



Study on the Effect of Cryogenic Pretreatment-Based Abrasive Water Jet Surface Modification on the Surface Integrity of 7075 Aluminum Alloy

Xiujie Yue¹, Yeran Gao¹, Youqiang Wang^{1,*} and Ping Zhang^{2,*}

¹ College of Mechanical and Automotive Engineering, Qingdao University of Technology, Qingdao 266520, China

² College of Mechanical and Power Engineering, Guangdong Ocean University, Zhanjiang 524088, China

Abstract

This study investigates the influence of a deep cryogenic treatment-abrasive water jet (DCT-AWJ) composite surface modification process on the surface integrity of 7075 aluminum alloy, with single abrasive water jet (AWJ) treatment as the control. Surface morphology, phase composition, residual stress, and microhardness were characterized by scanning electron microscopy (SEM), X-ray diffraction (XRD), and microhardness testing. Under AWJ treatment, the surface roughness increases with jet pressure (0.864, 1.082, and 1.325 μm at 5, 10, and 15 MPa). Under DCT-AWJ treatment, the roughness decreases with increasing cryogenic treatment time but increases with jet pressure, and it is lower than that obtained by AWJ alone at the same pressure. All samples exhibit α -Al and η -MgZn₂ diffraction peaks, with α -Al peaks at $2\theta = 38.5^\circ$, 44.7° , 65.1° , and 78.2° ,

indicating no significant phase transformation; the α -Al peaks broaden with increasing jet pressure and cryogenic duration. Both treatments introduce compressive residual stress, whose surface and maximum values increase with jet pressure and, for DCT-AWJ, with cryogenic duration, reaching -563 MPa and -1165 MPa, respectively. The surface microhardness after AWJ treatment increases with jet pressure (184.71, 185.78, and 189.41 HV), whereas DCT-AWJ treatment raises it to 202.87 HV and deepens the hardened layer to 264.63 μm . These results indicate that cryogenic pretreatment enhances the surface integrity of 7075 aluminum alloy relative to AWJ treatment alone.

Keywords: 7075 aluminum alloy, deep cryogenic treatment, abrasive water jet, surface roughness, surface quality, residual stress, microhardness.

1 Introduction

Deep cryogenic treatment, also known as ultra-low temperature treatment, involves subjecting metallic materials to extremely low temperatures (typically around -196°C using liquid nitrogen as the



Submitted: 17 July 2025

Revised: 27 September 2025

Accepted: 27 July 2026

Published: 12 October 2026

Vol. 2, No. 1, 2027.

10.62762/JMDE.2025.826186

*Corresponding authors:

✉ Youqiang Wang
wyq1970301@126.com

✉ Ping Zhang
zpqdhxy@126.com

Citation

Yue, X., Gao, Y., Wang, Y., & Zhang, P. (2026). Study on the Effect of Cryogenic Pretreatment-Based Abrasive Water Jet Surface Modification on the Surface Integrity of 7075 Aluminum Alloy. *Journal of Materials Durability and Engineering*, 2(1), 1–13.



© 2026 by the Authors. Published by Institute of Central Computation and Knowledge. This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>).

cooling medium) [1–4]. This process enhances the overall properties of metallic materials by improving their microstructure. As a typical high-strength Al-Zn-Mg-Cu alloy, 7075 aluminum alloy exhibits high specific strength and stiffness, excellent toughness, lightweight properties, good corrosion resistance, and machinability. Therefore, it finds widespread application in the aerospace industry, primarily as a structural material [5, 7, 8]. With increasing demands for lightweight and integrated structures, aluminum alloy components are trending toward larger dimensions, thinner walls, and greater geometric complexity, and higher requirements for dimensional accuracy and microstructural uniformity. However, in the face of increasingly complex service environments, structural materials still face the risk of fatigue fracture. Moreover, due to the relatively soft nature of aluminum alloys, adhesion tends to occur during machining and joining processes, rendering the material susceptible to damage, thereby affecting machining accuracy and surface quality [6, 9–11]. Meanwhile, the low melting point of aluminum alloys and their strong chemical affinity for tool materials promotes the formation of built-up edge and adhesion layers on the tool, which accelerates tool wear. Deep cryogenic treatment not only promotes grain refinement in aluminum alloys but also improves the distribution of second-phase particles, thereby significantly enhancing their mechanical properties and machinability [12, 13]. With the increasing performance demands on aluminum alloys in engineering applications, research on deep cryogenic treatment for enhancing aluminum alloy properties has become particularly important.

Numerous experts and scholars have conducted studies on the effects of deep cryogenic treatment on the mechanical properties and microstructural evolution mechanisms of metallic materials. Through experimental investigations and theoretical analyses, they have revealed the underlying mechanisms by which deep cryogenic treatment influences grain refinement, phase transformation behavior, and dislocation movement in metals [14–18]. Dong et al. [14] investigated the effects of deep cryogenic treatment on the microstructure, precipitates, and mechanical behavior of extruded Mg-2Nd-4Zn alloy. The results showed that deep cryogenic treatment promoted grain refinement and the precipitation of second-phase particles, while significantly enhancing the ductility of the alloy. Abbasi-Baharanchi et al. [15] studied the effects of severe plastic deformation

at cryogenic temperatures on the microstructure, mechanical, and tribological properties of 6061 aluminum alloy. The samples subjected to cryogenic deformation followed by aging exhibited significantly enhanced tensile strength, hardness, and wear resistance. This improvement was attributed to the formation of nanoscale β' and β'' precipitates, facilitated by high dislocation density and rapid atomic diffusion along dislocations. Yang et al. [16] proposed a novel aging process combining deep cryogenic treatment and ultrasonic vibration. By comparing untreated samples, cryogenically treated samples, and those subjected to deep cryogenic treatment plus ultrasonic vibration, they systematically revealed the microstructure, mechanical properties, stress relaxation mechanisms, and strengthening mechanisms of HR-2 austenitic stainless steel. The results showed that the samples treated with both deep cryogenic treatment and ultrasonic vibration exhibited the highest hardness (98.3 HRB), along with a favorable combination of high strength (423.46 MPa) and high elongation (46.51%). After deep cryogenic treatment and ultrasonic vibration, both surface and internal residual stresses were effectively relieved. Compared with the untreated condition, the surface residual stress and internal residual stress of the samples decreased by 52% and 84%, respectively, following the combined treatment.

Studies have found [19–21] that failure modes such as plastic deformation, cracking, and fracture typically originate at the surface of components and tend to propagate in areas with poor surface quality. Although deep cryogenic treatment improves the internal microstructure of materials and reduces the occurrence of internal defects, structural materials may still suffer from deformation, cracking, and fracture under more complex and harsh service conditions. Therefore, applying surface modification techniques to the specimens becomes particularly important. Yang et al. [22] investigated the high-cycle and very-high-cycle fatigue behavior of laser shock peened (LSP) regions on titanium alloy blades. The plastic deformation and residual compressive stress induced by LSP exhibited a gradient distribution along the depth direction. Deformation twinning increased the proportion of high-angle grain boundaries (HAGBs, $> 15^\circ$), with such boundaries introduced into the primary α phase during the plastic deformation process. Laser shock peening enhances material performance by inducing plastic deformation and residual stresses through the application of high-energy-density laser pulses on the

material surface. However, if the laser pulse energy is too high or the exposure time is excessive, such conditions can cause surface overheating, leading to grain growth, uneven residual stress distribution, or structural changes in the material. Due to its low cost, environmental friendliness, and high accessibility for components with complex geometries, water jet surface modification technology has been widely applied. Zhang et al. [23] studied the effect of water jet peening on the surface fatigue performance of pre-textured Inconel 718 alloy. Based on ABAQUS and Fe-safe, they established a finite element simulation model to analyze residual stress and surface roughness. The study showed that water jet peening induced a significant amount of residual compressive stress on the sample surface and markedly improved its fatigue performance. High-density water jet (WJ-Hd) produced the highest level of residual compressive stress, followed by low-density water jet (WJ-Ld) and standard water jet (WJ), with WJ-Hd generating more than twice the stress level of WJ and nearly 40% higher than that of WJ-Ld. Surface roughness increased with jet velocity, and its impact on the central and edge regions of the sample depended on the type of water jet used. In fatigue tests, the performance ranking from highest to lowest was WJ-Hd, WJ-Ld, WJ, and untreated samples.

Under cryogenic conditions, aluminum alloys exhibit simultaneous improvements in both strength and ductility, resulting in an anomalous dual enhancement effect characterized by increased plasticity and hardening. Research on water jet surface modification has primarily focused on the characterization of microstructural evolution and surface integrity. However, there are few reports on the microstructural evolution mechanisms, types of precipitates, and surface integrity of 7075 aluminum alloy after combined deep cryogenic treatment and abrasive water jet surface modification. This study investigates the surface integrity of 7075 aluminum alloy subjected to deep cryogenic treatment-abrasive water jet (DCT-AWJ) composite surface modification, based on experimental research.

2 Experimental Materials and Methods

2.1 Materials and Preparation

The specimen material used in this study is 7075 aluminum alloy with dimensions of 100 mm × 100 mm × 10 mm. An SX2-4-10 box-type resistance furnace was employed for the heat treatment process, followed by deep cryogenic treatment in a liquid nitrogen

environment at -196°C . The specific procedure is as follows: the sample was first heated with the furnace to 475°C and held for 1 h, then water-quenched to room temperature. Subsequently, it was reheated with the furnace to 140°C , held for 12 h, and air-cooled to room temperature. After completing the heat treatment, the 7075 aluminum alloy samples were placed in a liquid nitrogen environment at -196°C for holding times of 72, 120, and 168 h, respectively, and then returned to room temperature in air. The heat treatment process is illustrated in Figure 1.

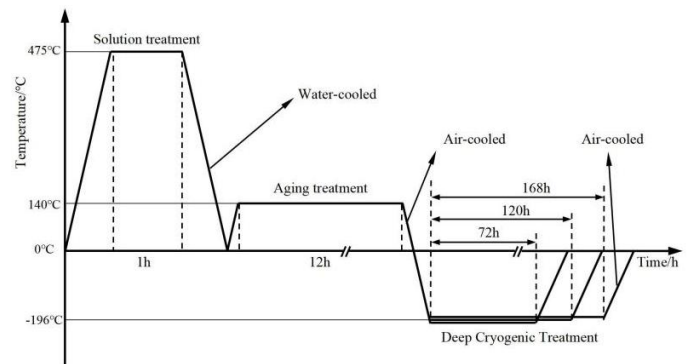


Figure 1. Heat treatment process of 7075 aluminum alloy.

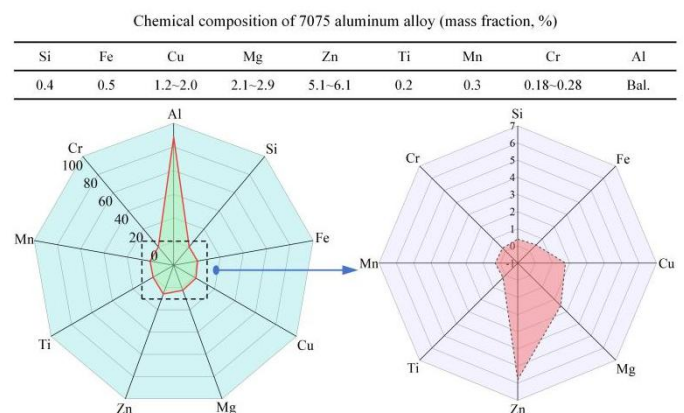


Figure 2. Chemical composition of 7075 aluminum alloy (mass fraction, %).

Energy-dispersive spectroscopy (EDS) was used to perform elemental quantitative analysis on the heat-treated 7075 specimens, as shown in Figure 2.

2.2 Experimental Plan

The heat-treated 7075 aluminum alloy specimens were subjected to abrasive water jet (AWJ) surface modification using a self-developed CNC water jet machine. The equipment mainly consists of a high-pressure pump, a CNC control panel, a nozzle, and a three-axis sliding table, as shown in Figure 3. The AWJ experimental procedure was as follows: the

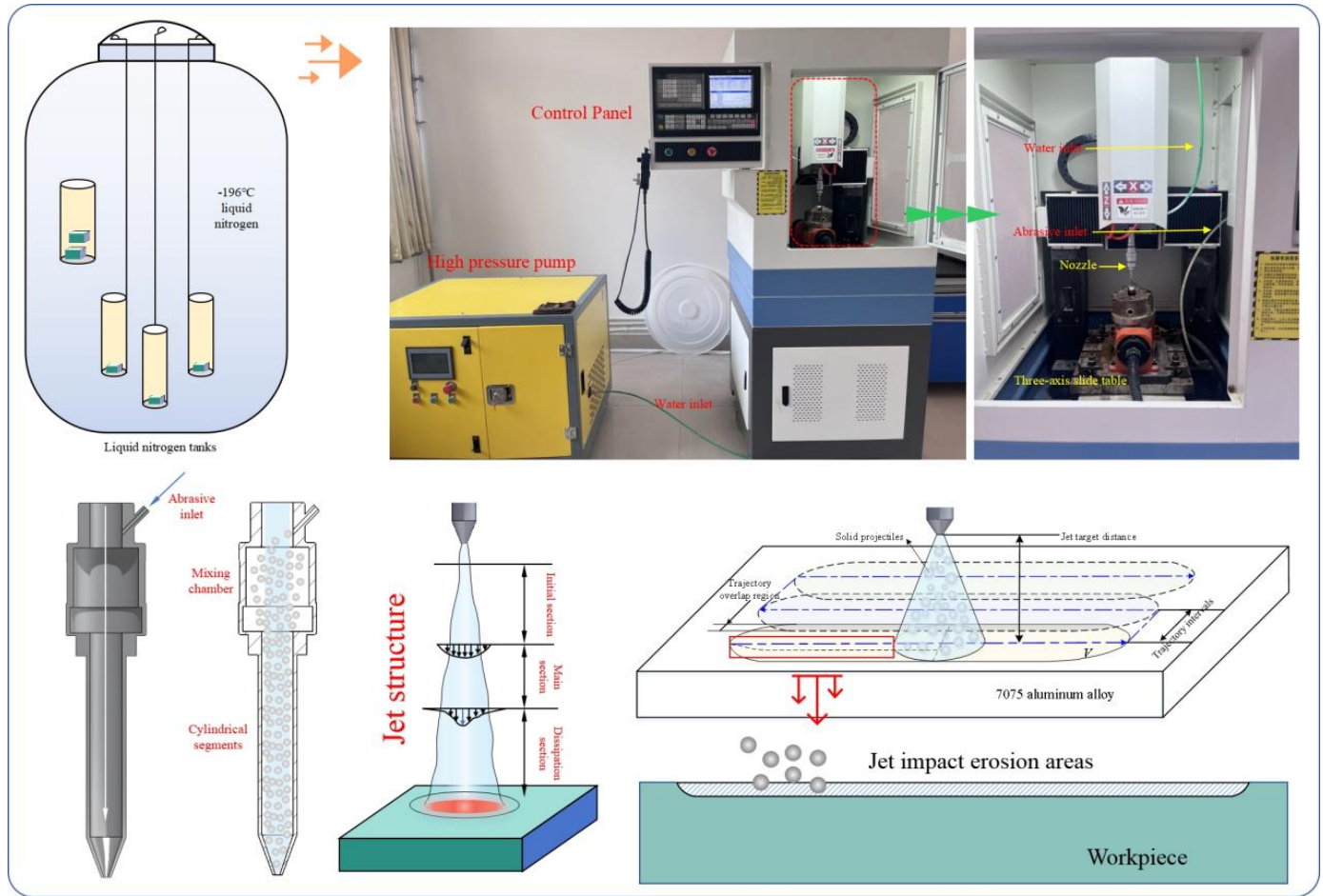


Figure 3. Deep cryogenic treatment experiment and abrasive water jet experiment.

specimen was first fixed using a fixture, ensuring that the water jet nozzle was perpendicular to the sample surface. Silicon carbide (SiC) particles of approximately 120 mesh were selected as the abrasive media. Based on previous research [24] and considering the high deformability of aluminum alloys, the jet pressures were set at 5 MPa, 10 MPa, and 15 MPa in order to prevent severe erosion of the 7075 aluminum alloy during the AWJ process. The standoff distance was maintained at 10 mm, the nozzle traverse speed was set at 600 mm/min, and the nozzle pass spacing was set at 0.5 mm. The detailed experimental parameters are presented in Table 1.

2.3 Characterization

An S-3400N scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectroscopy (EDS) module was used to observe the surface micro-morphology and elemental distribution of the specimens after deep cryogenic treatment (DCT), abrasive water jet (AWJ) treatment, and the combined DCT-AWJ surface modification.

A surface roughness tester (Model: SJ-210, Mitutoyo

Table 1. Experimental plan.

Number	AWJ/MPa	DCT-AWJ	
		DCT/h	AWJ/MPa
AWJ-#1	5	—	—
AWJ-#2	10	—	—
AWJ-#3	15	—	—
DCT-AWJ-#1	—	72	—
DCT-AWJ-#2	—	120	10
DCT-AWJ-#3	—	168	—
DCT-AWJ-#4	—	—	5
DCT-AWJ-#5	—	120	10
DCT-AWJ-#6	—	—	15

Precision Instruments (Shanghai) Co., Ltd., Shanghai, China) was used to measure the surface roughness of 7075 aluminum alloy specimens after different surface modification treatments. For each sample, five random locations were selected within the strengthened area for testing, with a measuring length of 10 mm. The average value of these measurements was taken as the surface roughness (R_a) of the specimens after each surface modification. (Note: for the AWJ-treated

samples, the measurement direction was aligned with the feed direction of the jet path.)

An X-ray diffractometer (Model: XRD-7000S/L, Shimadzu Corporation, Kyoto, Japan) was used to perform phase analysis on 7075 aluminum alloy specimens after different surface modification treatments. The diffraction peaks of the various phases were analyzed by importing the measured data into Jade 6.0 software for processing. During the measurement, the 2θ scanning range was set from 20° to 90° , with a scanning speed of $5^\circ/\text{min}$.

A microhardness tester (Model: SHSiWI, Shanghai Siwei Instrument Manufacturing Co., Ltd., Shanghai, China) was used to measure the work hardening of 7075 aluminum alloy after surface modification. The specimen was placed stably on a rigid support, ensuring that the indenter axis was perpendicular to the surface of the specimen. The indenter was then pressed into the surface, and average microhardness measurements were taken at $20\ \mu\text{m}$ intervals in the direction perpendicular to the machined surface. The measurements continued until the hardness converged to a stable value, representing the hardness of the material unaffected by work hardening.

Residual stress on the surface of 7075 aluminum alloy was measured using the X-ray diffraction (XRD) method, which determines stress by analyzing the diffraction angle shift caused by changes in interplanar spacing under stress. The measurements were conducted at a working voltage of 30 kV and a current of 8 mA, with the $\{311\}$ crystallographic plane selected for analysis. The standard $\sin^2\psi$ method was employed for residual stress determination. The ψ angle range was set from 0° to $\pm 45^\circ$, with 5° increments, resulting in 9 ψ angles used for curve fitting. An incident beam spot with a diameter of 1 mm was used, and the layer removal method was employed to gradually strip the material surface for gradient testing. This approach enabled the acquisition of the residual stress distribution along the depth direction. Each measurement point was tested three times, and the average value was taken to improve the accuracy and repeatability of the results.

3 Results

3.1 Surface Roughness and Surface Quality

Surface roughness is one of the key parameters for evaluating surface integrity. It directly affects the mechanical properties, fatigue performance, and corrosion resistance of materials. High surface

roughness can lead to issues such as fatigue crack initiation and propagation. Therefore, optimizing surface roughness contributes to improving the overall performance of the specimen and extending its service life [25–28]. Figure 4 shows the surface morphology and surface roughness of 7075 aluminum alloy specimens under different process parameters. As shown in Figures 4(a)–(c), under AWJ surface modification conditions, the surface roughness of 7075 aluminum alloy increases with jet pressure, measuring $0.864\ \mu\text{m}$, $1.082\ \mu\text{m}$, and $1.325\ \mu\text{m}$, respectively. This indicates that surface roughness is positively correlated with jet pressure under AWJ treatment. At a jet pressure of 5 MPa, the specimen surface appears relatively smooth. However, as the pressure increases, the surface exhibits intensified features such as pits, grooves, and plastic deformation, along with significant debris adhesion. This is attributed to the fact that higher jet pressure imparts greater initial velocity to the abrasive particles, significantly increasing the kinetic energy upon impact with the alloy surface, thus resulting in more intense impact and shearing effects. At lower jet pressures, the abrasive particles primarily cause mild erosion and localized plastic deformation, resulting in only minor changes in surface roughness. However, as the jet pressure increases to 10 MPa, the impact effect becomes more pronounced, leading to micro-scale damage such as debris detachment and the formation of small pits on the surface, thereby causing a noticeable increase in surface roughness. When the jet pressure is further raised to 15 MPa, the particle impacts not only intensify plastic deformation but also induce severe damage such as microcracks and delamination, resulting in further roughening of the surface morphology.

As observed in Figures 4(d)–(i), under DCT-AWJ composite surface modification conditions, the surface roughness of 7075 aluminum alloy exhibits a decreasing trend with increasing cryogenic treatment duration. Specifically, the surface roughness values for specimens DCT-AWJ-#1 to #3 are $0.981\ \mu\text{m}$, $0.822\ \mu\text{m}$, and $0.792\ \mu\text{m}$, respectively. With the increase in jet pressure, the surface roughness of 7075 aluminum alloy exhibits an increasing trend. The surface roughness values for specimens DCT-AWJ-#4 to #6 are $0.739\ \mu\text{m}$, $0.822\ \mu\text{m}$, and $1.211\ \mu\text{m}$, respectively. Compared with specimens treated with AWJ alone at the same jet pressure, the surface roughness of 7075 aluminum alloy after DCT-AWJ composite surface modification (120 h) is reduced by 14.5%, 24.0%, and 8.6% at 5,

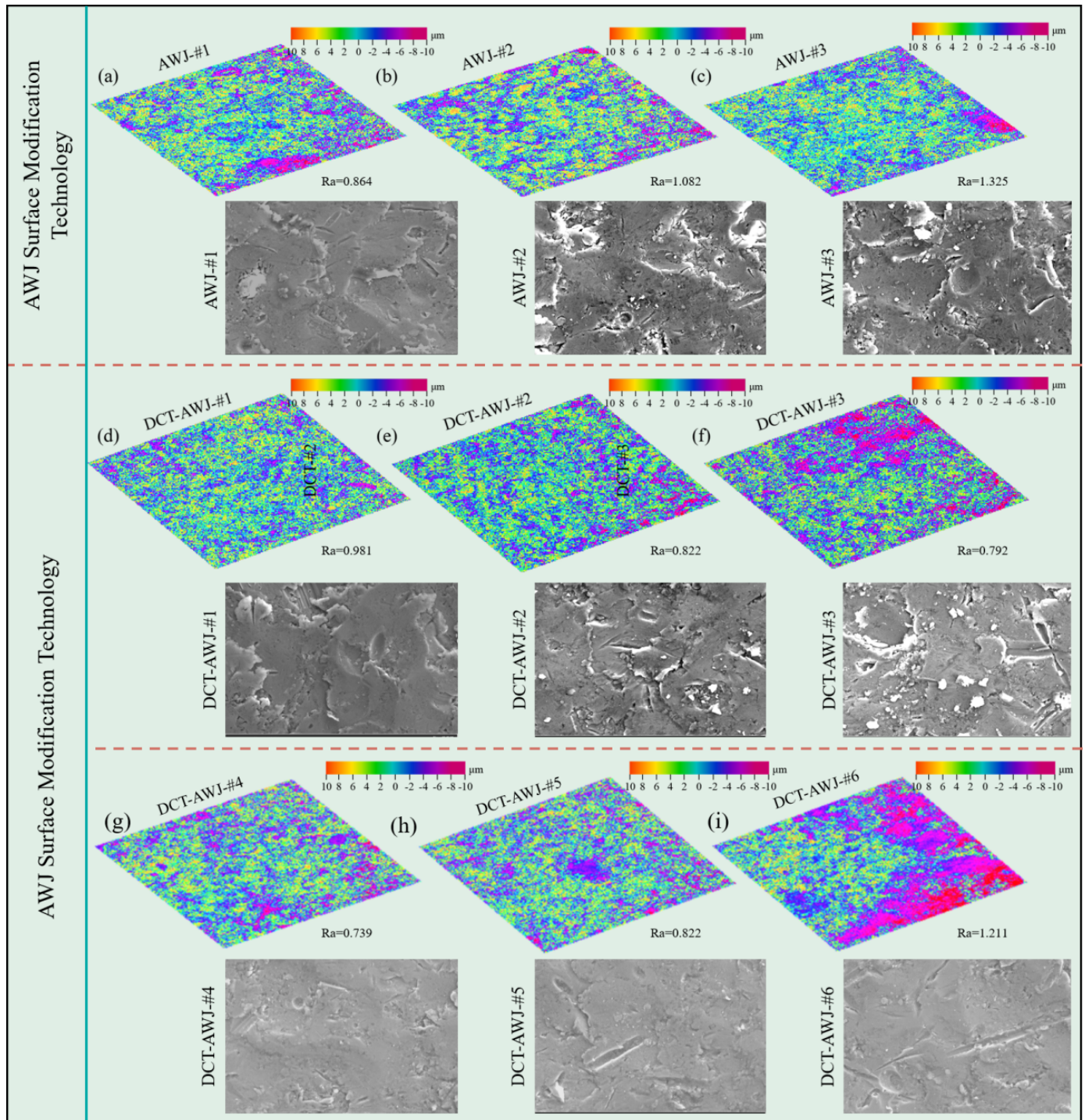


Figure 4. Surface morphology and surface roughness of 7075 aluminum alloy under different process parameters: (a)-(c) AWJ-#1 to #3; (d)-(f) DCT-AWJ-#1 to #3; (g)-(i) DCT-AWJ-#4 to #6.

10, and 15 MPa, respectively. This improvement is attributed to the effects of deep cryogenic treatment, which further relieves internal residual stresses, stabilizes microstructural defects, and promotes the precipitation and refinement of strengthening phases [29]. In particular, for 7075 aluminum alloy, DCT facilitates the more uniform and dispersed precipitation of the η' strengthening phase (the metastable precursor of η -MgZn₂), thereby enhancing

grain boundary strength and dislocation pinning capacity, as the interaction between honeycomb dislocation networks and dispersed secondary phases has been demonstrated to be a key mechanism for achieving stable and homogeneous mechanical performance in high-strength aluminum alloys [30]. As a result, the overall mechanical performance of the material becomes more stable and homogeneous. This microstructural optimization effect enhances

the surface layer's resistance to impact-induced deformation to a certain extent, thereby reducing severe erosion and plastic flow during the AWJ impact process, which leads to a noticeable decrease in surface roughness. In contrast, 7075 aluminum alloy without DCT treatment is more prone to localized plastic concentration during AWJ processing, resulting in the formation of microcracks, erosion pits, and grooves, which significantly increase surface roughness. After undergoing deep cryogenic treatment, the increased dislocation density and more uniform distribution of precipitates enhance the material's ability to withstand impact loads. As a result, the impact stress can be distributed across a wider grain region, suppressing localized damage and the unstable evolution of surface microstructures.

3.2 XRD Analysis

X-ray diffraction (XRD) is an essential technique for investigating the crystal structure and microstructural evolution behavior of metallic materials. By analyzing changes in the intensity, position, and full width at half maximum (FWHM) of diffraction peaks, it is possible to effectively identify the crystal structure, phase composition, texture characteristics, and strain state of the material. Figure 5 presents the XRD analysis of 7075 aluminum alloy under different process parameters. As shown in Figure 5, both AWJ- and DCT-AWJ-treated 7075 aluminum alloys exhibit prominent diffraction peaks corresponding to the α -Al matrix and the η -MgZn₂ phase. The diffraction peaks of the α -Al matrix are primarily located near $2\theta = 38.5^\circ$, 44.7° , 65.1° , and 78.2° , corresponding to the (111), (200), (220), and (311) planes, respectively, indicating that the main phase composition of the 7075 aluminum alloy remains stable, with no significant phase transformation observed. As shown in Figure 5(a), with the increase in jet pressure from 5 MPa to 15 MPa, the diffraction peaks of α -Al gradually broaden and the peak intensity slightly decreases. This suggests that the high-pressure jet impact leads to further grain refinement and the accumulation of dislocation density and microstrain. At higher jet pressures, abrasive water jet peening releases stronger impact kinetic energy, inducing intense plastic deformation on the material surface and generating a high density of dislocations and sub-grain structures [31]. As a result, the integrity of the crystal structure deteriorates, leading to the broadening and weakening of the XRD diffraction peaks.

Furthermore, as shown in Figures 5(b) and 5(c),

under DCT-AWJ composite treatment conditions, the diffraction peaks of α -Al also exhibit a gradual broadening trend with increasing cryogenic treatment time and jet pressure. This phenomenon indicates that DCT plays a significant role in regulating the microstructure. Cryogenic treatment promotes the dispersed precipitation of strengthening phases, relieves residual stresses, and facilitates the accumulation of microstrain [32], thereby providing a more stable and uniform structural foundation for subsequent AWJ impact strengthening. As a result, the grains become further refined and the defect structures become more abundant, leading to an increase in diffraction peak width, which reflects the synergistic evolution of microstructural stabilization and strengthening.

3.3 Residual Stress Analysis

Residual stress is one of the key indicators for evaluating the effectiveness of surface modification and the service performance of metallic materials. It refers to the self-equilibrated stress state that remains within the material after the removal of external loads [32, 35]. Surface modification processes such as machining and peening induce significant changes in residual stress states through thermomechanical interactions at the workpiece surface [33]. Figure 6 shows the residual stress distribution of 7075 aluminum alloy under different processing parameters. As illustrated in Figure 6(a), 7075 aluminum alloy treated with AWJ surface modification primarily exhibits residual compressive stress. Both the surface residual compressive stress and the maximum residual compressive stress increase in magnitude with rising jet pressure. Specifically, at jet pressures of 5, 10, and 15 MPa, the surface residual stresses for AWJ-#1 to #3 are -229 , -287 , and -360 MPa, respectively, while the corresponding maximum residual compressive stresses are -443 , -590 , and -687 MPa. This trend is attributed to the plastic deformation induced by the high-speed impact of abrasive particles during the AWJ surface modification process. As the jet pressure increases, the abrasive particles acquire higher kinetic energy, resulting in significantly greater impact loads and shear stresses upon striking the surface of 7075 aluminum alloy, thereby promoting more intense plastic deformation in the surface layer of the material [36–38]. This inhomogeneous deformation introduces a large number of dislocations, twin boundaries, and lattice distortions into the surface material, thereby forming a high-density

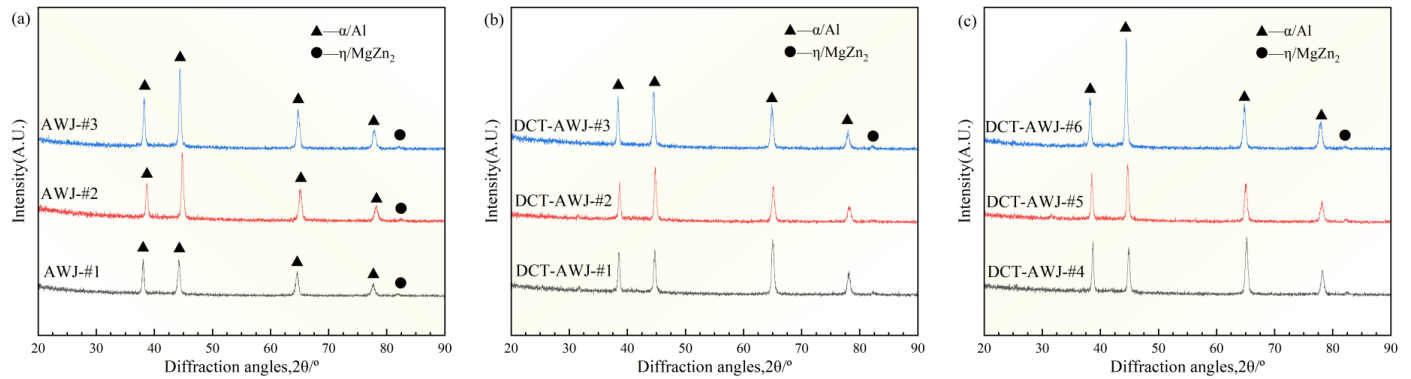


Figure 5. XRD patterns of 7075 aluminum alloy under different processing parameters: (a) different jet pressures under AWJ surface modification; (b) different cryogenic treatment durations under DCT-AWJ composite surface modification; (c) different jet pressures under DCT-AWJ composite surface modification.

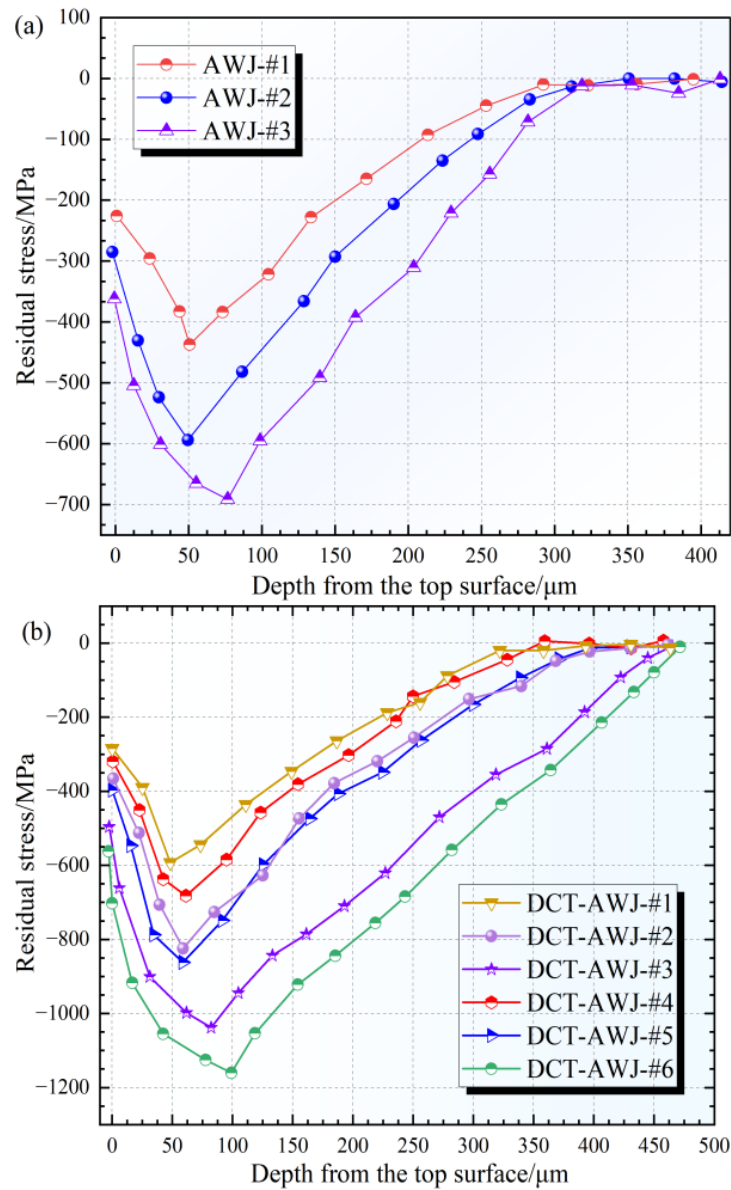


Figure 6. Residual stress distribution of 7075 aluminum alloy under different process parameters: (a) AWJ surface modification; (b) DCT-AWJ composite surface modification.

microstructural defect network. After the removal of the impact load, these microstructures undergo

redistribution to achieve mechanical equilibrium, thereby forming a stable residual compressive stress field on the surface and subsurface of the material [39, 40]. The increased impact intensity induced by high-pressure jets also promotes deeper penetration of the stress-affected zone into the material, enhancing the maximum compressive stress and extending its distribution depth.

As shown in Figure 6(b), during the DCT-AWJ composite surface modification process, both the surface residual compressive stress and the maximum residual compressive stress of 7075 aluminum alloy exhibit an increasing trend with longer cryogenic treatment durations and higher jet pressures. Specifically, for specimens DCT-AWJ-#1 to #6, the surface residual stresses are -291 MPa, -363 MPa, -502 MPa, -327 MPa, -394 MPa, and -563 MPa, respectively, while the corresponding maximum residual compressive stresses are -588 MPa, -816 MPa, -1027 MPa, -678 MPa, -859 MPa, and -1165 MPa. This is because the DCT process can induce the release of internal residual stresses in 7075 aluminum alloy, stabilize dislocation structures, and promote the refinement and uniform distribution of strengthening phases (η phases) [34]. Cryogenic treatment effectively enhances lattice distortion and hardening capacity, making the material more susceptible to intense and uniform plastic deformation during subsequent AWJ impact. As a result, higher-magnitude residual compressive stresses can be retained after unloading [41, 42]. Especially under prolonged cryogenic treatment, the alloy microstructure tends to become more stable, and its plastic response is enhanced, enabling the material to more effectively absorb and store external impact energy, which provides the foundation for the generation of higher residual compressive stresses [43]. As the AWJ surface modification process proceeds, it further activates dislocation sources, intensifies lattice slip, and promotes the accumulation of deformation zones, thereby increasing both the peak value and penetration depth of the residual compressive stress. Under the combined effects of cryogenic microstructural strengthening and high-pressure impact, a deeper and higher-magnitude compressive stress layer is formed on the surface of 7075 aluminum alloy, significantly improving its surface stress state.

3.4 Microhardness Analysis

Figure 7 presents the microhardness of 7075 aluminum alloy specimens under different processing parameters. As shown in the figure, the surface microhardness of the alloy after AWJ surface modification exhibits a positive correlation with jet pressure. Specifically, the microhardness values for specimens AWJ-#1 to #3 are 184.71 HV, 185.78 HV, and 189.41 HV, respectively. This indicates that the surface microhardness of 7075 aluminum alloy increases with rising jet pressure. Additionally, the corresponding surface hardened layer depths under different jet pressures are $147.13\ \mu\text{m}$, $179.48\ \mu\text{m}$, and $208.07\ \mu\text{m}$ for AWJ-#1, AWJ-#2, and AWJ-#3, respectively. This is because, during the AWJ process, abrasive particles are propelled at high speed by high-pressure jets, constituting a typical impact-based surface modification process. As jet pressure increases, the kinetic energy of the abrasive particles rises significantly, leading to higher impact energy and intensity. These high-energy impacts induce severe plastic deformation in the surface layer of the metal, causing a substantial increase in dislocation density. During deformation, dislocations continuously entangle and interact, eventually forming high-density dislocation structures such as dislocation cells and sub-grain structures, which is manifested as an increase in surface microhardness [44–46]. Therefore, the stronger strain hardening effect generated under higher jet pressure conditions leads to the observed increasing trend in specimen microhardness.

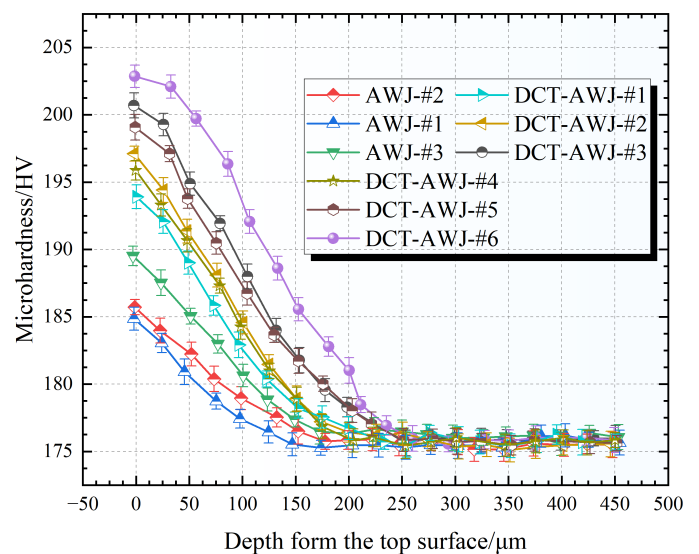


Figure 7. Microhardness-depth profiles of 7075 aluminum alloy under different process parameters.

As further observed in Figure 7, under DCT-AWJ composite surface modification conditions, both

the surface microhardness and the hardened layer depth of 7075 aluminum alloy increase with longer cryogenic treatment durations and higher jet pressures. Specifically, the surface microhardness values for specimens DCT-AWJ-#1 to #6 are 193.77 HV, 197.06 HV, 200.62 HV, 195.66 HV, 198.91 HV, and 202.87 HV, respectively. The corresponding hardened layer depths are 230.02 μm , 247.82 μm , 257.23 μm , 239.42 μm , 251.08 μm , and 264.63 μm . Compared with AWJ treatment alone, DCT-AWJ composite surface modification enhances both the surface microhardness and the depth of the hardened layer of 7075 aluminum alloy. Through prolonged exposure to extremely low temperatures, deep cryogenic treatment effectively promotes the precipitation of strengthening phases and the homogenization of the microstructure in 7075 aluminum alloy. During this process, the η' strengthening phase precipitates in a dispersed manner, with further refinement in particle size, which enhances interfacial strength and suppresses dislocation motion, resulting in a denser and more stable matrix structure [47, 48]. As a result, when the surface of 7075 aluminum alloy is subjected to high-energy impacts from abrasive particles, it is less prone to severe local yielding or fracture. Instead, the material stores deformation energy through the formation of high dislocation densities and uniform plastic deformation, thereby achieving a greater degree of strain hardening and improving its surface microhardness.

4 Conclusion

In this study, 7075 aluminum alloy was strengthened using both single abrasive water jet (AWJ) and composite deep cryogenic treatment-abrasive water jet (DCT-AWJ) surface modification processes. A comparative investigation was conducted to explore the evolution of surface integrity under different strengthening treatments. The main conclusions are as follows:

- (1) Under AWJ surface modification, the surface roughness of 7075 aluminum alloy increases with rising jet pressure, with the R_a value increasing from 0.864 μm to 1.325 μm . In contrast, under DCT-AWJ composite treatment, the surface roughness of 7075 aluminum alloy decreases with increasing cryogenic treatment time and increases with higher jet pressure. The lowest surface roughness (0.739 μm) was observed in specimen DCT-AWJ-#4, which was reduced by 14.5% compared with the AWJ-treated sample at

the same jet pressure.

- (2) Both AWJ- and DCT-AWJ-treated 7075 aluminum alloy samples exhibit distinct diffraction peaks corresponding to the α -Al matrix phase and the η -MgZn₂ precipitate phase, with the main peak positions concentrated at $2\theta = 38.5^\circ$, 44.7° , 65.1° , and 78.2° . As jet pressure and cryogenic treatment time increase, the α -Al diffraction peaks gradually broaden and the peak intensity slightly decreases, suggesting further grain refinement, increased dislocation density, and accumulation of microstrain.
- (3) Under AWJ treatment, stable residual compressive stress is generated on the surface of 7075 aluminum alloy, with the surface residual compressive stress increasing in magnitude from -229 MPa to -360 MPa and the maximum residual compressive stress from -443 MPa to -687 MPa as jet pressure increases. In the case of DCT-AWJ composite treatment, the residual stress level is further enhanced, with the highest surface residual compressive stress reaching -563 MPa and the maximum value reaching -1165 MPa. Cryogenic treatment promotes lattice distortion and the precipitation of strengthening phases, thereby enhancing the material's ability to absorb impact loads and inducing a deeper and stronger residual compressive stress layer.
- (4) Under AWJ treatment, the surface microhardness of 7075 aluminum alloy increases with rising jet pressure, with values of 184.71 HV, 185.78 HV, and 189.41 HV, respectively. The DCT-AWJ composite treatment further enhances the hardening effect, increasing the microhardness to 202.87 HV and the hardened layer depth to 264.63 μm . Cryogenic treatment promotes the dispersed precipitation of strengthening phases, hinders dislocation motion, and significantly strengthens grain boundaries, thereby achieving a greater degree of strain hardening.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported by the Natural Science Foundation of Shandong Province under Grant ZR2022QE149 and Grant ZR2023ME223.

Conflicts of Interest

Ping Zhang served as an Editor-in-Chief of the *Journal of Materials Durability and Engineering* at the time of manuscript submission. To ensure the integrity of the peer-review process, Ping Zhang was not involved in the editorial handling, peer review, or decision-making process for this manuscript, which was handled independently by another editor. The remaining authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

References

- [1] Jovičević-Klug, P., & Podgornik, B. (2020). Review on the effect of deep cryogenic treatment of metallic materials in automotive applications. *Metals*, 10(4), 434. [CrossRef]
- [2] Baldissera, P., & Delprete, C. (2008). Deep cryogenic treatment: A bibliographic review. *The Open Mechanical Engineering Journal*, 2(1), 1-11. [CrossRef]
- [3] Kalia, S. (2010). Cryogenic processing: a study of materials at low temperatures. *Journal of Low Temperature Physics*, 158(5), 934-945. [CrossRef]
- [4] Altas, E., Bati, S., Rajendrachari, S., Erkan, Ö., Dag, I. E., & Avar, B. (2024). Comprehensive analysis of mechanical properties, wear, and corrosion behavior of AA7075-T6 alloy subjected to cryogenic treatment for aviation and defense applications. *Surface and Coatings Technology*, 490, 131101. [CrossRef]
- [5] Dursun, T., & Soutis, C. (2014). Recent developments in advanced aircraft aluminium alloys. *Materials & Design*, 56, 862-871. [CrossRef]
- [6] Matsuda, K., Ramachandiran, N., & Gerlich, A. P. (2025). Improved fillet weld quality in AA 7075 sheets using flower pattern laser wobbling. *Optics & Laser Technology*, 192, 113438. [CrossRef]
- [7] Magarajan, U., Kumar, S. S., & Rodríguez-Millán, M. (2023). Effect of deep cryogenic treatment on the microstructural, mechanical and ballistic properties of AA7075-T6 aluminum alloy. *Defence Technology*, 30, 101-110. [CrossRef]
- [8] Heinz, A., Haszler, A., Keidel, C., Moldenhauer, S., Benedictus, R., & Miller, W. S. (2000). Recent development in aluminium alloys for aerospace applications. *Materials Science and Engineering: A*, 280(1), 102-107. [CrossRef]
- [9] Santos, M. C., Machado, A. R., Sales, W. F., Barrozo, M. A. S., & Ezugwu, E. O. (2016). Machining of aluminum alloys: A review. *The International Journal of Advanced Manufacturing Technology*, 86(9-12), 3067-3080. [CrossRef]
- [10] Gómez-Parra, A., Álvarez-Alcón, M., Salguero, J., Batista, M., & Marcos, M. (2013). Analysis of the evolution of the Built-Up Edge and Built-Up Layer formation mechanisms in the dry turning of aeronautical aluminium alloys. *Wear*, 302(1-2), 1209-1218. [CrossRef]
- [11] List, G., Nouari, M., Géhin, D., Gomez, S., Manaud, J. P., Le Petitcorps, Y., & Girot, F. (2005). Wear behaviour of cemented carbide tools in dry machining of aluminium alloy. *Wear*, 259(7-12), 1177-1189. [CrossRef]
- [12] Lulay, K. E., Khan, K., & Chaaya, D. (2002). The effect of cryogenic treatments on 7075 aluminum alloy. *Journal of Materials Engineering and Performance*, 11(5), 479-480. [CrossRef]
- [13] Mohan, K., Suresh, J. A., Ramu, P., & Jayaganthan, R. (2016). Microstructure and mechanical behavior of Al 7075-T6 subjected to shallow cryogenic treatment. *Journal of Materials Engineering and Performance*, 25(6), 2185-2194. [CrossRef]
- [14] Dong, N., Sun, L., Ma, H., & Jin, P. (2021). Effects of cryogenic treatment on microstructures and mechanical properties of Mg-2Nd-4Zn alloy. *Materials Letters*, 305, 130699. [CrossRef]
- [15] Abbasi-Baharanchi, M., Karimzadeh, F., & Enayati, M. H. (2017). Mechanical and tribological behavior of severely plastic deformed Al6061 at cryogenic temperatures. *Materials Science and Engineering: A*, 683, 56-63. [CrossRef]
- [16] Yang, Q., Dong, Z., Kang, R., & Wei, Z. (2024). Effect of ultrasonic vibration and deep cryogenic treatment on the residual stress, mechanical properties and microstructures of HR-2 austenitic stainless steel. *Materials Science and Engineering: A*, 900, 146502. [CrossRef]
- [17] Jovičević-Klug, M., Tegg, L., Jovičević-Klug, P., Dražić, G., Almásy, L., Lim, B., ... & Podgornik, B. (2022). Multiscale modification of aluminum alloys with deep cryogenic treatment for advanced properties. *Journal of materials research and technology*, 21, 3062-3073. [CrossRef]
- [18] Yao, E., Zhang, H., Ma, K., Ai, C., Gao, Q., & Lin, X. (2023). Effect of deep cryogenic treatment on microstructures and performances of aluminum alloys: a review. *Journal of Materials Research and Technology*, 26, 3661-3675. [CrossRef]
- [19] Seensattayawong, P., Brodmann, R., Stelzer, G., Seewig, J., & Kerscher, E. (2025). The study of surface in early stages of fatigue failure on carbon steels using a confocal microscope and a scattered light sensor. *Engineering Failure Analysis*, 178, 109720. [CrossRef]
- [20] Li, M., Zhao, W., Li, L., He, N., & Stepan, G.

- (2024). Influence of milling stability on machined surface integrity and fatigue performance of Ti-6Al-4V titanium alloy. *Engineering Failure Analysis*, 168, 109103. [CrossRef]
- [21] Liu, G., Huang, C., Zhao, B., Wang, W., & Sun, S. (2021). Effect of machined surface integrity on fatigue performance of metal workpiece: a review. *Chinese Journal of Mechanical Engineering*, 34(1), 118. [CrossRef]
- [22] Yang, K., Huang, Q., Zhong, B., Wang, Q., Chen, Q., Chen, Y., Su, N., & Liu, H. (2020). Enhanced extra-long life fatigue resistance of a bimodal titanium alloy by laser shock peening. *International Journal of Fatigue*, 141, 105868. [CrossRef]
- [23] Zhang, P., Gao, Y., Zhang, J., Yue, X., Zhou, H., & Sun, Y. (2024). Inconel 718 alloy strengthening mechanism and fatigue life of microtexture-induced microjet coupled with cavifying water jet. *Vacuum*, 222, 113060. [CrossRef]
- [24] Zhang, P., Yue, X., Jiang, X., & Wang, Y. (2025). Predictive model of residual stress and microstructural evolution in 7075 aluminum alloy modified by ultrasonic impact and water jet combined surface treatment. *Journal of Alloys and Compounds*, 1036, 181552. [CrossRef]
- [25] Novovic, D., Dewes, R. C., Aspinwall, D. K., Voice, W., & Bowen, P. (2004). The effect of machined topography and integrity on fatigue life. *International Journal of Machine Tools and Manufacture*, 44(2-3), 125-134. [CrossRef]
- [26] Suraratchai, M., Limido, J., Mabru, C., & Chieragatti, R. (2008). Modelling the influence of machined surface roughness on the fatigue life of aluminium alloy. *International Journal of Fatigue*, 30(12), 2119-2126. [CrossRef]
- [27] Fu, B., Gu, Y., Lin, J., Fu, L., Gao, T., Yu, H., Wang, T., & Zhang, Y. (2025). Influence mechanism of ultrasonic vibration and pulsed laser on the surface formation of SiCp/Al in cutting. *International Journal of Thermal Sciences*, 218, 110143. [CrossRef]
- [28] Arola, D., & Williams, C. L. (2002). Estimating the fatigue stress concentration factor of machined surfaces. *International Journal of Fatigue*, 24(9), 923-930. [CrossRef]
- [29] Zhang, Z., Liu, Y., & Li, M. (2025). Strengthening 316L stainless steel fabricated by laser powder bed fusion via deep cryogenic treatment. *Journal of Materials Science & Technology*, 239, 109-123. [CrossRef]
- [30] Liu, W., Zhang, L., Ye, F., Liu, X., Song, Y., Li, W., He, D., Yue, X., & Wu, J. (2025). Unveiling the high ductility-strength mechanism induced by honeycomb dislocations and dispersed vacancies in 7A52-DCI4 aluminum alloy. *Journal of Materials Science & Technology*, 229, 196-202. [CrossRef]
- [31] Wan, L., Qian, Y., Li, Y., Wu, S., Kang, Y., & Li, D. (2025). Surface characteristics and tribological performance of Ti6Al4V peened by sinking bead abrasive waterjet. *Journal of Manufacturing Processes*, 149, 331-344. [CrossRef]
- [32] Araghchi, M., Mansouri, H., Vafaei, R., & Guo, Y. (2017). A novel cryogenic treatment for reduction of residual stresses in 2024 aluminum alloy. *Materials Science and Engineering: A*, 689, 48-52. [CrossRef]
- [33] Damir, A., Shi, B., Elsayed, A., Thelin, J., M'Saoubi, R., & Attia, H. (2025). On the tribological and thermal aspects of cryogenic machining of Inconel 718 and their effects on surface integrity. *Wear*, 571, 205855. [CrossRef]
- [34] Su, R., Ma, S., Wang, K., Li, G., Qu, Y., & Li, R. (2022). Effect of cyclic deep cryogenic treatment on corrosion resistance of 7075 alloy. *Metals and Materials International*, 28(4), 862-870. [CrossRef]
- [35] Yao, S., Chi, Y., Zhu, X., Zhang, K., Lu, T., Li, K., ... & Tu, S. (2025). Gradient nanostructure enabled exceptional fretting fatigue properties of Inconel 718 superalloy through submerged abrasive waterjet peening. *Chinese Journal of Aeronautics*, 38(1), 103297. [CrossRef]
- [36] Chi, Y. X., Yao, S. L., Cheng, H. Y., Zhu, X. H., Liu, J. W., Liu, C. L., ... & Zhang, X. C. (2025). Bilateral submerged abrasive waterjet peening improved high-temperature fatigue strength of titanium alloy thin-walled simplified blades. *Journal of Manufacturing Processes*, 133, 992-1004. [CrossRef]
- [37] Siahpour, P., Omar, S. M. T., Griffin, D., Amegadzie, M. Y., Tieu, A., Donaldson, I. W., & Plucknett, K. P. (2024). Evaluating surface mechanical properties and wear resistance of Ti-6Al-4V alloy subjected to ultrasonic pulsed waterjet peening. *Wear*, 550-551, 205400. [CrossRef]
- [38] Lv, Z., Hou, R., Xue, B., Xu, J., & Sun, H. (2025). Study on surface roughness and fatigue property of abrasive waterjet peened aluminum alloy. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 12(4), 1195-1208. [CrossRef]
- [39] Arola, D., McCain, M. L., Kunaporn, S., & Ramulu, M. (2001). Waterjet and abrasive waterjet surface treatment of titanium: A comparison of surface texture and residual stress. *Wear*, 249(10-11), 943-950. [CrossRef]
- [40] Chakkravarthy, V., Manojkumar, P., Jerome, S., Evlashin, S. A., Arackal Narayanan, J., Mendagaliev, R. V., Sidorenko, A. O., & Narayan, R. L. (2024). Effect of impact angle on hot corrosion resistance of abrasive water jet peened Ti-6Al-4V alloy. *Surface and Coatings Technology*, 494, 131523. [CrossRef]
- [41] Liu, Y., Jiang, Q., Gao, J., Xu, Z., Chen, S., Lai, Y., ... & Ye, L. (2025). Influence of heat treatment combined with cryogenic treatment on contact fatigue properties of Cr12Mo1V1 steel members. *Scientific Reports*, 15(1), 22077. [CrossRef]
- [42] Mavi, A., Kaplan, Y., & Aksoz, S. (2021). Effects of

aging and deep cryogenic treatment on wear behavior of Al7075 Alloy. *Journal of Tribology*, 143(12), 121702. [CrossRef]

- [43] Gerosa, R., Panzeri, D., Rivolta, B., & Casaroli, A. (2023). Deep cryogenic treatment of AA7050: tensile response and corrosion susceptibility. *Discover Materials*, 3(1), 2. [CrossRef]
- [44] Wang, Z., Ma, Z., Chen, T., Fan, C., Yu, T., & Zhao, J. (2023). Experimental investigation into the effect of process parameters on the Inconel 718 surface integrity for abrasive waterjet peening. *Surface and Coatings Technology*, 454, 129186. [CrossRef]
- [45] Yao, S. L., Wang, G. Y., Yu, H., Wang, J., Li, K. S., Liu, S., Zhang, X. C., & Tu, S. T. (2022). Influence of submerged micro-abrasive waterjet peening on surface integrity and fatigue performance of TA19 titanium alloy. *International Journal of Fatigue*, 164, 107076. [CrossRef]
- [46] Yao, S., Wang, G., Li, K., Wang, N., Zhang, C., Liu, S., ... & Tu, S. (2022). Cavitation abrasive integrated waterjet peening process and the effect of process parameters on the surface integrity of TA19 titanium alloy. *Surface and Coatings Technology*, 440, 128477. [CrossRef]
- [47] Niu, X., Chen, Z., Jing, L., Huang, Y., & Liu, Y. (2024). Effect of cryogenic treatment on residual stress and microstructure of 6061 aluminum alloy and optimization of parameters. *Materials*, 17(19), 4873. [CrossRef]
- [48] Chankitmongkorn, S., Eskin, D. G., Patakh, U., Chanchaen, W., Sehanam, S., Limmaneevichitr, C., & Pandee, P. (2024). The improvement of deformability in AA7075 alloy through cryogenic treatment and its correlation with microstructural evolution and FE modelling. *Scientific Reports*, 14(1), 16755. [CrossRef]



Xiujie Yue The author's research focuses on surface and interface engineering of metallic materials and corrosion protection technologies, with systematic investigations into advanced surface treatment processes such as water jet surface modification, ultrasonic impact strengthening, and laser shock peening. Emphasis is placed on understanding the effects of impact-based strengthening techniques on surface microstructure evolution, residual stress distribution, surface roughness, and comprehensive material performance. By integrating experimental characterization with numerical simulation, the research aims to reveal the multi-scale coupling mechanisms between surface structure and properties. The ultimate goal is to enhance the mechanical and corrosion resistance properties of metallic materials under complex service conditions, providing theoretical support and technical solutions for extending the service life and ensuring the safety of high-performance components. (Email: yuexijiea@163.com)



Yeran Gao The author's research focuses on the application of water jet technology in surface modification of aerospace metallic materials, with particular emphasis on the effects of different types of water jets (such as abrasive water jets, cavitation water jets, and pulsed water jets) on surface microstructure, residual stress distribution, and surface roughness. The study explores the surface strengthening mechanisms induced by water jets and their influence on the fatigue performance of typical aerospace materials such as aluminum and titanium alloys. By integrating mechanical property testing with microstructural characterization, the research aims to reveal the correlation between water jet parameters and fatigue life, providing theoretical support and technical guidance for fatigue life extension and surface treatment optimization of aerospace components. (Email: gyr0311@163.com)



Youqiang Wang is a Professor who has long been engaged in research in the field of tribology and surface engineering, with a primary focus on transient elastohydrodynamic lubrication (EHL) theory and numerical simulation under non-Newtonian fluid conditions. His work extensively explores the lubrication performance and failure mechanisms of key mechanical components such as gears, bearings, and cams. In the area of surface engineering, he is dedicated to the study of microstructural modification of metal surfaces and the mechanisms of friction and wear. He places particular emphasis on advanced surface technologies such as laser cladding, plasma spraying, and micro-texturing, and their effects on enhancing tribological performance. Additionally, he has conducted a series of studies on green lubrication and the development of high-performance lubricants, including research on nano-additives, magnetorheological fluids, and superhydrophobic lubricating interfaces. In recent years, his research scope has expanded to include mechanical system reliability evaluation and surface integrity control, covering topics such as high-speed machining, micro-scale residual stress regulation, and the construction of multifunctional composite surfaces, demonstrating significant engineering application value. (Email: wyq1970301@126.com)

Ping Zhang is a Professor and doctoral supervisor at Guangdong Ocean University, long dedicated to research in high-precision cutting processes and equipment, tool design, and surface modification for corrosion protection. He serves as a Youth Editorial Board Member of Transactions of Nonferrous Metals Society of China, Guest Editor for Coatings and Lubricants, and Youth Editorial Board Member or Editorial Board Member for several Chinese journals, including Journal of the Chinese Nonferrous Metals Society, Diamond & Abrasives Engineering, Materials Engineering, and Journal of Aeronautical Materials. He has also been invited as a peer reviewer for over 40 internationally renowned SCI journals. (Email: zpqdhxy@126.com)