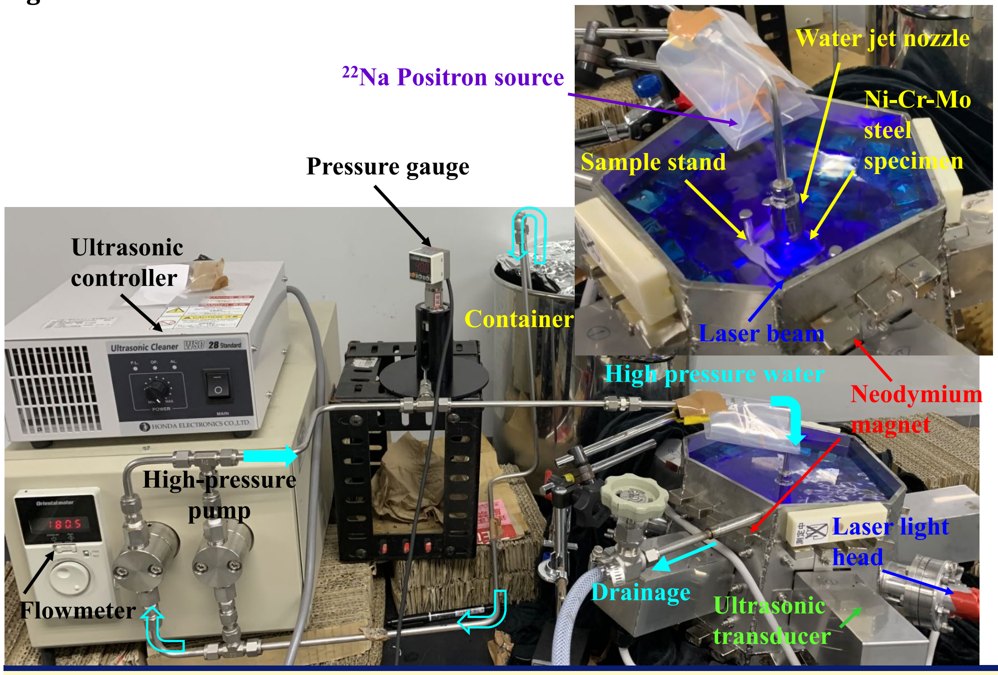


Figure 2 Photographic Images of the Equipment Used for Energy-Intensive Multifunction Cavitation in a Strong Magnetic Field with Positron and Laser Light Excitation.

Table 1

Table 1 Chemical Composition of the SNCM420 Steel Specimens Used in this Work (mass%).

C	Si	Mn	P	Cu	Ni	Cr	Mo	Fe
0.21	0.21	0.60	0.011	0.12	1.65	0.54	0.15	Bal.

To ensure stable positioning of the neodymium magnets, the number of magnets employed in this work was partly reduced compared with the quantity used in previous work Yoshimura et al. (2023c). This setup was used during the M-MFC, PLM-WJC, LMEI-MFC and PLMEI-MFC trials. Under these conditions, the MFC processing involved both a Coulomb force and a bell-shaped cavitation jet. In addition, ultrasonic radiation was applied using a pentagonal geometry to prevent the radiation sources from directly facing one another (as occurs in the EI-MFC device) and to avoid sound pressure interference or cancellation Yoshimura et al. (2021a). The 72 neodymium magnets were arranged in a heptagonal geometry based on previous work using the MEI-MFC Yoshimura et al. (2022b) and LMEI-MFC techniques Yoshimura et al. (2023b). As a result of this arrangement, a strong magnetic field of more than 10 mT was present in the region between the WJ nozzle exit and the cavitation cloud. Monitoring of the photons emitted from the MFC multi-bubbles generated in this device indicated that the laser irradiation resulted in multiphoton excitation and increased the valence numbers of ions inside the bubbles Yoshimura et al. (2023b).

After cavitation processing, residual stress on the surface of each specimen was evaluated using a portable X-ray device (PULSTEC μ-X360s, Pulstech Industries Co., Ltd.). The surface morphology and roughness of each sample were evaluated by three-dimensional laser microscopy (OLS5100, Olympus Corporation). Micro Vickers hardness measurements were also performed (HM-210B, Mitutoyo Corporation).

A ^{22}Na positron source (NA351) provided by the Japan Radioisotope Association and consisting of a disc-shaped isotope specimen sandwiched between two 7.5 µm Kapton® films was installed at the upper surface of the water tank. This type of source emits positrons in essentially all directions and is commonly used to analyze voids in certain materials based on positron annihilation. When ^{22}Na decays to ^{22}Ne, a positron is emitted according to the reaction ${}^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + e^{+} + \nu_e$ (neutrino). In the present work, as positrons were emitted in the 4π direction, the β^+ rays were affected by the magnetic field and bent toward the liquid such that they came into contact with cavitation bubbles rising to the surface. The β^+ decay of ^{22}Na has a half-life of 2.6 years, a β^+ ray energy of 546 keV and a γ ray energy of 1.275 MeV. The radioactive output of the apparatus was 1 MBq and so no special radiation control provisions were required.

3. RESULTS AND DISCUSSIONS

3.1. COMPRESSIVE RESIDUAL STRESS ASSESSMENTS

Figure 3 summarizes the compressive residual stress values determined before and after PLM-WJC processing. A high residual tensile stress of 733 MPa was present at the milled surface prior to machining whereas the compressive residual stress after machining was -453 MPa. Hence, there was a stress change of 1186 MPa. This significant change in residual stress is attributed to the effect of attaching the insulating tape to the 1 mm thick test piece, which had a minimal heat capacity. This result was similar to those obtained in prior trials using Cr-Mo steel Yoshimura et al. (2023c).

Figure 3

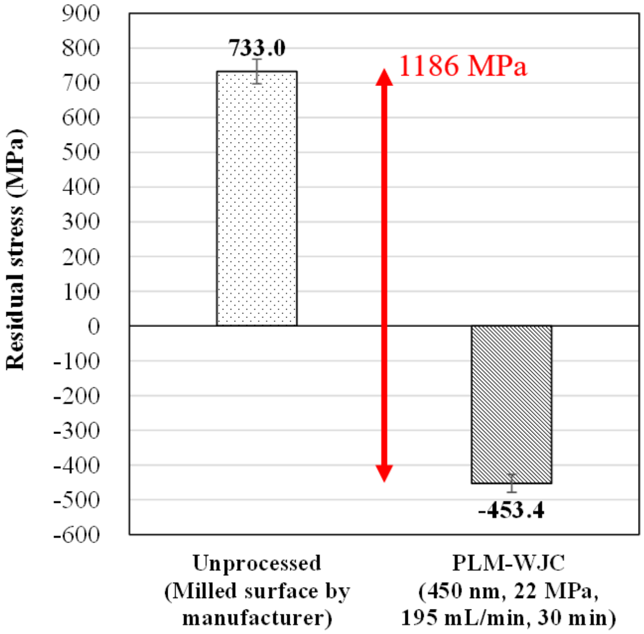


Figure 3 Residual Stress in a 1 mm Thick Steel Specimen Before and After PLM-WJC Processing with Insulation of the Sample (the error bars: standard deviation).

Photoionization is a physical process in which one or more electrons (also referred to as photoelectrons) are ejected from an atom, ion, or molecule by an incident photon. This phenomenon is responsible for the photoelectric effect in metals. Note that, in the case that the photon energy is lower than the electron binding energy, the photon will be absorbed or scattered, and no photoionization will occur. Therefore, not all photons that collide with atoms/ions contribute to photoionization. Recently, it has become possible to generate closely aligned waves of light that can induce a phenomenon known as multiphoton ionization (MPI). In this process, multiple photons, each with energy below the ionization threshold, can combine to ionize the atom. This enhanced cavitation treatment technique, based on using laser light excitation Yoshimura et al. (2023b), was applied to Ni-Cr-Mo steel and was found to improve the strength and functionality of the metal. The MPI phenomenon is believed to have occurred within the bubbles during the LMEI-MFC, PLMEI-UC, LMEI-UC and PLM-WJC trials in this study.

The stress value obtained following an MEI-MFC treatment of a specimen is provided in Figure 4. This process, which included the effect of a magnetic field, changed the residual stress by 1073 MPa. This technique was therefore somewhat less effective than the PLM-WJC process (Figure 3), possibly because the latter used positrons together with a laser whereas the MEI-MFC apparatus added a magnetic field and concentrated ultrasonic energy.

Figure 4

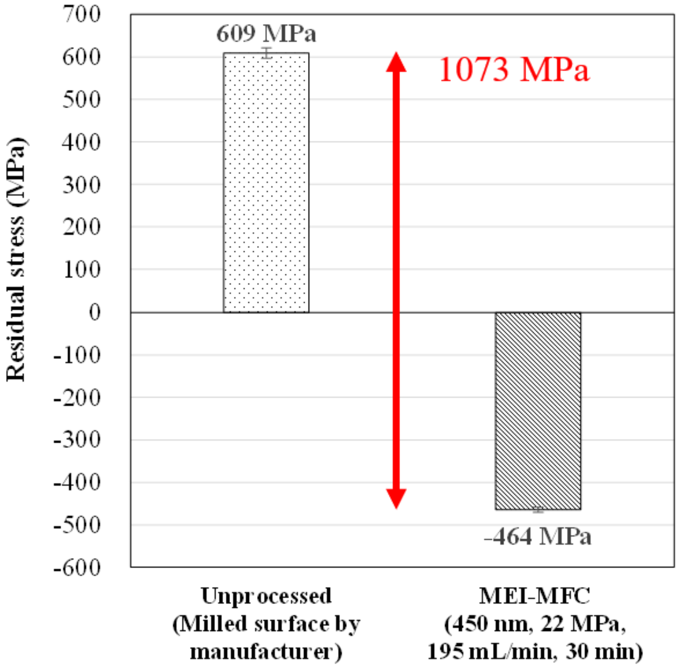
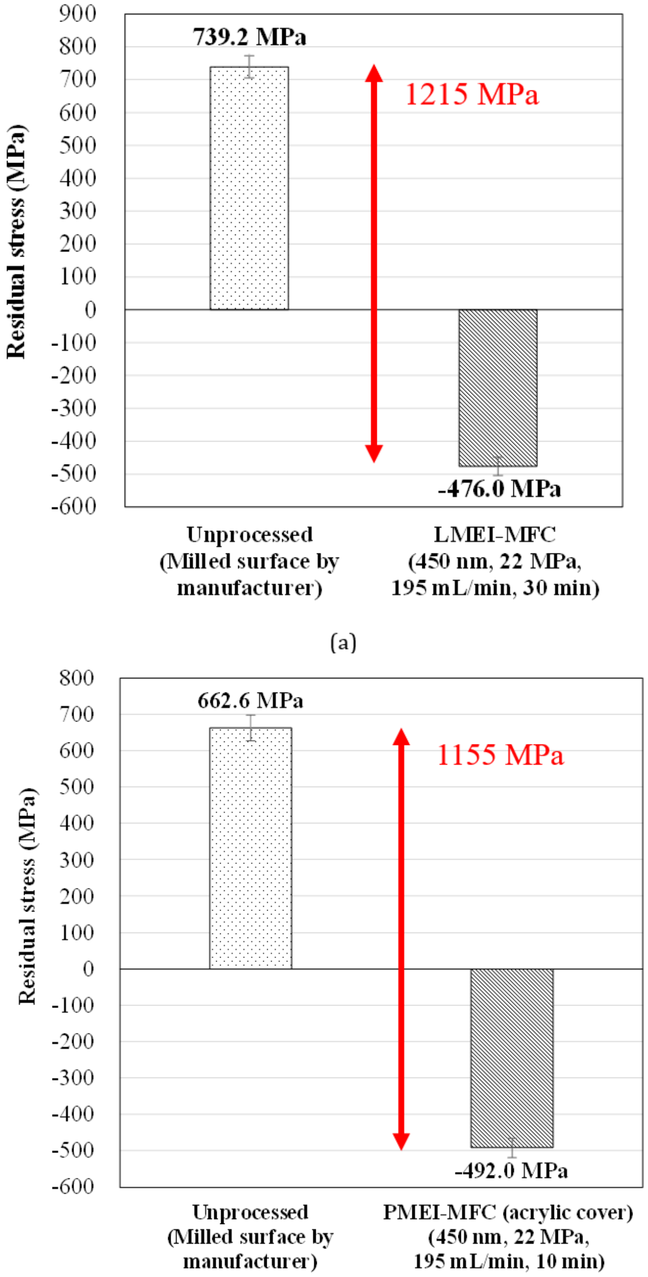


Figure 4 Residual Stress in a 1 mm Thick Steel Specimen Before and After MEI-MFC Processing with Insulation of the Sample.

Figure 5 shows the compressive residual stress values before and after processing with the LMEI-MFC and PMEI-MFC methods. The stress improvements obtained from these techniques were 1215 and 1155 MPa, respectively. The change in stress induced by the LMEI-MFC is ascribed to the effect of multiphoton ions. The LMEI-MFC treatment is thought have had a greater effect than the MEI-MFC method because the former added a laser to the magnetic field effect. The data in Figure 3 and Figure 5 (b) demonstrate the effect of incorporating positrons into the processing system. In the case that a positron enters a bubble, it immediately undergoes an annihilation reaction with an electron, producing two γ ray photons and releasing energy ($e^+ + e^- \rightarrow 2\gamma + 1.02$ MeV). This reaction is believed to have increased the cavitation energy during the processing of metal specimens in this work.

During the initial trials, the experiments had short durations because strong gravitational waves were generated as a consequence of the positron energy. An acrylic lid was later attached to the top of the tank as a safety precaution so that the processing time could be increased to 30 min (generating the data shown in Figure 3). Even so, the PLMEI-MFC trial producing the results summarized in Figure 5 (b) was only 10 min in duration Yoshimura et al. (2023c).

Figure 5



(a)

(b)

Figure 5 Residual Stress in a 1 mm Thick Steel Specimen Before and After (a) LMEI-MFC and (b) PMEI-MFC (with an acrylic cover) Processing with Insulation of the Sample.

Figure 6 shows the extents of stress improvement obtained with the LMEI-UC and PLMEI-UC processes, which were able to process large sample areas. The associated changes in stress were 32 and 82 MPa. Similar to the case of WJC with positron irradiation, the exposure of bubble nuclei to positrons in these experiments caused the positron pairs to be annihilated in the bubble nuclei, increasing both the energy imparted to the metal and the stress value.

Figure 6

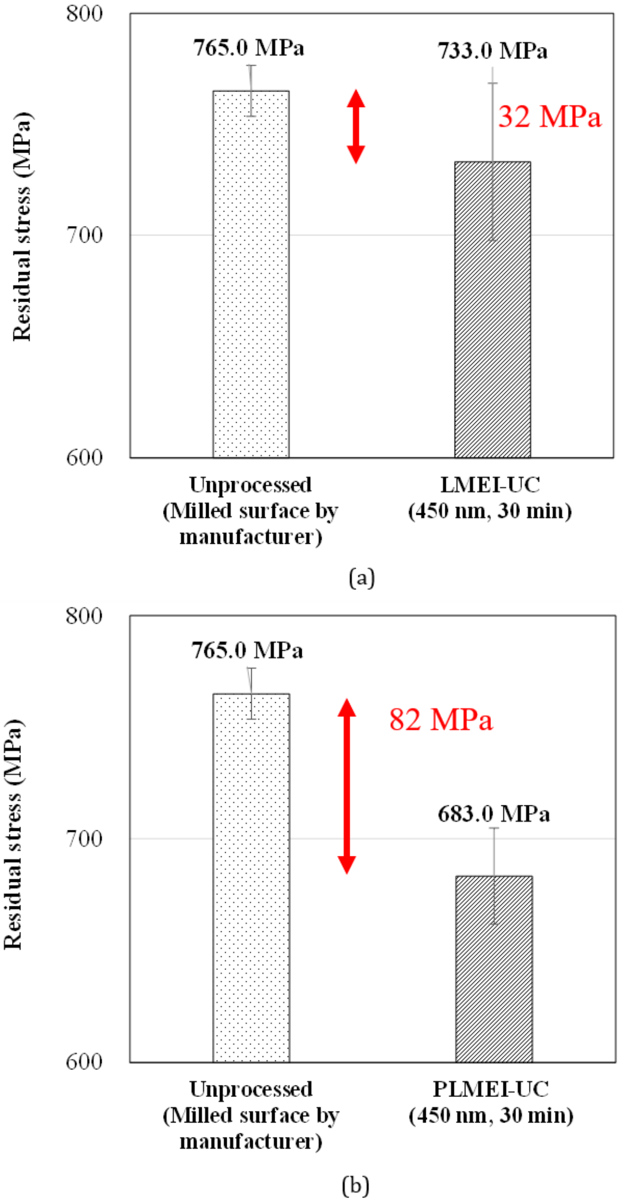
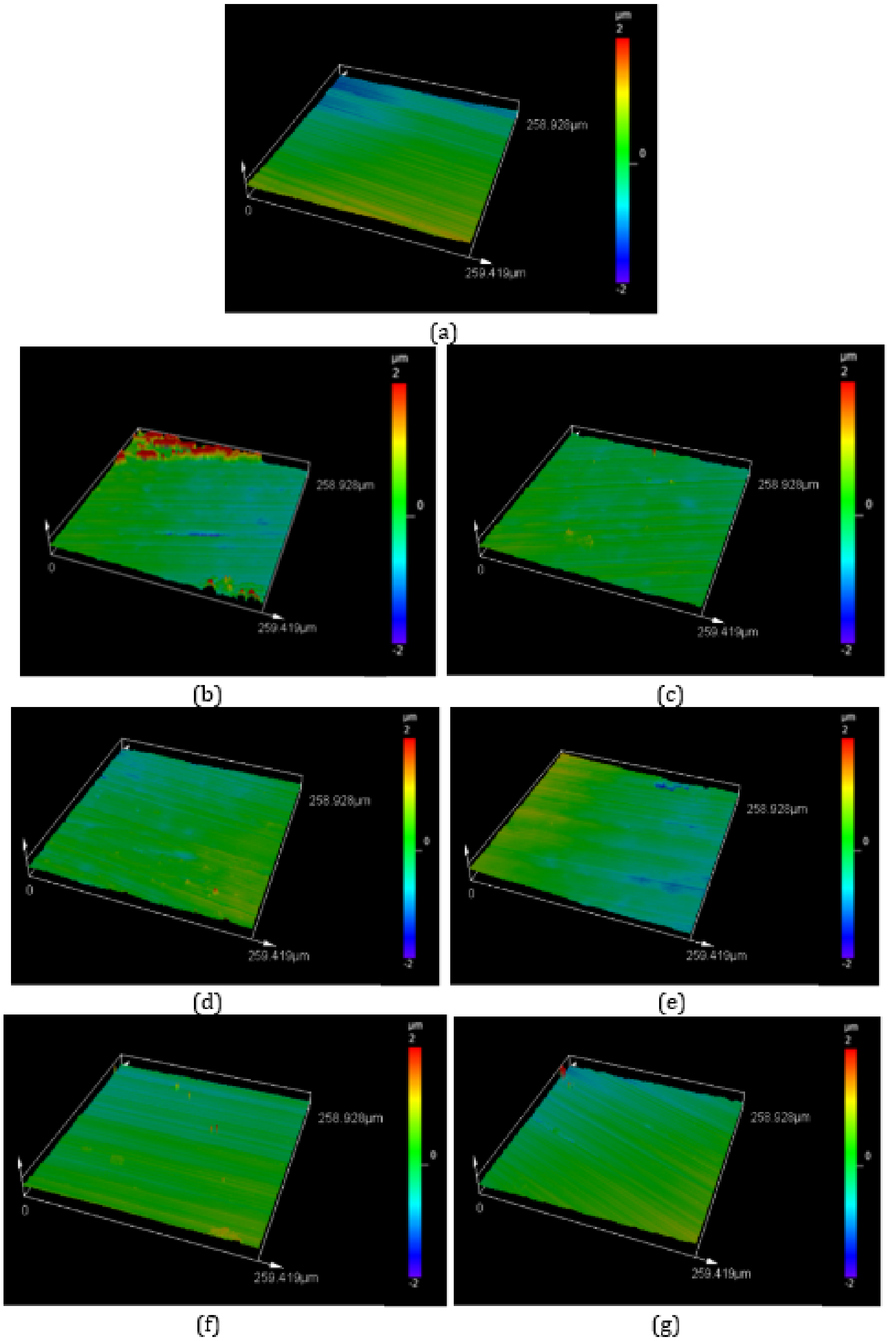


Figure 6 Residual Stress in a 1 mm Thick Steel Specimen Before and After (a) LMEI-UC and (b) PLMEI-UC Processing with Insulation of the Sample.

3.2. SURFACE OBSERVATION USING A LASER MICROSCOPE

Figure 7 provides laser microscopy images showing the morphologies of various metal specimens following the different cavitation processes. It should be noted that the roughened appearance of the PLM-WJC specimen is attributed to the formation of rust. This rusting is ascribed to the lack of any improvement in the corrosion resistance of the metal, which normally is imparted by MFC, as a consequence of the absence of concentrated ultrasonic waves. The PMEI-MFC specimen shows flattened machining marks and reduced surface roughness compared with the untreated material. During this process, the surface was raised to a high temperature by exposure to concentrated energy. The surface was therefore smoothed as a consequence of microjet processing at elevated temperatures and pressures.

Figure 7



(a)

(b) (c)

(d) (e)

(f) (g)

Figure 7 Surface Morphologies of Steel Specimens as Observed by Laser Microscopy. These Images Show Specimens (a) Before Processing and After Processing with (b) PLM-WJC (30 min, 195 mL/min), (c) PMEI-MFC (10 min, Acrylic Cover, 195 mL/min), (d) LMEI-MFC (30 min), (e) MEI-MFC (30 min), (f) LMEI-UC (30 min) and (g) PLMEI-UC (30 min).

3.3. SURFACE ROUGHNESS MEASUREMENTS

Figure 8 presents the roughness data acquired following the application of various cavitation treatments. The surface roughness values were reduced from 0.4 µm to approximately 0.1 µm following the PMEI-MFC, MEI-MFC, PLMEI-UC and LMEI-UC experiments. This represents an exceptionally smooth surface for SCM400 Cr-Mo steel specimens. Processing at 22 MPa with a flow rate of 195 mL/min provided a superior peening effect compared with treatment at 40 MPa with a flow of 180 mL/min. The surface conditions were evidently affected by both nozzle pressure and flow rate, and these factors should therefore be the subject of future study. The lack of ultrasonic irradiation during the PLM-WJC treatment seems to have limited the extent of flattening. In addition, a greater degree of flattening was obtained using the MEI-MFC method compared with the LMEI-MFC process.

Figure 8

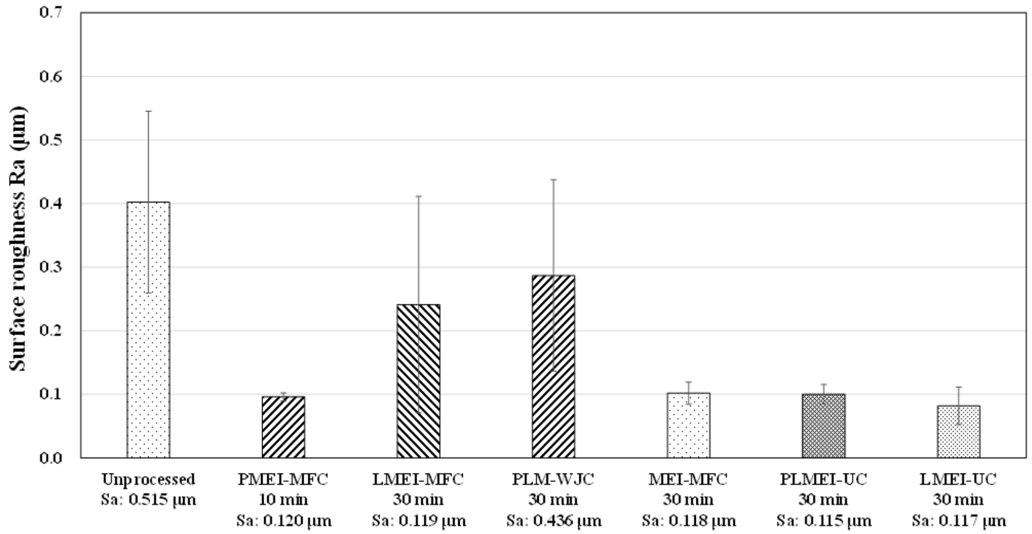


Figure 8 Surface Roughness Values of 1 mm Thick Steel Specimens after Processing at a Flow Rate of 190 mL/min with Insulation, as Determined by Laser Microscopy.

3.4. VICKERS HARDNESS TESTS

Figure 9 compares the micro-Vickers hardness data of specimens subjected to various processing conditions. The MEI-MFC process can be seen to have generated a slightly increased hardness. In addition, the hardness value obtained from the LMEI-MFC treatment was approximately 100 HV higher than that of the untreated material. This result suggests that the valence values of ions in the bubbles were increased due to the MPI effect. Hence, the surface processing effect of the microjets was enhanced as a result of increased collisions between bubbles. In the case of the PLM-WJC and PMEI-MFC treatments, both of which produced high compressive residual stress values, the extent of work hardening was reduced as a consequence of the high-temperature, high-pressure processing using positrons. It is thought that surface recrystallization of the metal was also induced.

Figure 9

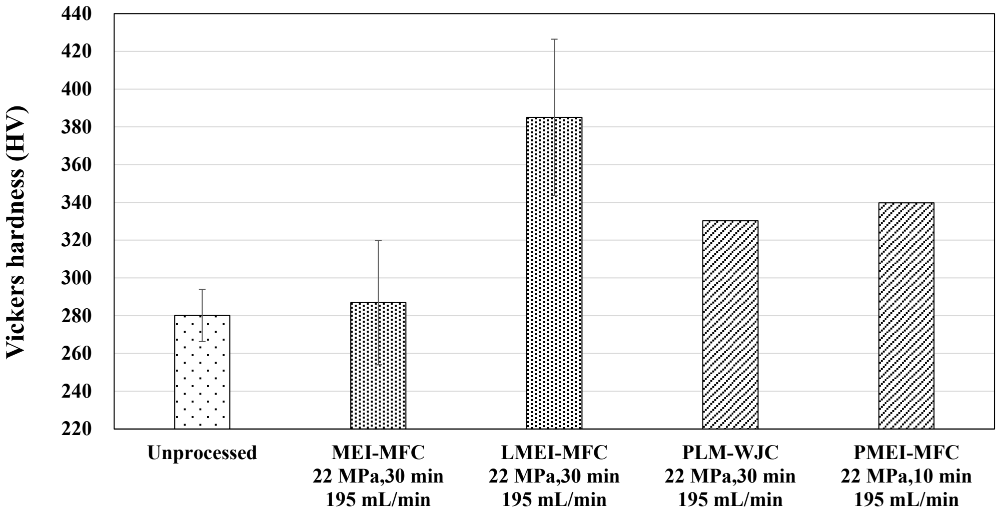


Figure 9 Surface Hardness Values of 1 mm Thick Steel Specimens After Processing at a Flow Rate of 195 mL/min with Insulation, as Measured Using a Vickers Hardness Tester.

4. CONCLUSIONS AND RECOMMENDATIONS

The peening characteristics of Ni-Cr-Mo steel were investigated using a variety of processing techniques. The PMEI-MFC, MEI-MFC, LMEI-UC and PLMEI-UC methods were able to reduce the surface roughness of the unprocessed material by approximately 25%. In addition, the newly developed PMEI-MFC technology was found to significantly improve the stress value of the metal, by approximately 1155 MPa. Each cavitation process modified the surface hardness of the metal, but this increase was not as pronounced following treatment with the PLM-WJC and PMEI-MFC methods, both of which were high-temperature processes, compared with the LMEI-MFC technique. This difference is attributed to recrystallization of the metal during processing using positrons, which eliminated work hardening at the outermost surface. Compared with the PLMEI-MFC process, the PMEI-MFC technique without laser irradiation provided a greater decrease in surface roughness along with a significant flattening effect. The data obtained from the present work confirm that precision peening together with reductions in surface roughness and the production of high compressive residual stress can all be achieved using various cavitation methods.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

REFERENCES

Asoka-Kumar, P., Lynn, K. G., & Welch, D. O. (1994). Characterization of Defects in Si and SiO2−Si Using Positrons. Journal of Applied Physics, 76(9), 4935-4982. https://doi.org/10.1063/1.357207

Dupasquier, A., & Mills, A. P. (1995). Positron Spectroscopy of Solid, IOS Press, Amsterdam.

Gendanken, A. (2004). Using Sonochemistry for the Fabrication of Nanomaterials. Ultrason. Sonochem, 11(2), 47-55. https://doi.org/10.1016/j.ultsonch.2004.01.037

Gompf, B., Gunther, R., Nick, G., Pecha, R., & Eisenmenger, W. (1997). Resolving Sonoluminescence Pulse Width with Time-Correlated Single Photon Counting. Physical Review Letters, 79, 1405-1408. https://doi.org/10.1103/PhysRevLett.79.1405

Ishii, A. (1993). Positrons at Metallic Surfaces. Trans. Tech. Pub., Aedermannsdorf. https://doi.org/10.4028/b-5U4gLx

Nagata, Y., Watanabe, Y., Fujita, S., Dohmaru, T., & Taniguchi, S. (1992). Formation of Colloidal Silver in Water by Ultrasonic Irradiation. Journal of the Chemical Society, Chemical Communications, 21, 1620-1622. https://doi.org/10.1039/c39920001620

Puska, M. J., & Mieminen R. M. (1994). Theory of Positrons in Solids and on Solid Surfaces. Reviews of Modern Physics, 66, 841-897. https://doi.org/10.1103/RevModPhys.66.841

Saitou, N., Enomoto, K., Kurosawa, K., Morinaka, R., Hayashi, E., Ishikawa, T., & Yoshimura, T. (2003). Development of Water Jet Peening Technique for Reactor Internal Components of Nuclear Power Plant. J. Jet. Flow Eng., 20(1), 4-12.

Suslick, K. S., Choe, S. B., Clochowise, A. D., & Grinstaff, M. W. (1991). Sonochemical Synthesis of Amorphous Iron. Nature, 354, 414-416. https://doi.org/10.1038/353414a0

Yeung, S., Hobson, T., Biggs, S., & Grieser, F. (1993). Formation of Gold Sols using Ultrasound. Journal of the Chemical Society, Chemical Communications, 4, 378-379. https://doi.org/10.1039/c39930000378

Yoshimura, T. (2023a). Cavitation Fusion by Energy-Intensive Multifunction Cavitation in a Strong Magnetic Field with Laser Light Excitation. International Journal of Engineering Science Technologies, 7(2), 1-16. https://doi.org/10.29121/ijoest.v7.i2.2023.492

Yoshimura, T. (Inventor). (2020, March, 17). Assignee: Sanyo-Onoda City public university, Patent no. US, 10(590), 966 B2, Date of Patent, Method for Generating Mechanical and Electrochemical Cavitation, Method for Changing Geometric Shape and Electrochemical Properties of Substance Surface, Method for Peeling off Rare Metal, Mechanical and Electrochemical Cavitation Generator, and Method for Generating Nuclear Fusion Reaction of Deuterium, International PCT Pub. No.: W02016/136656, Pet Care Trust. No: PCT/JP2016/055016.

Yoshimura, T., Fujinaga, S., & Ijiri, M. (2022a). Modifying Resin Viscoelasticity by Multifunction Cavitation Processing in a Magnetic Field. International Journal of Engineering Science Technologies, 6(4), 1-10. https://doi.org/10.29121/ijoest.v6.i4.2022.364

Yoshimura, T., Ijiri, M., & Sato, K. (2021b). Estimation of Nuclear Fusion Requirements in Bubbles during Ultra-High-Pressure, Ultra-High-Temperature Cavitation Promoted by Magnetic Field. International Journal of Engineering Science Technologies, 5(6), 102-115. https://doi.org/10.29121/ijoest.v5.i6.2021.257

Yoshimura, T., Noda, T., & Ijiri, M. (2023b). Processing of Magnesium Alloy by Energy-Intensive Multifunction Cavitation in a Strong Magnetic Field with Laser Light Excitation and Associated Sonoluminescence. Results in

Materials, 18(100391), 1-11. https://doi.org/10.1016/j.rinma.2023.100391

Yoshimura, T., Sugae, Y., Ogi, T., Kato, F., & Ijiri, M. (2021a). Development of Energy Intensive Multifunction Cavitation Technology and its Application to the Surface Modification of the Ni-Based Columnar Crystal Superalloy CM186LC. Heliyon, 7(12), 1-11. https://doi.org/10.1016/j.heliyon.2021.e08572

Yoshimura, T., Tanaka, K., & Ijiri, M. (2018). Nanolevel Surface Processing of Fine Particles by Waterjet Cavitation and Multifunction Cavitation to Improve the Photocatalytic Properties of Titanium Oxide. Intech open access, Open Access Peer-reviewed Chapter 4, Cavitation - Selected Issues, 43-72. http://dx.doi.org/10.5772/intechopen.79530

Yoshimura, T., Tanaka, K., & Yoshinaga, N. (2018). Nano-Level Material Processing by Multifunction Cavitation. Nanoscience & Nanotechnology-Asia, 8(1), 41-54. https://doi.org/10.2174/2210681206666160922164202

Yoshimura, T., Tanaka, K., Yoshinaga, N. (2016). Development of Mechanical-Electrochemical Cavitation Technology. Journal of Jet Flow Eng, 32(1), 10-17.

Yoshimura, T., Waseda, K., Sato, K., & Takarayama, N. (2007). Development of Water Jet Peening in Air and Application to Fretting Fatigue. J. Jet Flow Eng., 24(1), 11-17.

Yoshimura, T., Watanabe, S., Ijiri, M., & Ota, S. (2022b), Development of Processing Technology using Extremely High Concentration Cavitation Energy by Strong Magnetic Field. Results in Materials, 14 (100289), 1-11. https://doi.org/10.1016/j.rinma.2022.100289

Yoshimura, T., Yamamoto, S., & Watanabe, H. (2023c). Precise Peening of Cr-Mo Steel Using Energy-Intensive Multifunction Cavitation in Conjunction with a Narrow Nozzle and Positron Irradiation. Results in Materials, 20 100463, 1-9. https://doi.org/10.1016/j.rinma.2023.100463