Improving the low-cycle fatigue properties of laser-welded Al–Zn–Mg–Cu alloy joints using double-sided ultrasonic impact treatment

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Abstract
To improve the low-cycle fatigue properties of Al–Zn–Mg–Cu 7075 aluminum alloy laser-welded joints, a post-weld treatment method for double-sided ultrasonic impact treatment (DSUIT) was used to treat the joints. The mechanism of different DSUITs on the microstructure and fatigue properties of welded joints was analyzed. The results showed that DSUIT reduced the welding defects and roughness of the joint surface, and the dendrite structure at the upper and lower surfaces of the joints was broken to form a plastic deformation layer (PDL) with an approximate thickness of 100 μm. Furthermore, the texture strength and grain size at the PDL were reduced. A beneficial residual compressive stress was introduced into the upper and lower surfaces of the joints after DSUIT. When the number of cycles was 2 × 10⁶, the maximum fatigue strength of the joints was 103.02 MPa after DSUIT, indicating an increase of 111.8% of the untreated joints of 48.62 MPa. Moreover, observance of the fatigue fracture of the joints revealed that the PDL produced by the DSUIT inhibited the initiation and propagation of cracks at the surface. Therefore, the DSUIT effectively improved the low-cycle fatigue properties of the joints.

1. Introduction

The Al–Zn–Mg–Cu 7075 aluminum alloy is characterized by high specific strength, good fracture toughness and excellent low-cycle fatigue resistance. It is widely used in transportation, aerospace, and other fields [1–4]. The 7075 aluminum alloy is generally welded using tungsten-insert gas welding, metal-insert gas welding, and laser welding [5]. Laser welding can achieve high welding speed, high energy density, narrow weld, and less deformation for high-precision welding [6–9]. Therefore, the laser-welding method is adopted in the present study for the 7075 aluminum alloy.

In the welding process, the 7075 aluminum alloy faces serious weldability problems, especially in the fusion-welding process where the weld microstructure is loose and the weld exhibits serious porosity and other defects [10], which reduce its application in actual situations. Most of the fatigue fractures in the welded components of aluminum alloy in actual engineering application originate from the welded joints. Therefore, to improve the fatigue properties of 7075 aluminum alloy laser-welded joints, post-weld mechanical treatment, which is a relatively common method, is applied. Generally, the post-weld mechanical treatment methods are the following: laser shock peening (LSP) [11, 12], ultrasonic surface rolling extrusion (USRE) [13], ultrasonic shot peening (USP) [14], and ultrasonic impact treatment (UIT) [15, 16]. Each of these technologies has its own unique characteristics, which exert different effects on the surface morphology, the depth of plastic deformation layer (PDL), and degree of grain refinement of aluminum alloy. Therefore, the fatigue properties of the laser-welded joint of 7075 aluminum alloy can be improved by selecting an appropriate treatment.

Kashaev et al [17] improved the fatigue behavior of AA6056-T6 laser beam butt joints by applying laser shock strengthening. Their results showed that LSP is a very promising technology that can increase the fatigue life of welded joints by 20%. Liu et al [18] studied the fatigue behavior of Ti–6Al–4 V alloy after USRE. Their results demonstrated that the fatigue properties of the Ti–6Al–4 V alloy were significantly enhanced after USRE, but its
surface suffered from large surface roughness. Vaibhav et al. [19] studied the microstructure and low-cycle fatigue behavior of 7075 aluminum alloy after USP and demonstrated that a suitable USP process can prolong the fatigue life of the sample. However, a too long USP reduces the fatigue life. Li et al. [20] discussed the strengthening mechanism of ultrasonic impact and showed that the UIT technology can significantly improve the hardness, strength, and wear resistance of a material surface. In addition, the residual tensile stress at the material surface could be released by ultrasonic impact on the material surface while restoring the beneficial compressive stress and improving the material performance.

The above-mentioned several post-weld mechanical treatment methods can prolong the fatigue life of welded joints. However, the cost of LSP is high, and the processing method is more complicated. The surface of the samples processed by USRE has relatively large roughness, and this processing method is more suitable for treatment of flat materials. Because the 7075 aluminum alloy laser-welded joints are uneven, USRE is not suitable for their post-weld mechanical treatment. USP is more suitable for processing small-sized samples. Those with different shapes must be produced according to their corresponding fixtures. UIT is characterized by low cost, portability, ease in operation, flexible replacement of impact head, and wide applicability. Therefore, in this study, the UIT post-weld mechanical treatment is used to treat 7075 aluminum alloy laser-welded joints.

In this study, we perform a post-weld double-sided UIT (DSUIT). The upper and lower surfaces of the welded joints are treated by ultrasonic impact. The influence mechanism of different DSUIT processes on the microstructure and fatigue properties of the welded joints is investigated and analyzed. We believe that this study can provide a theoretical foundation for the application of laser welding of 7075 aluminum alloy.

2. Materials and methods

The test material was a 3 mm thick 7075 aluminum alloy rolled sheet (SW Aluminum, Chongqing, China). Its chemical composition is listed in table 1. The welding equipment comprised an IPG YLS-10000 fiber laser (IPG Potonics Corporation, Santa Clara, CA, USA) and a KUKA welding robot (KUKA Roboter GmbH, Augsburg, Bavaria, Germany), which performed butt welding on a 160 × 80 × 3 mm³ base metal. The schematic diagram of the laser welding is shown in figure 1. The laser-welding process parameters are listed in table 2.

In the ultrasonic impact test, a UIT-125 ultrasonic impact machine (Tianjin Dongcheng Science and Technology Development Co., Ltd., Tianjin, China) and a self-developed three-dimensional sliding-platform system were combined to treat the welded joints. The test impacted both the upper and lower surfaces of the
welded joints. The movement of the impact needle from the start to the end of the welded joints was counted as one impact. The DSUIT test parameters are listed in table 3. The designations of the samples after different DSUITs are listed in table 4. The DSUIT schematic is shown in figure 2.

An optical microscope (Zeiss, Oberkochen, Jena, Germany) was used to observe the changes in the weld-zone microstructure under different processes. An LSM 700 laser scanning confocal microscope (Carl Zeiss, Germany) was used to investigate the surface roughness of the welded joints before and after the ultrasonic impact. Vickers hardness test (Matsuzawa, Akita, Japan) was used to test the microhardness of the welded joints surface under the different processes. The test loading force was 1 N, the loading time was 10 s. A FEI-QUANTA

**Table 3. DSUIT test parameters.**

| Working frequency \(f\) KHz\(^{-1}\) | Working current \(i\)/A | Diameter of impact needle \(d\) mm\(^{-1}\) | Velocity of impact needle movement \(v\) mm\(^{-1}\) s\(^{-1}\) | Impact times/N |
|----------------------------------------|-------------------------|---------------------------------|---------------------------------|----------------|
| 20                                     | 2.0                     | 3                               | 30                              | 150            |

**Table 4. Designations of the samples after different DSUITs.**

| Treatment process | Impact times of upper surfaces of the welded joints/N | Impact times of lower surfaces of the welded joints/N | Names of sample |
|-------------------|-------------------------------------------------------|------------------------------------------------------|-----------------|
| 0                 | 0                                                     | 0                                                    | UN              |
| 150               | 0                                                     | 0                                                    | DSUIT0          |
| 150               | 50                                                    | 100                                                  | DSUIT1          |
| 150               | 100                                                   | 150                                                  | DSUIT2          |
| 150               | 150                                                   | 150                                                  | DSUIT3          |
650 scanning electron microscope (FEI, Hillsborough, FL, USA) was used to perform point scanning, electron backscatter diffraction (EBSD) analysis of the welded joints under DSUIT, and scanning electron microscopy (SEM) analysis of the fractures of the fatigue specimens. The phase of the joints was analyzed using X-ray diffraction (XRD). A μ-X360s residual stress test (Pulstec, Japan) was performed to analyze the longitudinal and transverse residual stresses of the welded joints under different processes. The microstructure observation and residual-stress test method of the welded joints are shown in figure 3.

The fatigue properties of the welded structural parts were investigated using the MTS landmark servo-hydraulic test system (Mets Industrial Systems Co., Ltd., China). Stress cycle ratio $R = 0.1$, and the loading frequency was 45 Hz. The fatigue specimen size are shown in figure 4.

3. Results and discussion

3.1. Effect of DSUIT on the microstructure of welded joints

Figure 5 shows the surface morphology, surface roughness, and the surface PDL of the welded joints before and after the DSUIT. Figure 5(a) show that the surface of the UN welded joints without DSUIT displayed a regular water-wave stripe, and the surface of the joint was uneven with obvious welding defects. After the DSUIT, the uneven water-wave lines at the joint surface disappeared, the originally rough joint surface became flat and smooth, and the welding defects were significantly reduced (figure 5(b)). The surface roughness of the welded joints before and after the DSUIT was observed using a laser confocal scanning microscope. The results are shown in figures 5(c) and (d). On the other hand, the UN joint surface-roughness value was 116.77 $\mu$m, and the DSUIT3 joint surface-roughness value was 14.96 $\mu$m. Figure 5(e) and (f) show the PDL microstructure at the upper and lower surfaces of the DSUIT3 joints, respectively. The PDL thickness at the upper surface was 95 $\mu$m, and that at the thickness of PDL on the lower surface was 107 $\mu$m. According to the Vickers hardness test, the
UN welded joint surface microhardness was 132 HV, however, after the ultrasonic impact of the welded joint, the surface microhardness of the PDL reached 184 HV.

Comprehensive analysis revealed that the welding defects and roughness of the joint surface were significantly reduced after the DSUIT, and the smooth and flat joint surface effectively reduced the stress-concentration phenomenon of the welded components in the stress process, which was beneficial in prolonging the fatigue life of the welded components. Moreover, a dense PDL was formed at the surfaces of the welded joint after the DSUIT. The original dendrite structure at the welded joints was broken after the DSUIT. The PDL formed at the surface layer was composed of fine grains, and the microhardness of this area was strengthened. This structure inhibited crack initiation and propagation during the fatigue process of the welded components. We found that the PDL thickness at the upper surface was less than that at the lower surface after the DSUIT. This phenomenon was caused by the high-temperature volatilization of the 7075 aluminum alloy welded joints of the Zn and Mg elements and local depletion of these volatile elements (usually via irregular vaporization), which led to keyhole collapse. Thus, the upper surface of the welded joint was lower than that of the base metal [21]. Therefore, during the DSUIT of the upper surfaces of the welded joint, the weld toe part was impacted first so that the ultrasonic impact strength at the upper surface was lower than that at the lower surface. Hence, the PDL thickness of the upper surface was small.

Figure 6 shows the microstructure and phase-element composition of the welded joints. Similar to those shown in figure 6(a), the grains of the joints affected by the DSUIT were very fine, and no obvious grain and grain-boundary morphology were observed. The plastic deformation zone (Q1) and undeformed zone not affected by the DSUIT (Q2) were selected for analysis of the joints. When the welded joint was not subjected to the DSUIT, the microstructure of the joint was similar to that of cast dendrite (figure 6(b)). When the welded joints were subjected to DSUIT, the dendrite structure was broken, and no dendrite structure appeared at the surface layer of the joints (figure 6(c)). The dendrite grains and grain boundaries in the Q2 zone were analyzed using a point-scan element analysis (figure 6(d)). The results are shown on figures 6(e) and (f), respectively. The grain boundary at point 1 was composed of AlZnMgCuSi eutectic, and that at point 2 was composed of T (AlZnMgCu) phase.

In summary, the dendrite structure of the surface layer of the welded joints was transformed into a dense PDL after DSUIT, which was very beneficial in improving the mechanical properties of the welded joints. Because of the coarse dendrite structure, the grain boundary was composed of AlZnMgCuSi eutectic, and the Si element content was high. Thus, the eutectic phase at the grain boundary was brittle. During the plastic deformation of the welded joints, because of the incongruity between the deformation of the matrix and brittle phase, pores were easily produced on some brittle-phase particles and at the boundary of the matrix. This condition resulted in microcracks inside the joints and development of macro cracks in the joints, which were
very detrimental to the plasticity and fracture toughness of the welded joints. Moreover, the fatigue properties of the joint were indirectly reduced. Therefore, the DSUIT refined the brittle-phase particles by breaking the coarse and non-uniform dendrite structure at the welded joints, effectively reduced the generation of internal microcracks in the plastic deformation process, and improved the service life of the welded components.

3.2. EBSD characterization of the weld zone after DSUIT of the welded joints

To study the microstructure and stress changes of the welded joint after the DSUIT, the microstructure of the welded zone was investigated using the EBSD method. The TSL-OIM Analysis software was used to analyze the EBSD test results, and the grain, stress distribution, and pole were obtained. The TSL-OIM Analysis software was also used to analyze the grain size of the different areas in the joints, and the average grain size was calculated. The analysis results are shown in figure 7.

PDL was formed in the welded joints after the DSUIT, and the internal microstructure was changed. Therefore, Z1, Z2, and Z3 were selected on the samples corresponding to the undeformed zone that was not affected by the DSUIT, transition zone between the undeformed and plastic-deformation zones, and plastic-deformation zone, respectively (figure 7(a)). From the EBSD analysis of these three zones, the influence of

![Figure 7. EBSD characterization of the weld zone after DSUIT of the joints. (a) Microstructure zones. (b) Grain figure. (c) EBSD stress-distribution figure. (d)–(f) Z1–Z3 polar figure. (g)–(i) Z1–Z3 average grain size.](image-url)
DSUIT on the microstructure and stress of the welded joints was explained. From the grain figure (figure 7(b)), we can intuitively to observe the changes in the grains in different zones. The grains in the Z1 zone were equiaxed grains, those in the Z2 zone were composed of equiaxed grains that were partially deformed by impact and partially broken fine grains, and those in the Z3 zone were composed of the all fine grains. After the DSUIT, the microstructure was strengthened. Moreover, a large residual compressive stress was observed at the range of approximately 200 μm near the surface of the welded joints (figure 7(c)). Figure 7(d) shows the pole of the Z1 zone. The maximum texture strength in this zone in the {100} and {111} planes was 5.541. The average grain size in the Z1 zone was 29.34 μm (figure 7(g)). Figure 7(e) shows the pole of the Z2 zone. The maximum texture strength in this zone on the {100} and {111} planes was 5.761. The average grain size in the Z2 zone was 16.64 μm (figure 7(h)). Figure 7(f) shows the pole of the Z3 zone. The texture strength in the {100} and {111} planes was reduced to 3.265, the strength of the texture was the lowest, and the Z2 zone exhibited the highest texture strength. The average grain size in the Z3 zone decreased to 3.72 μm (figure 7(i)).

Therefore, DSUIT refined the grain at a certain depth near the surface of the welded joints. Moreover, because the impact energy continuously acted on the joints, the residual tensile stress at the joints was transformed into a residual compressive stress. A high residual compressive stress existed in the depth range of 200 μm from the joint surface. Through the mechanical-strengthening effect of the ultrasonic impact, the equiaxed grains in the plastic-deformation zone of the welded joint were refined, and the texture of the joints was broken under the impact. We could observe from the grain figure that the grains at the joint had a free-grain orientation. We could also learn from the pole of each zone that the texture strengths in the {100} and {111} planes were not very different, which indicated that the texture of the joint was freely oriented. The texture strength of the Z2 zone was higher than that of the Z1 and Z3 zones, which was due to the severe plastic deformation of the grains in the transition zone, leading to a slight increase in the texture strength in this zone. However, the grains in each zone of the joint still had a free-grain orientation. The difference was that the free-grain orientation in the plastic-deformation zone was higher. Moreover, the texture strength in the plastic-deformation zone of the joints was lower than that in the undeformed zone of the joints (The untreated joint crystal grains were equiaxed crystals, and the texture strength in the direction parallel to the welded joint was relatively large; thus, the strength of the welded components in the direction perpendicular to the weld seam was relatively low.) This type of texture was beneficial for the application of welded components in a complex stress environment. During the loading process of the 7075 aluminum alloy laser-welded joints, the cracks usually originated from the joint surface. However, the grains in the plastic-deformation zone of the joints from the DSUIT exhibited a high density and favorable texture conditions, which effectively prevented the initiation and expansion of the joint cracks. Moreover, the refined texture significantly improved the fatigue life of the welded components in the direction perpendicular to the weld zones.

### 3.3. Effect of DSUIT on the phase of welded joints

Figure 8 shows the XRD phase-analysis results of the UN and DSUIT3 welded joints. Figure 8 shows that the phase of the joint did not change after the DSUIT. The results showed that the width of the phase peaks became

![Figure 8. XRD results of the UN and DSUIT3 welded joints.](image)
wider after the DSUIT, which indicated that the ultrasonic impact made the grains at the surface finer. Scherrer equation [22] was used to calculate the grain size at the surface of the DSUIT3 joint, as expressed in equation (1).

\[ D = \frac{K\lambda}{(\beta \cos \theta)} \]  

(1)

\( K \) is a constant, and \( K = 1 \); \( \lambda \) is the wavelength of the X-ray, \( \beta \) is the full width at half maximum of the diffraction peak, and \( \theta \) is the diffraction angle.
The results demonstrated that the grain size at the surface of the joint was 38.66 nm. Therefore, only the grain size of the joint was refined after the DSUIT, and the original phase of the joints was not changed.

3.4. Effect of DSUIT on the residual stress of welded joints

Figure 9 shows the comparison results of the longitudinal and transverse residual stresses of the UN welded joints parallel to the welding direction. The variation trends in the longitudinal and transverse residual stresses of the joints were roughly the same. Furthermore, the longitudinal residual stress indicated a tensile stress, and the transverse residual stress indicated a compressive stress. Because the residual stress of the joints after the DSUIT must be a residual compressive stress, we selected the longitudinal residual stress of the welded joints at different treatment stages for comparative analysis so that we could more intuitively analyze the influence of the DSUIT on the residual stress of the joints, as shown in figure 8.

Figure 10 shows the comparison of the longitudinal residual stresses of the welded joints under different treatment processes. Figure 10(a) shows the residual stress in the parallel welding direction at the upper surface, and the residual stress of the UN joint was determined as a tensile stress. When the surface was ultrasonically impacted, the stress at the joint changed from a residual tensile stress to a residual compressive stress. The residual compressive stress at the upper surface in the DSUIT0 joint was the largest, followed by that in the DSUIT1, DSUIT2, and DSUIT3 joints. Figure 10(b) shows the residual stress at the lower surface parallel to the welding direction. The residual tensile stress in the UN and DSUIT0 joints and that at the lower surface in the DSUIT0 joint were slightly affected by the ultrasonic impact at the upper surface. The residual compressive stress at the lower surface in the DSUIT3 joint was the largest, followed by that in the DSUIT2 and DSUIT1 joints. According to the residual stress in the vertical welding direction at the upper and lower surfaces of the joints shown in figure 10(c) and (d), respectively, the influence range of the DSUIT on the residual stress in the vertical welding direction was from 4 to 6 mm.

When the joint was not subjected to DSUIT, the upper and lower surfaces were in the residual tensile-stress stage, and no significant difference existed between them. When the joint was subjected to ultrasonic impact, the residual tensile stress at the upper and lower surfaces of the joints began to change into a residual compressive stress. The residual compressive stress at the upper surface in the DSUIT0 joint was the largest, followed by that in the DSUIT1, DSUIT2, and DSUIT3 joints. The residual compressive stress at the upper surface in the DSUIT0 joint were slightly affected by the ultrasonic impact at the upper surface. The residual compressive stress at the lower surface in the DSUIT3 joint was the largest, followed by that in the DSUIT2 and DSUIT1 joints. According to the residual stress in the vertical welding direction at the upper and lower surfaces of the joints shown in figure 10(c) and (d), respectively, the influence range of the DSUIT on the residual stress in the vertical welding direction was from 4 to 6 mm.

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3.5. Effect of DSUIT on the fatigue properties of welded joints

Figure 11 shows the fatigue properties of the joints under different treatment processes. According to the stress range–number of cycle ($S-N$) curve of the welded joints under different treatment processes shown in figure 11(a), the fatigue properties of the welded joints obviously improved after the DSUIT treatment. The fatigue properties of the DSUIT0 and DSUIT1 joints were close. The fatigue properties of the DSUIT0 joints were better than those of the DSUIT1 joints before the stress range of 120 MPa. However, the fatigue properties of the DSUIT0 joints were worse than those DSUIT1 joints after the stress range of 120 MPa. As a result of the continuous ultrasonic impact, the fatigue properties of the DSUIT2 and DSUIT3 joints relatively improved, and those of the DSUIT3 joints were the best. According to the fatigue data-processing method proposed by the International Institute of Welding, the fatigue strength of the joints was obtained under different treatment processes when the number of cycles was $2 \times 10^6$ (figure 11(b)).

According to the analysis of the fatigue properties of the joints under different treatment processes, the DSUIT significantly affected the improvement of fatigue strength of the 7075 aluminum alloy laser-welded joints. The fatigue strength of the DSUIT3 joints was 111.88% higher than that of the UN joints. The improvement in the fatigue properties was closely related to the stress and microstructure of the joints. When the joints were subjected to DSUIT, some residual compressive stresses were introduced to the upper and lower surfaces of the joints. Furthermore, the fatigue properties increased with the increase in the residual compressive
stress. The microstructure of the joints affected the crack initiation and propagation during the fatigue process. Usually, the fatigue fracture of welded components starts from the joint surface. However, DSUIT can reduce the welding defects at the joint surface and improve the compactness of the microstructure, effectively inhibiting the crack initiation and thus improving the fatigue properties of the joints.

3.6. Fatigue fracture analysis of the welded joints under different treatment processes

Figure 12 shows the macro fatigue-fracture morphology of the joints under different treatment processes. The crack source (A1) of the fatigue fracture is indicated by the river pattern, the crack propagation zone (A2) is indicated by silver white, and the instantaneous fault zone (A3) is indicated by the rough dark-gray shade. Multiple crack sources could be observed on the fatigue fracture of the UN joints, and they all originated from the surface (figure 12(a)). In the fatigue fracture of the DSUIT0 joint, the crack source was located in the defects at the lower surface where the crack began to propagate to the upper surface (figure 12(b)). In addition, with regard to the fatigue fracture of the DSUIT1 joint, the cracks were generated from the defects of the joint that was not subjected to ultrasonic impact as well as from the cross section of the joints (figure 12(c)). With respect to the fatigue fracture of the DSUIT2 and DSUIT3 joints, only the crack source was observed at the joint section (figures 12(d) and (e)).

Figure 13 shows the micromorphology of the fatigue fracture of the UN joint. When the joint was not subjected to DSUIT, the crack would sprouted from the defect at the joint surface and might have multiple crack sources (figure 13(a)). During the crack-propagation process, a river pattern (figure 13(b)). Further, some typical fracture morphologies, for example, transgranular cleavage fracture (figure 13(c)) and fatigue striation (figure 13(d)), could occur because of the complex arrangement of the grains. Many secondary cracks with different sizes appeared in the instantaneous-fault zone of the 7075 aluminum alloy laser-welded joints (figure 13(e)). Dense dimples were distributed in the instantaneous-fault zone, and the fracture mode was a ductile fracture (figure 13(f)).

Figure 14 shows the micromorphology of the fatigue fracture of the DSUIT3 joint. After the DSUIT, the crack source initiated from the side of the joints and propagated parallel to the welding direction. Further, the crack-source initiation at the joint surface was effectively suppressed (figure 14(a)). Because of the increase in the PDL hardness, cleavage steps appeared when the crack propagated at the PDL (figure 14(b)). A typical fatigue-fracture morphology of the cleavage facet appeared on the cleavage step (figure 14(c)). Because of the difference in the microstructure density and hardness between the PDL and undeformed zone, a tearing-edge feature...
appeared when the crack propagated into the transition zone (Figure 14(d)). Figure 14(e) and 14(f) show the fatigue-fracture morphology of the instantaneous-fracture zone of the DSUIT3 joint. Two different fracture morphologies can be seen from the figure: one was dense while the other was very rough. The dense structure was the PDL, which played an important role in strengthening the fatigue process of the welded components.

The laser-welded joints of the Al–Zn–Mg–Cu alloy featured certain porosity [21]. The DSUIT could allow the occurrence of dense PDL at the upper and lower surfaces of the joints, which reduced the porosity at the joints. Moreover, the welding defects at the surface could be reduced or even eliminated after the DSUIT. The macro fatigue fracture of the joints under different treatment processes were compared, and the microfatigue fracture of the UN and DSUIT3 joints was analyzed. When the laser-welded joints of the 7075 aluminum alloy were not subjected to DSUIT, the cracks initiated from the defects at the surface and began to propagate inward. After the DSUIT, dense PDL was formed near the joint surface, which effectively inhibited crack initiation at the joint surface. When the joints were not subjected to DSUIT, the fatigue fracture was a ductile fracture. However, when the joints were subjected to DSUIT, high-strength and high-density PDL occurred because of the impact at the upper and lower surfaces of the joints, and the fracture form of the plastic-deformation zone was a brittle fracture. Therefore, the fracture form after the DSUIT was a mixture of ductility and brittleness. The composite fracture form made the joint maintain high stability under a fatigue load. Meanwhile, because of the high dislocation density and strength of the PDL, the strength of the joint could be improved when it instantaneously fractured. Combined with the residual compressive stress, this process could improve the fatigue properties of the joints. Therefore, the DSUIT of the 7075 aluminum alloy laser-welded joints achieved the objective of improving the fatigue properties.

4. Conclusion

In this study, the microstructure and fatigue mechanical properties of 7075 aluminum alloy laser-welded joints without DSUIT and under different DSUIT processes were compared and analyzed. The conclusions drawn after the DSUIT are presented as follows.

(1) The welding defects at the joint surface were reduced, and the surface roughness of the joints decreased from 116.77 to 14.96 μm. Simultaneously, the dendritic structure at the upper and lower surfaces of the joint was broken, forming a PDL with an average thickness of approximately 100 μm.

(2) The joints were divided into plastic-deformation, transition, and undeformed zones. A certain amount of residual compressive stress was introduced into the upper and lower layers of the joints. Moreover, the texture strength of the plastic-deformation zone decreased from 5.541 to 3.265, and the average grain size decreased from 29.34 to 3.72 μm.

(3) The phase of the joint surface did not change and only the size of the crystal grains changed. From the Scherrer equation, the grain size of the joints surface was 38.66 nm.

(4) The maximum residual compressive stress at the upper and lower surfaces of the joints was approximately −240 MPa. After the ultrasonic impact, the residual compressive stress was complete at the lower surface of the joints, and a small part of the residual compressive stress at the upper surface was relieved. The influence range of the DSUIT on the residual stress in the vertical welding direction was 4–6 mm.

(5) Comparison of the fatigue properties of the joints without DSUIT and under different DSUITs revealed that the ultrasonic impact significantly improved the fatigue strength of the joints. When the number of cycles was $2 \times 10^6$, the fatigue strengths of the DSUIT3 and UN joints were 103.02 and 48.62 MPa, respectively, or an increase of 111.8%.

(6) PDL was produced at the upper and lower surfaces of the joints, which reduced the defects of the weld surfaces and effectively inhibited the initiation of cracks at the joint surfaces. The fatigue-fracture form of the UN joints was a ductile fracture, whereas that of the DSUIT joints was a mixed ductile–brittle fracture. This composite fracture form greatly improved the fatigue performance of the 7075 aluminum alloy laser-welded joints.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflicts of Interest

The authors declare no conflict of interest.

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