REVIEW ARTICLE

Research Progress, Challenges, and Prospects of High-Pressure Water Jet Surface Modification Technology for Aerospace Materials

Xiujie Yue[1], **Ping Zhang**[2,*], **Yeran Gao**[3] and **Xuezhao Wang**[2]

[1] College of Mechanical and Electrical Engineering, Qingdao Huanghai University, Qingdao 266520, China
[2] College of Mechanical and Power Engineering, Guangdong Ocean University, Zhanjiang 524088, China
[3] College of Intelligent Manufacturing, Qingdao University of Technology, Qingdao 266520, China

Abstract

The water jet surface modification technology does not introduce thermal stress and thermal deformation during operation, reducing changes in the material's phase transformation temperature or grain growth, and avoiding problems related to thermal stress and deformation. It contains no chemical substances, posing no environmental pollution, and features low cost. It enables treatment of surfaces in narrow spaces, deep grooves, and on small components, and can operate under complex environmental conditions. Moreover, it is easy to mechanize and automate, showing great application prospects across many industries. This paper first reviews the development history and working principles of high-pressure water jet surface strengthening technology, explaining the mechanisms and recent research progress of abrasive water jet, cavitation water jet, and pulsed water jet technologies. It then summarizes the residual stress, grain refinement, fatigue life, and comparisons of internal and external flow field structures of different water jet surface modification techniques. Finally, it discusses the practical challenges of high-pressure water jet technology, such as poor workpiece surface quality, specific nozzle requirements, and nozzle wear.

Keywords: high-pressure water jet, fatigue life, residual stress, nozzle structure, internal and external flow field structure.

1 Introduction

With the continuous development of global manufacturing, the innovation and development of high-end machinery and equipment has become one of the key factors driving industrial technology upgrading in China, and the fatigue-resistant manufacturing processes for critical basic components are at the core of quality improvement. Therefore, comprehensive collaboration is needed to enhance equipment quality, which is also one of the "four fundamental principles" of Made in China 2025.

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***Corresponding author:**
Ping Zhang
zpqdhhxy@126.com

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However, it is well known that during the service life of components, fatigue fractures often initiate at the surface, and fatigue cracks mostly occur in areas with poor surface quality of the workpiece [1–4]. Therefore, the concept of "no stress concentration" fatigue-resistant manufacturing has been proposed, which emphasizes control over surface integrity and the altered surface layer, and points out that the core of fatigue-resistant manufacturing lies in surface modification, i.e., the treatment of the material surface [5].

In recent years, the widely applied material surface strengthening technologies mainly include mechanical shot peening surface strengthening [6, 7], ultrasonic rolling surface strengthening [8–10], laser surface strengthening [11–13], and water jet surface strengthening technologies [14–17], as shown in Figure 1. Mechanical shot peening surface strengthening involves high-speed impact of the target surface by hard material-made shot particles, inducing a significant plastic deformation layer and residual compressive stress in the target material [18]. However, due to the limitation of shot size, mechanical shot peening unavoidably increases the surface roughness of the material during strengthening, and for small-sized but stress-concentrated complex structures, under-coverage or over-coverage may occur in mechanical shot peening. Ultrasonic surface rolling strengthening technology enhances surface integrity by using a rolling head to strengthen the workpiece surface, and the surface roughness can be reduced to the nanometer level, significantly improving the surface hardness of the component [19]. However, for complex components with narrow areas, the strengthening effect is greatly reduced due to the size limitation of the rolling head. Laser surface strengthening technology introduces residual compressive stress and work hardening on the material surface through laser-induced plasma shock waves, and has advantages such as significant strengthening, strong controllability, and good adaptability [11, 20]. However, its cost is relatively high, and laser surface strengthening typically requires point-by-point or line-by-line scanning, resulting in low processing efficiency, especially for large-sized components. Meanwhile, it easily introduces thermal deformation and thermal stress during the operation, affecting the surface integrity of the workpiece.

Water jet peening (WJP) is a surface modification technology for components that has emerged and rapidly developed in recent decades. Compared with the aforementioned surface strengthening technologies, the WJP process exhibits strong adaptability and unique advantages, which are mainly reflected in the following aspects:

1. No heat-affected zone: Water jet peening is a cold working process, which does not introduce thermal stress or thermal deformation during operation, reducing the likelihood of altering the material's phase transformation temperature or inducing grain growth, and avoiding problems associated with thermal stress and deformation.

2. Environmentally friendly: The water jet surface modification process does not generate harmful substances, and contains no chemical substances, making it non-polluting, low-cost, highly efficient, and recyclable.

3. Wide applicability [21]: It allows surface treatment of parts in confined spaces, deep grooves, and small components, and can be used under complex environmental conditions, and is easy to mechanize and automate.

4. High control precision: Water jet peening allows precise control over processing parameters, enabling fine adjustment of the strengthened regions.

Water jet peening technology uses water as the carrier, and converts mechanical energy into pressure energy through the liquid amplification principle using a specially designed nozzle, forming a high-energy jet through the nozzle orifice. This jet impacts the workpiece surface at high speed, causing significant plastic deformation and generating a deep residual compressive stress layer [22], thereby achieving an optimized microstructure and stress distribution on the workpiece surface. According to technical characteristics, water jet surface strengthening technology can be categorized into continuous jets, cavitation jets, and pulsed jets, among which continuous jets include pure water jets and abrasive jets.

As shown in Figure 1, this paper first reviews the development history and working principles of high-pressure water jet surface strengthening technology (Section 1). Then, in view of the various types of water jet technologies, it presents a comparative analysis of their effects on residual stress and grain refinement after surface modification, as well as fatigue life and the structure of internal and external flow fields of nozzles (Section 2).

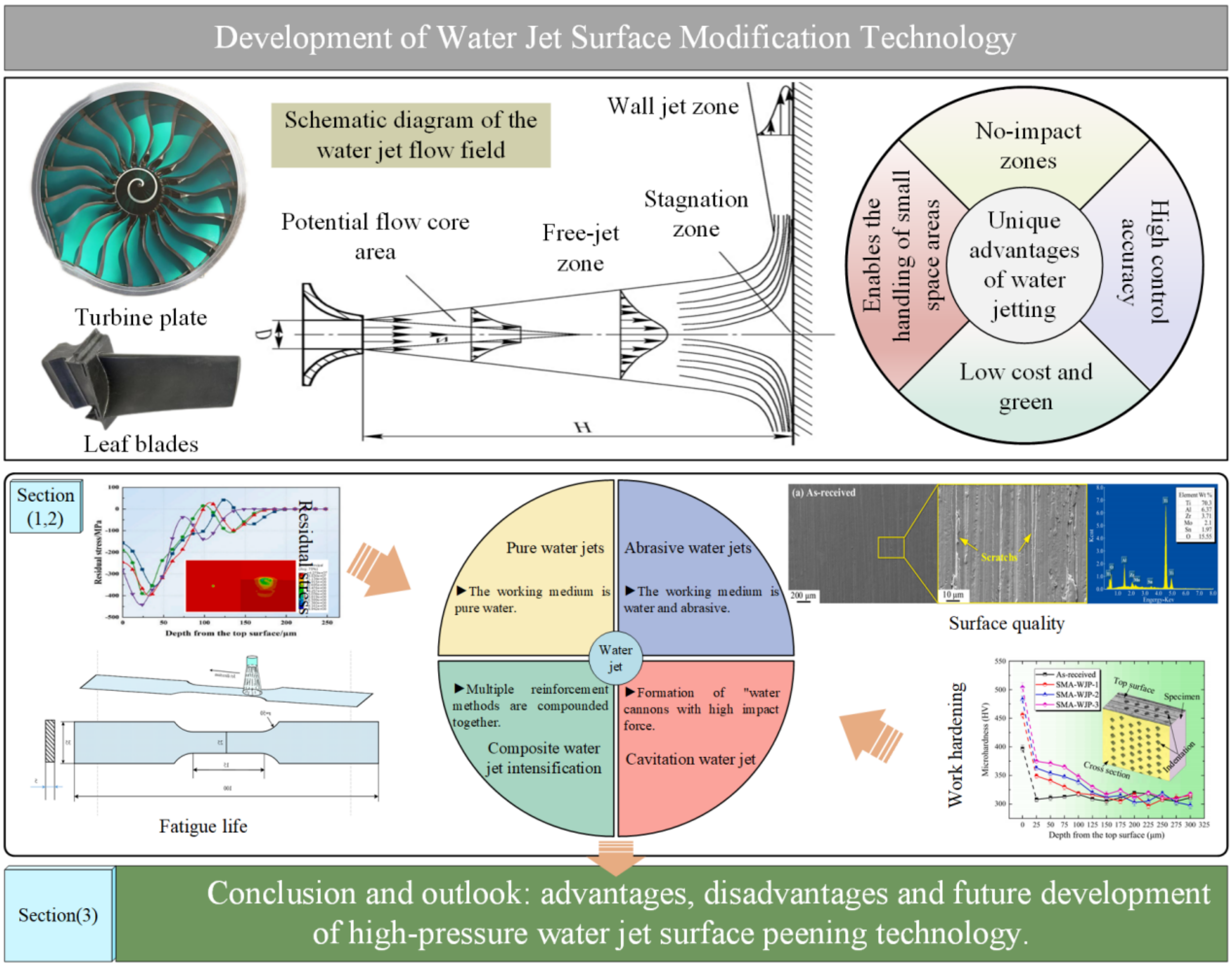

Figure 1. Schematic structure of this study.

Finally, the challenges and issues encountered in specific applications of high-pressure water jet surface modification technology are discussed, with a focus on the advantages and disadvantages of abrasive water jets in surface strengthening. The paper concludes with a summary and provides an outlook on the future development of high-pressure water jet surface modification technology.

2 The development process and principle of water jet surface modification technology

High-pressure water jet technology has a history of more than half a century, but it experienced rapid development in the 1970s. In its early stages, water jet technology was mainly used in mining and wood cutting, and by the 20th century, with advancements in high-pressure pump and pressure-resistant material technologies, high-pressure water jet technology began to attract attention from the industrial sector. In the early 1980s, the academic research community began to conduct more systematic and in-depth studies on the potential of high-pressure water jet in material surface treatment. During this period, the idea of water jet shot peening was first proposed, and the application of high-pressure water jet technology evolved from cleaning, cutting, rock breaking, etc. to surface processing (surface treatment and surface shot peening) [23]. Figure 2 outlines the development history of various water jet technologies along a timeline. With years of technological evolution, water jet technology has demonstrated rich application potential and innovative achievements in interdisciplinary integration. Due to its unique processing advantages and adaptability, it has provided efficient and precise solutions across multiple fields. Specifically, based on the fundamental properties and mechanisms of water jets, high-pressure water jet technology can be mainly classified into continuous water jets (pure water jets and abrasive water jets), cavitation water jets, and pulsed water jets enhanced by ultrasonic technology.

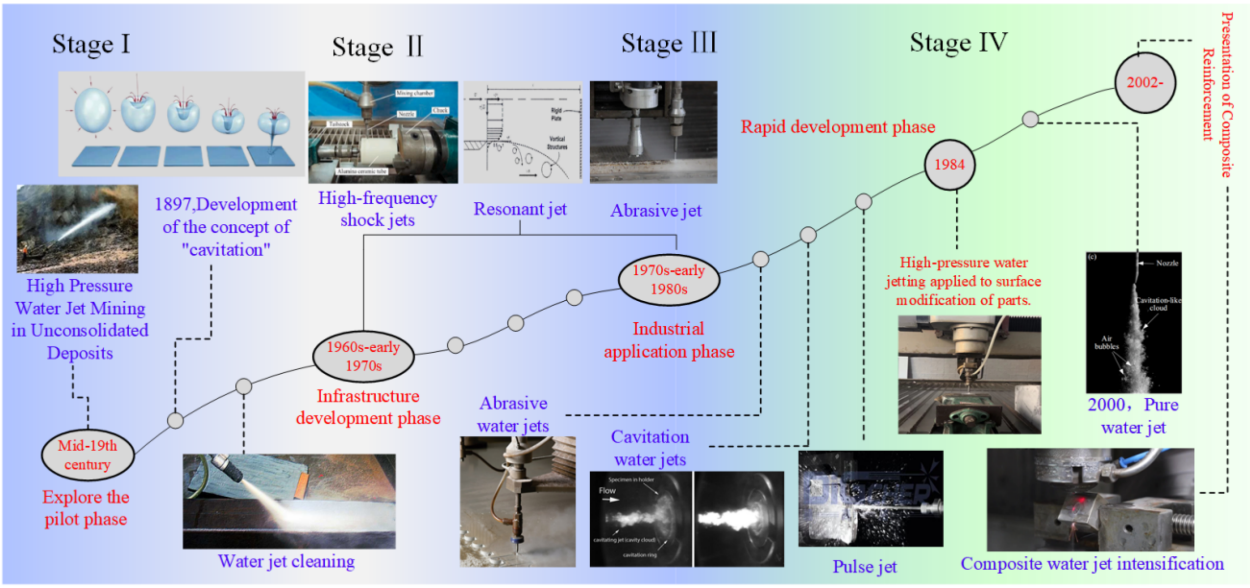

Figure 2. Development history of water jet surface modification technology.

2.1 The principle of abrasive water jet strengthening

Abrasive water jet and pure water jet strengthening technologies both belong to continuous water jet technologies, and abrasive water jet technology is developed based on pure water jet technology. The abrasive water jet surface strengthening technique mainly uses high-speed water jets generated by high-pressure pumps to carry abrasive particles (such as glass beads, ceramic shots, or steel balls), which are accelerated through nozzles with very small diameters to form a high-energy mixed jet. Its working principle is illustrated in Figure 3(a) [24]. During the abrasive water jet process, the abrasive particles diffuse radially within the jet stream, that is, the central region has higher particle density, while the edge region has lower density, as shown in Figure 3(b) [24].The corresponding microstructural changes are illustrated in Figure 3(c) [25].

In 2000, Ramulu et al. [26] experimentally investigated the effects of abrasive water jet processing on the surface integrity of metallic materials, identifying the depth of plastic deformation and surface quality during the material removal process, and analyzed the residual stress field generated during the process. The study found that abrasive water jet strengthening induced surface plastic deformation comparable to that of shot peening. In the same year, Sadasivam et al. [27] also demonstrated that abrasive water jet surface strengthening can induce significant residual compressive stress on titanium alloy surfaces. Compared to ion beam coating techniques, titanium alloys strengthened by abrasive water jets exhibited more pronounced residual compressive stresses and improved the fatigue strength of the components. Predeep et al. [28] conducted a comparative study based on pure water jet (WP) and abrasive water jet (AWJ) technologies, comparing their effects on the surface integrity of Ti6Al4Nb. Compared with AWJ, WP exhibited a 73% higher material removal rate and a 50% increase in average surface roughness Ra, while AWJ demonstrated better surface integrity. Research on abrasive water jet technology in China has developed rapidly, emerging as a rising force in the field. Wan et al. [29] from Wuhan University employed an abrasive water jet peening technique using sediment beads as the medium to strengthen the surface of Ti6Al4V titanium alloy. The results showed that the process could induce significant plastic deformation without altering the phase composition, refine the grains, and produce surface residual compressive stress exceeding 800 MPa. After treatment, the surface microhardness of the sample increased by up to 40.1%, and the wear rate decreased by as much as 16.8%. The main wear mechanisms were abrasive wear, oxidative wear, and adhesive wear. Gongyu et al. [30] from East China University of Science and Technology investigated the effects of abrasive water jet process parameters on the surface integrity and fatigue life of TA19 titanium alloy. The samples were treated by adjusting water pressure and standoff distance (SoD), and the changes in microstructure, surface roughness, microhardness, and residual compressive stress were evaluated, along with room-temperature fatigue performance tests. The results showed that

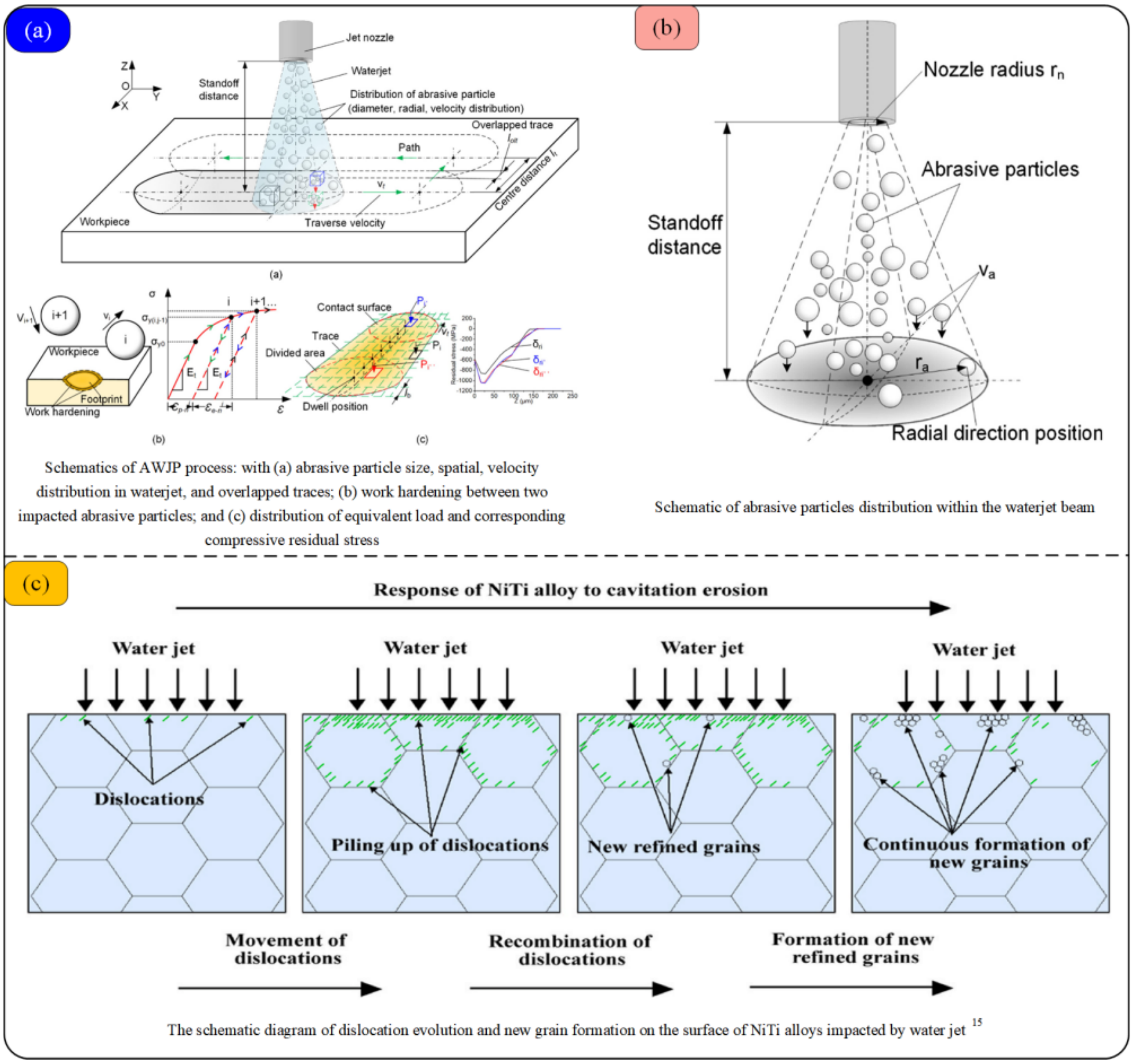

Figure 3. Schematic diagram of abrasive water jet machining mechanism [15, 24, 25].

under optimized parameter conditions, the fatigue life of the material could be increased to 5.46–6.28 times that of the untreated condition, which was attributed to significantly improved surface integrity; while inappropriate parameters caused increased surface roughness due to erosion, resulting in a decrease in fatigue life to only 0.55–0.69 times of the original value. Their research team focused on GH4169 nickel-based superalloy [31, 32], and conducted a comparative analysis between deflected abrasive water jet peening (DAWJP) and conventional shot peening (SP), systematically evaluating their impact on dovetail groove surface integrity and fretting fatigue (FF) performance. The results showed that DAWJP treatment, at various path spacings (0.05, 0.1, and 0.15 mm), could form a plastic deformation layer with a thickness of 22–43 μm, significantly increasing surface hardness to 541–591 HV, and inducing residual compressive stresses of 1005–1169 MPa, representing increases of 16%–27% and 178%–224% compared to the untreated state, while maintaining low surface roughness (Ra: 0.391–0.501 μm).

In summary, abrasive water jet impacts the specimen surface by carrying abrasives in a high-speed water stream, causing significant plastic deformation and introducing a residual compressive stress layer to a certain depth in the surface layer, which significantly improves the surface finish of the workpiece. Meanwhile, abrasive water jet treatment also refines the grains and enhances the fatigue life of the component.

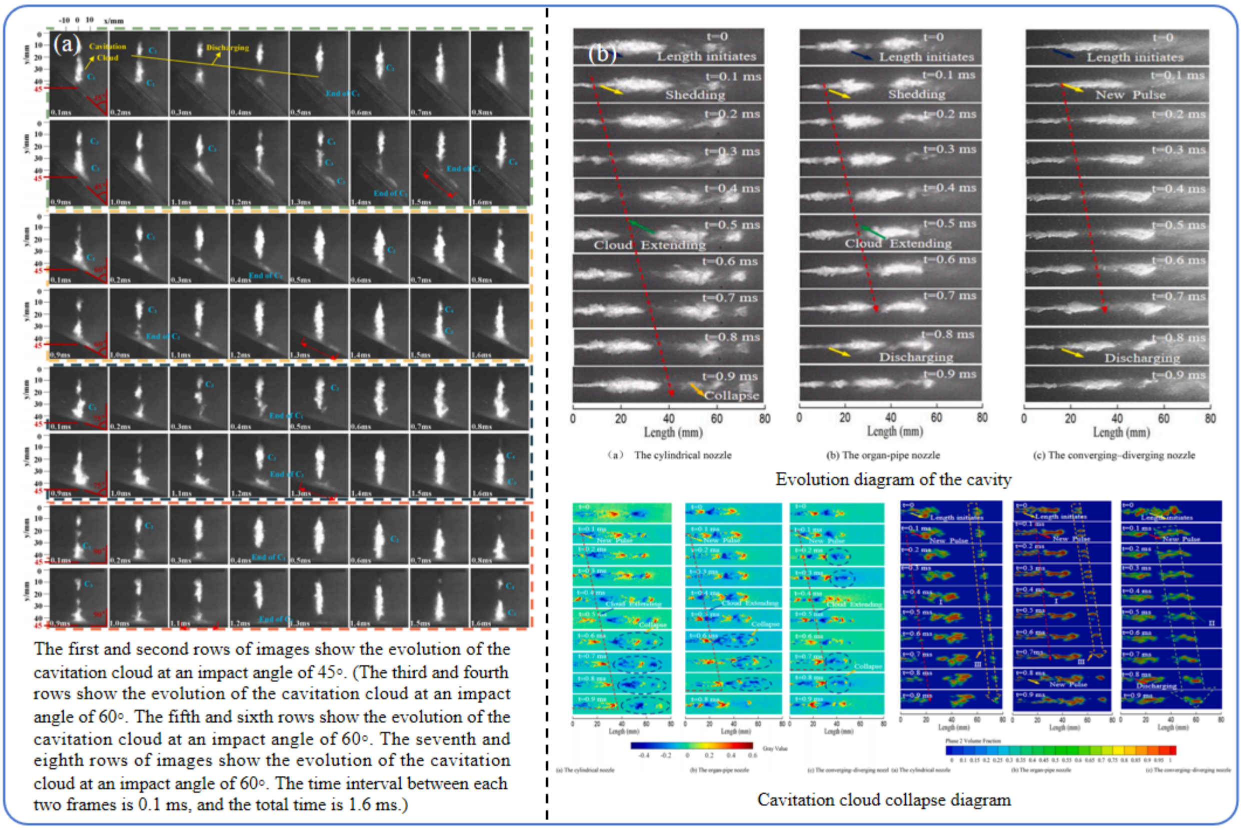

Figure 4. Schematic diagram of cavitation water jet machining mechanism [37, 38].

2.2 The principle of cavitation water jet enhancement

Cavitation occurs when the local pressure in a liquid drops to the vapor pressure of the liquid, leading to the formation, growth, and collapse of vapor bubbles within the liquid or at the liquid–solid interface [33–36]. High-pressure water jet systems are the most widely used carriers for cavitating water jet applications. The basic principle of the cavitating water jet strengthening process is to improve the surface properties of materials using cavitating water jets by controlling the system inlet pressure and nozzle geometry. A large number of cavitation nuclei undergo aggregation, inception, and growth inside and outside the nozzle, forming cavitation bubble clusters along with the high-speed liquid stream, as shown in Figure 4(a) [36]. When the bubble clusters approach the specimen surface, strong turbulent pressure pulsations cause a rapid increase in the ambient pressure around the bubbles, triggering cavitation collapse. The collapse of the bubbles releases a large amount of energy, which repeatedly acts on the workpiece surface, causing fragmentation of surface grains, thereby enhancing grain refinement and surface densification, and effectively increasing the surface microhardness, as shown in Figure 4(b)-(c) [37, 38].

In 1949, Plesset [39] defined three flow regimes of fluids, namely non-cavitating flow, cavitating flow with small bubbles, and cavitating flow with large bubbles, and derived the motion equations for cavitation bubble growth and collapse based on the second type of flow. By the 1960s, the concept of cavitating water jets was proposed. In 2002, Soyama et al. [40] from the United States proposed modifying surfaces in a manner similar to shot peening, where cavitation impacts could cause surface pinning without the need for shot media, achieving better surface roughness compared to traditional shot peening and significantly improving the fatigue strength of aluminum alloys. In 2019, Soyama [41] conducted a comparative study of various peening techniques applied to 316L stainless steel, including cavitating water jet peening, water jet peening, laser peening, and conventional shot peening, and the results showed that the sample treated with cavitating water jet peening exhibited the highest fatigue strength of 348 MPa. Peng et al. [42] successively confirmed the significant strengthening effect of cavitating jet peening on material surfaces, and demonstrated that it achieved better surface quality than conventional shot peening. The team led by Li

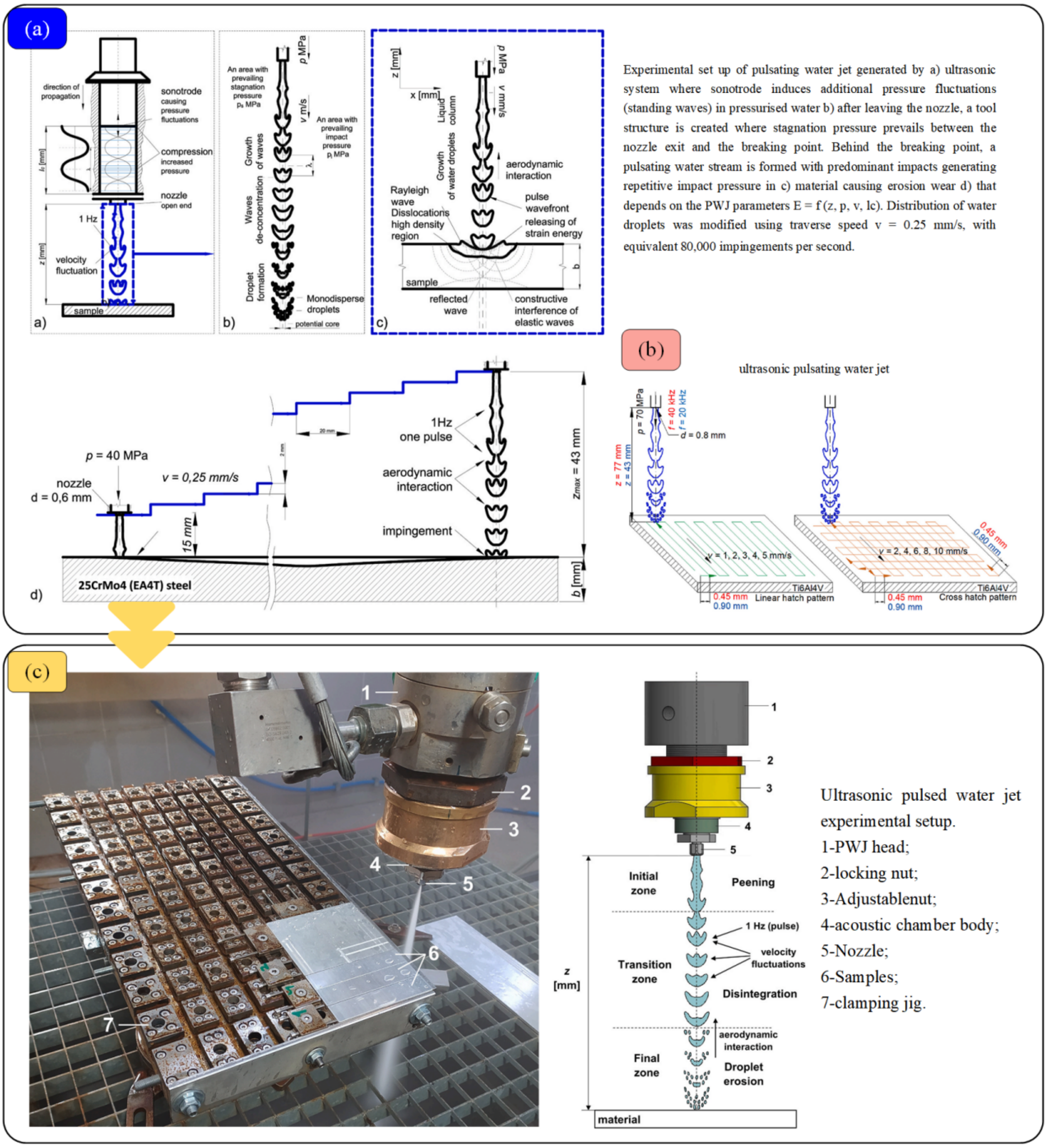

Figure 5. Schematic diagram of ultrasonic pulse water jet machining mechanism [45–47].

et al. [43] carried out in-depth research on cavitating water jet surface modification, observing the dynamic evolution of cavitation bubble clouds during the jetting process using high-speed cameras, and illustrated the action zone of the cavitating jet from a standard cylindrical nozzle with schematic diagrams, as shown in Figure 4(e). Balamurugan et al. [44] studied the residual stress state of workpieces after cavitating water jet treatment, and the results indicated that a shorter standoff distance could induce greater residual compressive stress, with reduced surface roughness compared to the untreated sample. In 2022, Yao et al. [38] proposed a hybrid surface modification technique combining cavitating and abrasive water jet peening. The results showed that it produced a deeper plastic deformation layer, reduced surface roughness by 28.5%, increased the maximum surface hardness by 21.1%, and generated a residual compressive stress layer as deep as 360 μm. Additionally, dislocation tangles and dislocation walls were observed in the subsurface at a depth of 15 μm.

2.3 The principle of ultrasonic pulse water jet enhancement

Pulsed jet impacts the target by utilizing the sudden increase in instantaneous jet velocity to achieve surface modification of the material. Compared to continuous jets, pulsed jets are inherently unsteady flows, with a velocity that varies periodically, and their impact force is much greater than that of continuous jets, as illustrated in Figure 5 [45–47]. Ge et al. [48] combined pulsed jet theory with hydraulic intensification principles, using a valve spool to alter fluid flow direction and drive the piston to reciprocate within the cylinder, and achieved synergistic coupling of "pulsing" and "pressurization" of the jet via the differential effective area between the piston's front and rear chambers, thereby generating an efficient self-sustained pulsed water jet (SSPWJ). Results showed that the generated jet exhibited distinct periodicity, and could achieve higher pulse peak pressure under relatively low inlet water pressure, with a measured pressure ratio error of less than 3%, confirming the feasibility of the method. In this study, Liu et al. [49] revealed through experiments and numerical simulations the nonlinear flow characteristics of impact-type pulsed water jets and the formation mechanism of their typical umbrella-shaped structure, and clarified the influence of multiple factors on pulse intensity and jet convergence performance. Srivastava et al. [50] found that ultrasonic pulsed water jet surface strengthening exhibited significant advantages over mechanical shot peening and laser shock peening. Lower pressure, slower nozzle traverse speed, and larger standoff distance significantly enhanced the surface residual stress (540 MPa) and microhardness (570 HV) of the workpiece. Siahpour et al. [51] employed ultrasonic pulsed water jet strengthening on commercially pure titanium and found that, compared with conventional shot peening, ultrasonic pulsed water jets induced greater residual compressive stress (391 MPa) and resulted in better surface roughness.

3 Comparison of Water Jet Surface Modification Technologies

3.1 Water jet surface modification grain refinement and residual stress analysis

Residual stress refers to the self-equilibrated internal stress present in a material or structure without the application of external forces [52]. When residual stress exists on the part surface, its ability to withstand external loads decreases, and deformation is more likely to occur. Components with residual tensile stress tend to exhibit reduced fatigue and corrosion resistance. However, controlling residual stress within a certain range can also yield beneficial effects. Residual compressive stress can improve the fatigue life of materials, suppress the formation of fatigue cracks, and refine grain size [53]. During the surface strengthening process of abrasive water jet, although inducing residual compressive stress can improve the fatigue life of the workpiece, the interaction between abrasive particles and the workpiece in the abrasive water jet process has randomness, superposition, and overlap, as shown in Figure 6(a). Liu et al. [17] proposed a theoretical model for predicting the plastic deformation and residual compressive stress of workpieces after surface modification with abrasive water jet (AWJP). (1)Analyzed the non-uniformity of AWJP jet beam energy distribution caused by the non-uniformity of abrasive size, spatial distribution, and impact velocity; (2) Material hardening between multiple impacts of abrasive particles; (3) Overlapping trajectory caused by AWJP jet beam. Based on different jet pressures, lateral velocities, and trajectory intervals, AWJP experiments were conducted for single channel, multi-channel, and multi overlapping trajectories, and the predicted models were in good agreement with the experiments. Research has shown that as the injection pressure increases, the residual compressive stress in the depth direction also increases, as shown in Figure 6 [54]. Abrasive particles with high kinetic energy provide higher external forces on the workpiece, resulting in a larger plastic deformation layer. In this case, the workpiece needs to generate higher internal stresses at deeper locations, namely residual compressive stresses. However, the model assumes that the shot peened surface is 100% covered and does not take into account the influence of uneven surface plastic deformation in local areas on residual stress distribution. During the strengthening process, abrasive particles collide with the surface of the workpiece, causing plastic deformation. The thickness of the plastic deformation layer increases with the increase of impact energy. The essence of plastic deformation lies in dislocation movement, and compared to untreated specimens, samples subjected to abrasive water jet strengthening exhibit significant dislocation accumulation at grain boundaries, which suppresses plastic flow in the work-hardened regions of the metal. The increased dislocation density leads to grain refinement and the formation of additional grain boundaries, requiring extra grain boundary energy to initiate and propagate cracks, thereby preventing the

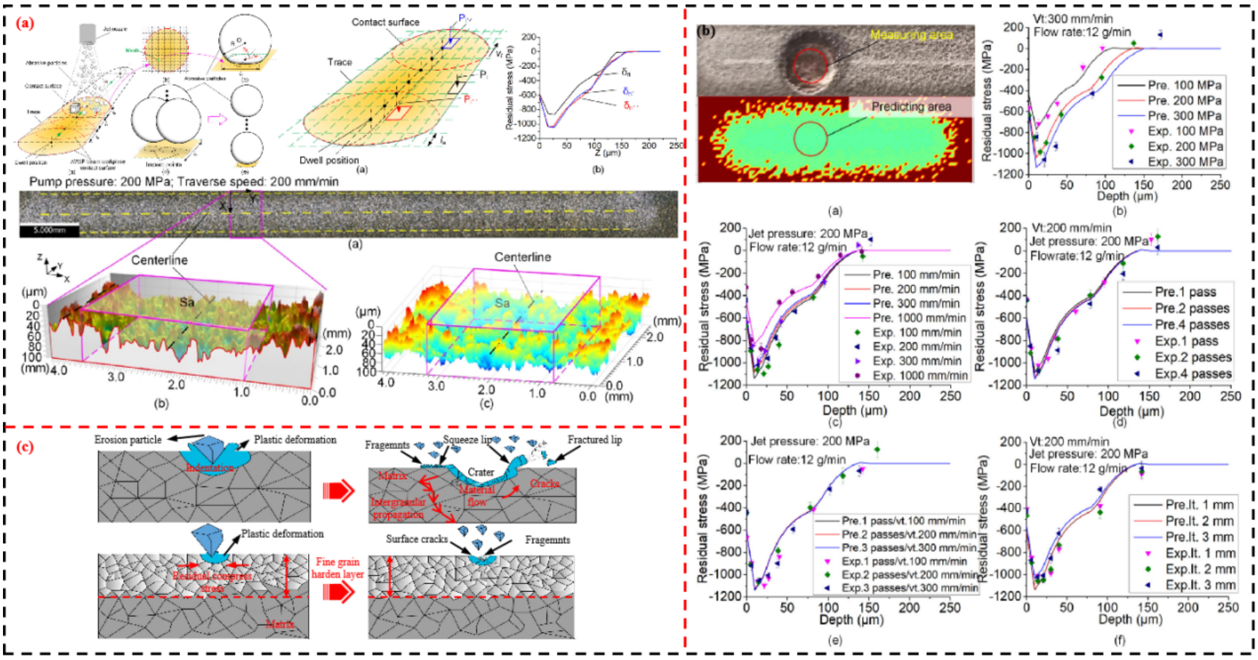

Figure 6. (a) Schematic diagram of abrasive particle–workpiece interaction and corresponding residual stress distribution [27]; (b) Schematic illustration of residual compressive stress prediction and experimental validation under different jet parameters [54]; (c) Schematic representation of plastic deformation and grain refinement in workpieces after abrasive water jet peening [55].

development of slip bands. The penetration depth of a single particle impact is relatively shallow due to the reduced impact effect caused by the presence of a hardened surface layer, as shown in Figure 6 [55]. Moreover, the metal specimen is strengthened through repeated particle impacts, and the grain refinement hinders grain boundary sliding, thereby impeding crack initiation and propagation, which ultimately improves the surface integrity of the workpiece.

In the cavitating water jet process, the mechanism of residual stress generation differs significantly from that of abrasive water jets. Cavitating water jet strengthens metals through a process involving cavitation bubble formation, growth, expansion, and collapse, during which the resulting micro-jets impact the surface. This causes the jet energy to be highly concentrated and confined within a narrow area, subjecting the workpiece to extremely high impact pressures and stress concentrations, resulting in substantial plastic deformation and achieving the strengthening effect, as shown in Figures 7(a)–(b) [56, 57]. Moreover, during the surface modification of metallic workpieces by cavitating water jets, dislocation accumulation and twinning deformation can also occur in the surface or subsurface layers, as a series of shock waves generated by the collapse of cavitation bubbles induce significant strain, high strain rates, and multi-directional cyclic loading on the specimen surface. These effects cause plastic deformation within the material, essentially through slip generation within grains, leading to dislocation accumulation, overlapping, and interaction with twinning deformation inside the material [33, 35]. As a result, the near-surface microstructure changes, leading to the formation of residual stress. With the increase in jet standoff distance, the impact energy applied to the specimen and the blocking effect of internal grain boundaries significantly decrease, resulting in considerable variation in impact effects among grains at different depths from the surface. This phenomenon was verified by Zhuang et al. [58] through cavitating water jet surface modification of Ti-Ni alloy, where the energy impact from bubble collapse caused partial surface grains to form sub-grains. During this process, dislocation density increased, leading to the activation of multiple slip systems, the formation of dislocation walls, subsequent plastic deformation, and the generation of residual compressive stress, as shown in Figure 7(c). During the cavitating water jet surface modification of 7075 aluminum alloy, Zhang et al. [59] similarly found that dislocation slip was the dominant deformation mechanism, accompanied by extensive plastic strain that induced the formation of high-density dislocation walls, dislocation tangles, and dislocation cells, as shown in Figure 7(b) [59]. Meanwhile, they concluded that the grain refinement process during cavitating water jet treatment could be divided into five stages:

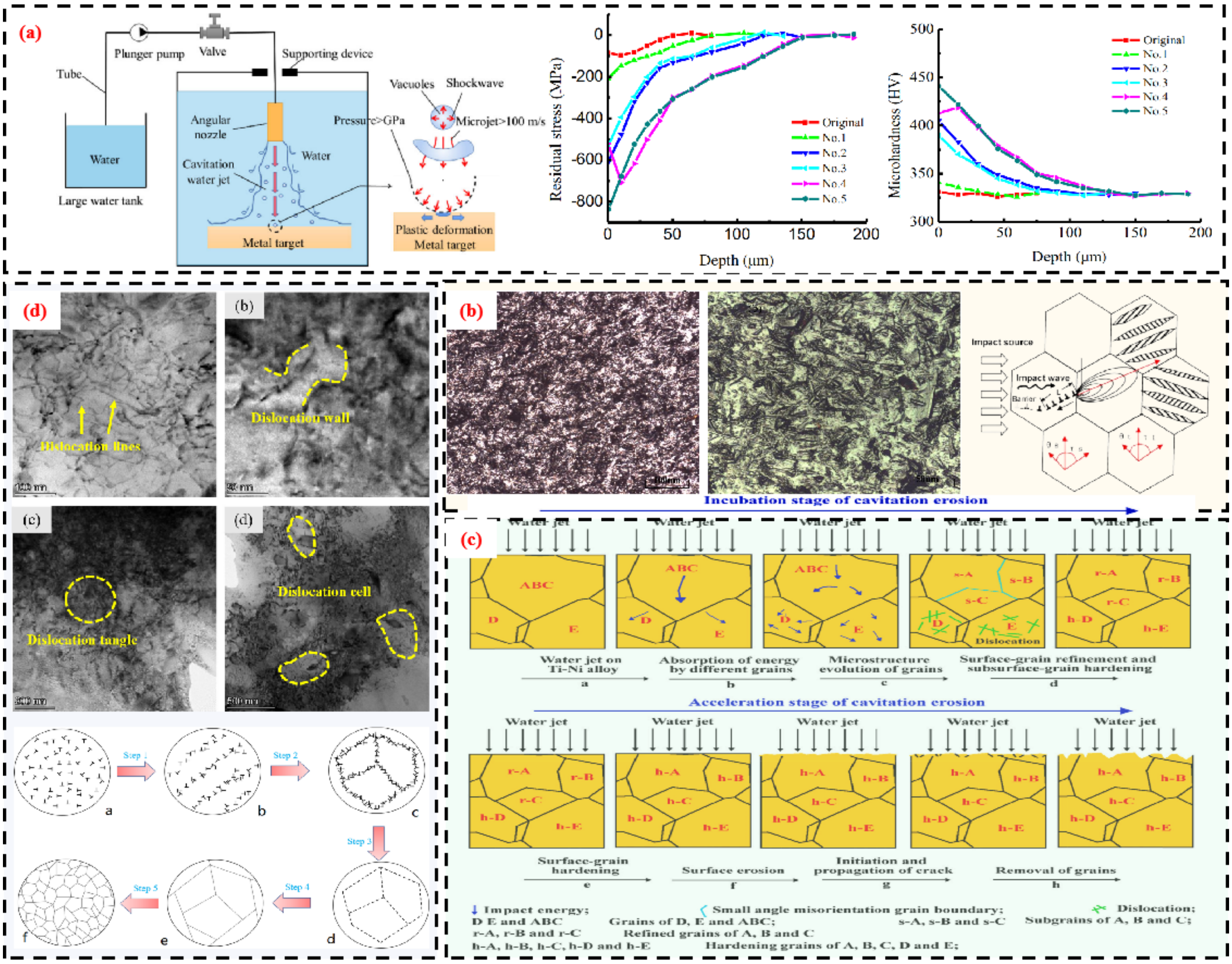

Figure 7. (a) Cavitating water jet system and curves of residual stress and microhardness before and after treatment [56];(b) Metallographic and microstructural features of the impact region [57];(c) Schematic diagram of microstructural evolution under water jet impact [58];(d) Dislocation phenomena in the workpiece after cavitating water jet surface modification [59].

- Step 1: The behavior of dislocations leads to the formation of dislocation lines within the original coarse crystal.
- Step 2: The accumulation of dislocation lines leads to the formation of dislocation walls and entanglement.
- Step 3: As the strain further increases, the individual dislocation units initially entangled by dislocations and separated by dislocation walls will gradually be subdivided into primitive subgrains.
- Step 4: When the deformation strain reaches a certain level, that is, when the dislocation density of the dislocation wall and the dislocation density of the dislocation entanglement reach a certain value, the annihilation of these dislocation rearrangements forms low angle grain boundaries and subdivides the original coarse grains into different subgrains.
- Step 5: The high-level accumulation of fault energy and dislocation slip leads to a continuous dynamic recrystallization process, resulting in further increase in grain boundary misorientation. Finally, the grain boundary properties gradually change until high angle grain boundaries are formed.

During the pulsed water jet surface modification process, the method is primarily based on an ultrasonically driven forced pulsed water jet, in which water is compressed into a high-pressure pulsed state and ejected at extremely high velocity, as shown in Figure 8(a) [60]. When these water jets impact the metal surface in pulsed form, it is equivalent to repeatedly "hammering" the metal surface. This high-speed impact generates a residual compressive stress layer of considerable depth, which can significantly improve the material's fatigue strength and hardness. The plastic deformation caused by the combined action of pulsed water jet and ultrasonic waves can result in strain hardening of the material surface and subsurface, i.e., deformation strengthening of the microstructure, and lead to grain refinement. Siahpour et al. [61] found that ultrasonic pulsed water jet (UPWJ) treatment can induce significant plastic deformation in the workpiece, as shown in Figure 8(b), and the UPWJ-treated specimens exhibited noticeable microcracks, which is mainly attributed to the periodic pulsed impact effect of UPWJ. Additionally, sufficient residual compressive stress was introduced during the process to induce work hardening in the material, and these microcracks mainly nucleated at grain boundaries. Surface erosion is an inherent phenomenon in surface modification processes, and it plays a critical role in the fatigue life of the workpiece. Therefore, Srivastava et al. [60] conducted an in-depth investigation into the effects of UPWJ on surface morphology. As shown in Figure 8(c) [50], they found that repeated pulsed impacts induced plastic deformation in the surface and subsurface layers, which resulted in microstructural changes in the affected zones. Moreover, lower pressure, slower traverse speed, and larger stand-off distance led to higher residual compressive stress and microhardness.

3.2 Fatigue Life Analysis of Water Jet Surface Modification

The fatigue failure process is mainly divided into three stages: crack initiation, crack propagation, and crack instability. Fatigue cracks often initiate in regions with stress concentration and low strength. The main mechanisms of crack initiation include: slip band cracking, cracking caused by second-phase particles, and grain boundary cracking [62]. Under cyclic loading, a large number of slip bands are generated within the grains of the specimen. Dislocation motion is hindered at grain boundaries, and with sustained cyclic stress, the strain at grain boundaries caused by slip bands continues to increase. This leads to intensified dislocation pile-up and stress concentration at grain boundaries, and when the stress exceeds the grain boundary strength, grain boundary cracking occurs, initiating microcracks. Therefore, water jet surface modification can induce plastic deformation in the material, altering its microstructure, increasing dislocation density, and refining grains, which suppresses the transmission of cyclic stress [63]. Additionally, plastic deformation introduces residual compressive stress to counteract the tensile stress induced by cyclic loading. This increases the energy required for crack propagation, thereby improving the fatigue life of the component.

Figure 9 illustrates the fatigue behavior after various types of water jet surface modifications. Abrasive water jet peening (WJP) is a novel surface modification technique with environmental and economic benefits, and the grains of the specimens are refined after WJP treatment, with the surface residual stress being primarily compressive. The strengthening effect is more pronounced in high-cycle fatigue conditions than in low-cycle regimes, as shown in Figure 9(a) [63]. Meanwhile, its microhardness, residual compressive stress, and tensile strength are significantly improved, while suppressing crack initiation and reducing crack growth rate. Macroscopically and microscopically, the fatigue striation spacing is smaller than in untreated specimens. It is found that after double-sided abrasive water jet peening treatment, the fatigue lives at stress levels of 93, 132, and 150 MPa were approximately 2,182,922, 258,000, and 56,575 cycles, respectively, representing a significant improvement compared to single-sided or untreated samples. Crack initiation often starts from surface defects, and water jet surface modification can effectively eliminate surface defects on components, as shown in Figure 9(b) [54]. Figure 9(d) shows the effects of pulsed laser water jet, shot peening, and cavitation water jet surface modification on the fatigue life of Ti6Al4V alloy. Pulsed laser water jet, shot peening, and cavitation water jet increased the fatigue life of AM Ti6Al4V by 3.5, 3.2, and 1.4 times, respectively [64].

3.3 Analysis of flow field structure inside water jet surface modified nozzle

The nozzle is the key to the final formation of water jet streams, and the shape of the nozzle directly affects the surface modification effect and application cost of various types of water jets. A water jet is generated through a nozzle or a series of structures that convert the pressure energy of water into kinetic energy and then eject a streamlined jet of water with high velocity and dynamic pressure. According to the ambient medium, water jets can be categorized into non-submerged and submerged jets. As shown in Figure 10(a) [65], it illustrates the schematic of jet structures under non-submerged and submerged conditions. Under non-submerged conditions, the jet travels through air after exiting the nozzle. The jet first passes through the potential core, where it maintains high velocity and minimal mixing with

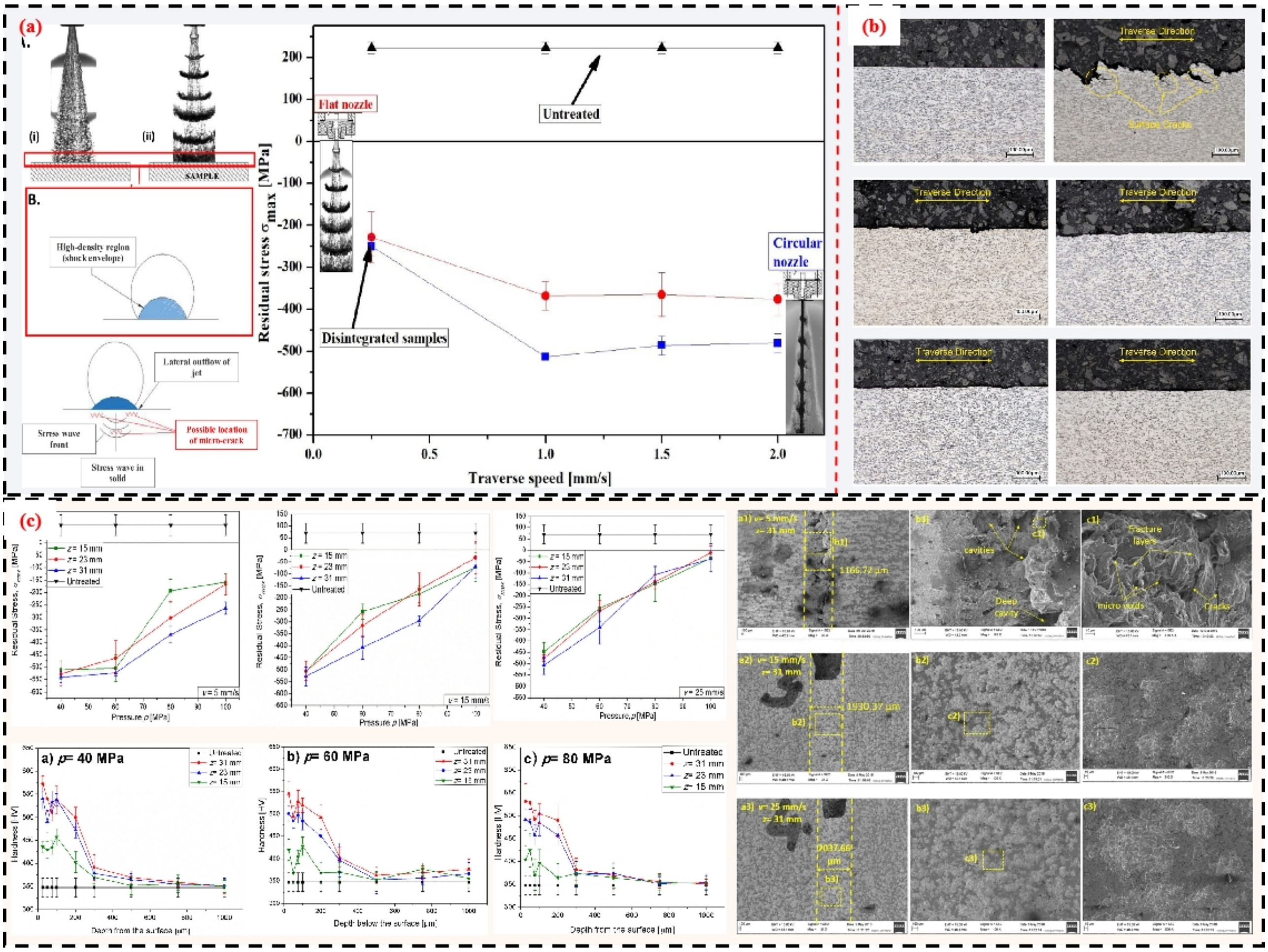

Figure 8. (a) Schematic illustration of pulsed water jet surface modification [60];(b) Plastic deformation of the specimen after pulsed water jet treatment [61];(c) Residual stress distribution and surface morphology of the specimen after pulsed water jet surface modification [50].

air. As the distance increases, the jet enters the main region, where the water begins to mix with air. Due to aerodynamic effects, the jet breaks into droplets and forms a ring-shaped droplet cloud. The momentum is mainly transferred to the surrounding air, the jet velocity gradually decreases, and lateral diffusion begins. In the droplet dispersion zone, the droplets are finer and nearly fully mixed with air. As shown in Figure 10(b) [66], the nozzle outlet geometry plays a crucial role in shaping the abrasive water jet (AWJ) flow field, directly affecting jet focusing efficiency, velocity distribution, stability, and abrasive particle distribution and velocity. Zheng et al. [66] conducted a comparative study on three abrasive water jet (AWJ) nozzle geometries—square, elliptical, and triangular—and found that the elliptical nozzle exhibited the greatest divergence in the jet stream. Among the three, the square nozzle showed the slowest axial velocity decay, while the elliptical nozzle displayed the fastest velocity attenuation and the shortest potential core region. Within a certain axial distance, the elliptical jet maintained a significantly broader high dynamic pressure zone compared to the other shapes, indicating a wider effective treatment area. This makes it particularly suitable for applications requiring large-area surface strengthening, such as weld surface enhancement. In general, AWJ systems utilize conical straight nozzles with abrasive feed ports to achieve high-efficiency material impact. In contrast, for cavitating water jets, nozzle design plays a pivotal role in initiating and sustaining cavitation, as specific geometries are required to generate localized pressure drops that lead to vapor cavity formation and collapse.

Cavitation nozzles are typically designed with specialized geometries that induce a localized pressure drop within the water jet stream, facilitating the formation of vapor bubbles. These bubbles subsequently collapse in downstream high-pressure regions, generating intense shock waves and shear forces. As shown in Figure 10(c), the

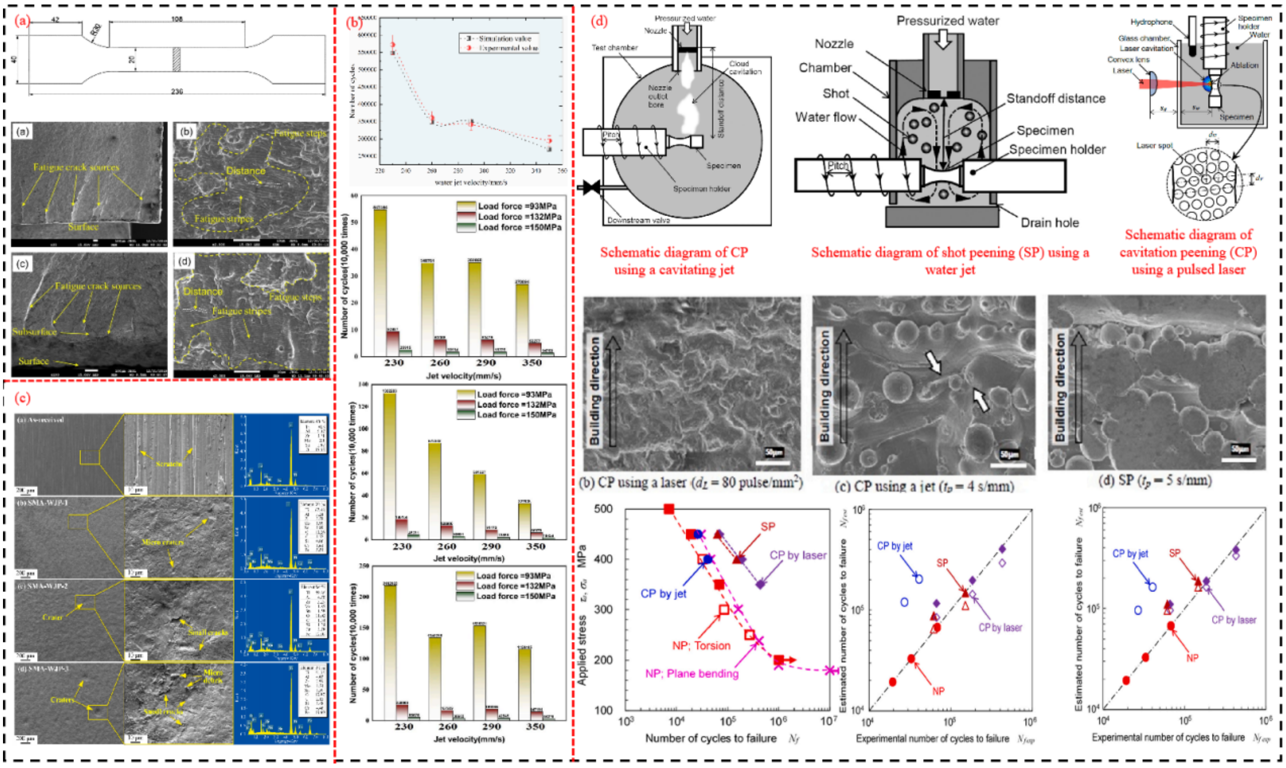

Figure 9. (a) Fatigue fracture morphology [63];(b) Fatigue life cycle characterization [54];(c) Surface morphology of specimens after surface modification;(d) Schematic diagrams of different water jet surface modification techniques [64].

convergent-divergent (C-D) nozzle represents a typical cavitation nozzle configuration [67]. Numerical simulation results indicate that cavitation first initiates at the entrance of the throat section, with the vapor volume fraction reaching its maximum in the expansion region where pressure remains relatively elevated. Once the jet exits the nozzle, strong turbulence develops in the external flow field. Shear-induced effects further intensify the cavitation process, with bubbles predominantly concentrated in the shear layer surrounding the jet core. As the distance from the nozzle increases, the jet moves beyond the low-pressure zone, resulting in a gradual decrease in bubble concentration until cavitation eventually ceases.

Figure 10(d) illustrates three nozzle geometries used in pulsed water jet applications: straight, conical-straight, and convergent-divergent designs [68]. For the straight nozzle, the water jet begins to expand laterally upon exiting the nozzle, forming a characteristic mushroom-shaped jet. As the jet velocity increases, the degree of lateral expansion becomes more pronounced, resulting in thinner radial liquid films. Under the combined influence of surface tension and aerodynamic forces, the edge of the liquid film begins to exhibit slight atomization. In this configuration, the jet develops more rapidly in the axial direction than in the radial direction. Compared to the straight nozzle, the conical-straight nozzle provides a longer effective range for pulsed water jet applications. Its converging section accelerates the jet further before it exits into the surrounding air, thereby enhancing jet coherence and exit velocity. Although the jet still undergoes lateral expansion due to air resistance—forming a mushroom-shaped profile—and experiences stronger aerodynamic disturbances than the straight nozzle, the conical-straight nozzle maintains superior jet velocity and focus, resulting in a more pronounced lateral spread. In contrast, the gradually diverging nozzle induces lateral expansion at the initial stage of jet formation. At the jet front, the lateral width reaches its maximum due to flow deceleration and loss of collimation caused by the divergent section, promoting a more turbulent flow regime that enhances the jet's tendency to expand radially in the external environment.

4 The application difficulties of water jet surface modification technology

In practical applications, water jet surface modification technologies inevitably encounter various challenges. A comprehensive analysis of the induced residual stress, fatigue life, and internal–external flow field characteristics associated with different water jet

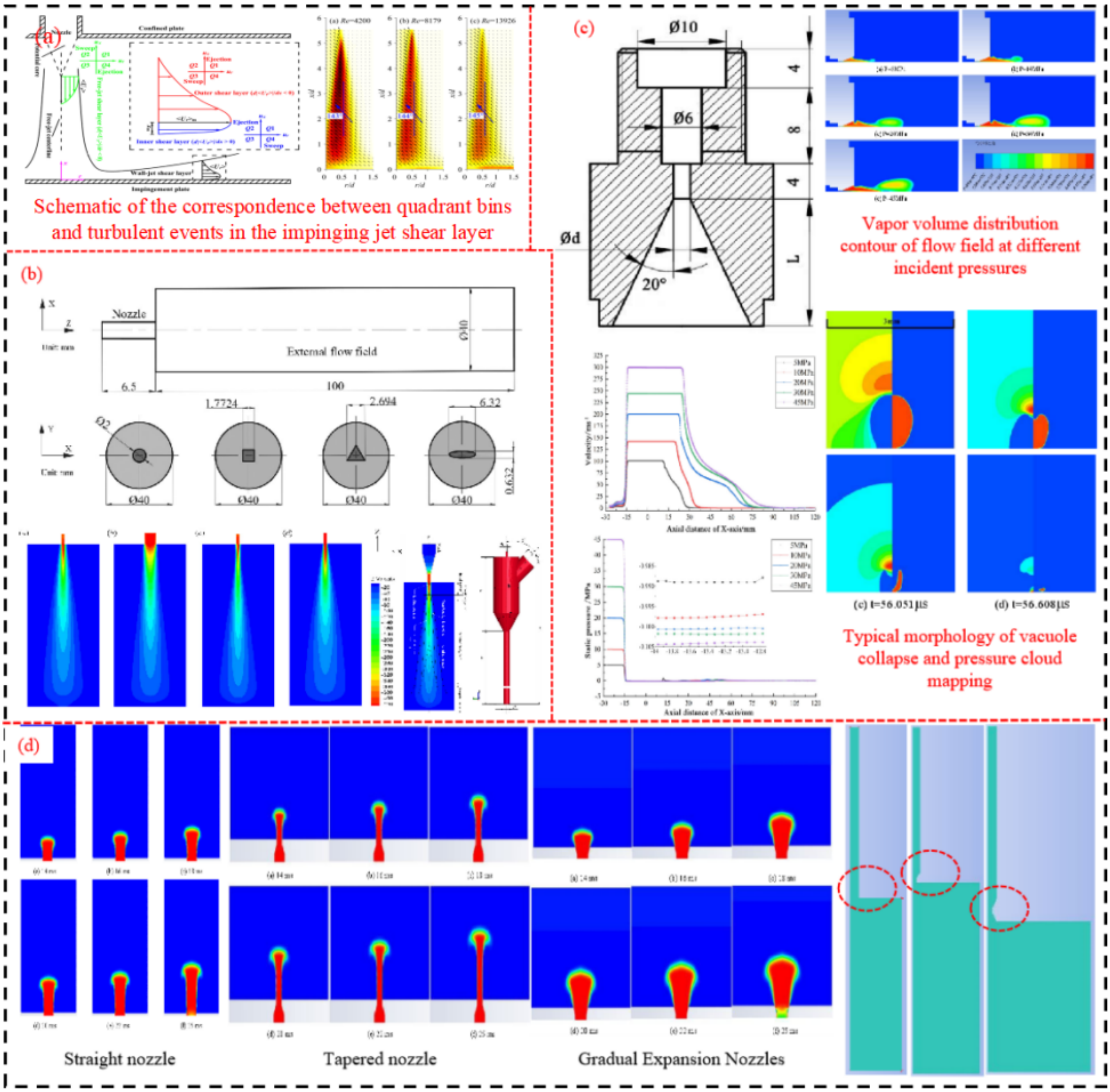

Figure 10. (a) Flow field structures under submerged and non-submerged conditions;(b) Outlet geometries of abrasive water jet nozzles and their corresponding flow field structures;(c) Simulated flow field contour map of cavitating water jet;(d) Simulated flow field structure of pulsed water jet [65, 66].

nozzle types can provide valuable insights for selecting the most appropriate water jet surface modification technique.

At present, research on water jet surface modification technologies is gradually shifting from macroscopic performance evaluation toward the exploration of microstructural evolution mechanisms. However, one of the major challenges in applying water jet surface modification lies in the complexity of process parameter control. Particularly for abrasive water jets (AWJ), cavitating water jets (CWJ), and pulsed water jets (PWJ), key parameters such as jet pressure, standoff distance, nozzle traverse speed, path spacing, and nozzle geometry have a direct impact on the surface quality of treated specimens. In AWJ, the type and concentration of abrasive particles must be carefully optimized. For CWJ, the dynamic behavior of cavitation bubbles—including their formation, growth, and collapse—must be considered. PWJ, on the other hand, involves the interaction of pressure waves and unsteady fluid dynamics, making its influence on surface integrity equally critical. When the high-speed jet impinges on the specimen surface, it can induce significant plastic deformation and introduce a compressive residual stress layer. However, this impact is often accompanied by material erosion, which increases surface roughness. For instance, in aluminum alloy surface modification using jet pressures ranging from 20 to 50 MPa, the resulting surface roughness was reported to fall within the range of 0.86 to 0.958 μm.

As a critical component in water jet surface modification technologies, nozzles must be specifically designed to accommodate different types of jetting mechanisms. Abrasive water jet (AWJ) nozzles require effective mixing and uniform ejection of abrasive-laden water streams, which imposes high demands on the nozzle's wear resistance and internal structure. During operation, abrasive particles move irregularly within the nozzle and inevitably collide with the inner walls, causing significant erosion. Du et al. [67], through simulation-based analysis, confirmed that the primary wear regions in AWJ nozzles are located at the junction between the mixing chamber and the focusing tube. For cavitating water jets (CWJ), the nozzle must be capable of generating stable cavitation by inducing pressure fluctuations within the water stream that facilitate the rapid formation and collapse of vapor bubbles. This requires careful control of fluid velocity and pressure, and such nozzles typically adopt specialized geometries to enhance both cavitation generation and bubble collapse. In contrast, pulsed water jets (PWJ) demand rapid release of large amounts of energy within short durations, requiring nozzles to withstand intermittent high-pressure loading. Accordingly, PWJ nozzles are generally robust, often incorporating fast-actuating mechanisms to modulate jet pulsation. These nozzles may require advanced materials and structural designs to mitigate wear and extend service life.

5 Conclusion

This review summarizes the latest research progress in water jet surface modification technologies for metallic components. It primarily discusses the current development status and processing mechanisms of various water jet-based surface modification techniques. Through a comparative analysis of different water jet approaches, the following conclusions can be drawn:

1. The abrasive water jet (AWJ) surface modification technique utilizes high-speed jets carrying abrasive particles to impact the specimen surface, inducing localized severe plastic deformation. This process introduces a compressive residual stress layer of considerable depth and promotes grain refinement, which helps suppress the initiation and propagation of fatigue cracks, thereby enhancing the material's fatigue life. During AWJ operation, the internal and external flow fields of the nozzle are characterized by uniform jet velocity and high kinetic energy. The internal nozzle design must ensure thorough mixing of water and abrasive particles and facilitate their uniform ejection, minimizing the risk of clogging and erosion. A smooth internal flow field is essential to reduce turbulence and maintain the stable distribution of abrasives within the jet. Externally, the jet's focusing ability and effective coverage area must be considered to achieve precise control over the treatment depth and coverage on the workpiece surface.

2. Cavitating water jet (CWJ) technology enhances material surfaces by inducing cavitation phenomena through high-speed water jets. Cavitation refers to the formation of vapor bubbles or cavities in a fluid due to localized pressure drops, followed by their rapid collapse as pressure recovers, releasing significant energy. This process generates micro-jets and high-pressure shockwaves that repeatedly impact the material surface. By appropriately controlling the peening duration, grain fragmentation in the surface layer can be achieved, thereby improving grain refinement and microstructural densification, and significantly increasing surface microhardness. The collapse of cavitation bubbles acts as a soft "hammering" effect that plastically deforms the surface and sub-surface layers, inducing beneficial compressive residual stresses and enhancing the material's fatigue life. The working principle of CWJ relies on abrupt changes in jet velocity that create localized low-pressure zones where vapor bubbles form. These bubbles subsequently collapse in high-pressure regions, producing intense shockwaves. The key to nozzle design in CWJ lies in generating and sustaining effective cavitation zones, which requires precise control of pressure and flow velocity. Typically, convergent-divergent nozzle geometries are employed to support the formation, growth, and collapse of vapor bubbles.

3. Pulsed water jet (PWJ) surface modification technology enhances material surfaces by intermittently applying high-pressure water jets. Compared to continuous jets, pulsed jets deliver significantly higher peak impact forces, enabling efficient surface treatment within shorter durations. A typical PWJ system comprises a high-pressure pump, a pulse generator, and a nozzle. The high-pressure pump generates a continuous jet stream, which is then modulated by the pulse generator into a pulsating flow. This pulsed flow is subsequently accelerated and ejected through the nozzle. Upon impingement on the workpiece surface, the high-energy pulsed jets generate intense shockwaves that induce plastic deformation in the surface and subsurface regions while introducing compressive residual stresses. These effects contribute to improved fatigue life. The residual stresses and plastic deformation are primarily achieved through mechanical impact and stress wave propagation. Additionally, grain refinement and increased dislocation density further suppress tensile stresses caused by cyclic loading, enhancing the material's fatigue resistance.

Data Availability Statement

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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Xiujie Yue The 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: yuexiujiea@163.com)

Ping Zhang 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: zpqdhhxy@126.com)

Xuezhao Wang, male, Ph.D./Postdoctoral Fellow, born in December 1994, Binzhou, Shandong Province, is a member of the Chinese Society of Mechanical Engineering and the Nonferrous Metals Society. He has long been engaged in research on the preparation and processing of high-strength light alloy materials, plastic toughening mechanism and corrosion protection against friction and wear. (Email: wxzqut_edu@163.com)

Yeran Gao The 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)