Effect of Ultrasonic Peening Treatment on VHCF Behavior of Friction Stir Welded Joints in Aluminum Alloys

Ruofan Zhang¹², Xue Li³⁴, Yongjie Liu³⁴, Chao He² and Qingyuan Wang²³⁴,*

¹School of Architecture and Civil Engineering, Xihua University, Chengdu 610039, China
²School of Architecture and Civil Engineering, Chengdu University, Chengdu 610106, China
³MOE Key Laboratory of Deep Earth Science and Engineering, College of Architecture and Environment, Sichuan University, Chengdu 610065, China
⁴Failure Mechanics and Engineering Disaster Prevention and Mitigation Key Laboratory of Sichuan Province, Sichuan University, Chengdu 610207, China

*Corresponding author

Abstract. Studying the mechanical properties of aluminum alloy 6061 friction stir welded (FSW) joints after ultrasonic peening treatment (UPT) under very high cycle fatigue (VHCF) loading. The effect of joints ultrasonic peening treatment was explored. It can be seen from the results that the ultrasonic peening treatment can form a reinforced layer on the surface of joints, and the fatigue crack source is transferred from the surface of the specimen to the inside. However, the change of fatigue crack initiation site does not improve the fatigue strength of specimen through ultrasonic peening treatment. The fatigue strength of the aluminum alloy 6061 joint after ultrasonic peening treatment is even lower than as a received condition. The characteristics of fatigue crack initiation and the mechanism of surface strengthened layer on fatigue strength were analyzed and discussed.

Keywords: friction stir welding; S-N Curves; ultrasonic peening treatment; very high cycle fatigue; ultrasonic Fatigue; fatigue crack initiation.

1. Introduction

Ultrasonic peening treatment (UPT) was proposed by Russian scholars in the early 1970s [1, 2]. The principle of UPT was that Ultrasonic frequency vibration displacement pushed the peening head to produce pressure, which was applied to the welding seam surface. The plastic deformation layer on the specimen surface was induced and the mechanical properties of the impact site were strengthened. Ultrasonic peening produced beneficial residual compressive stress layer on the surface of the welding seam as well; the stress can significantly improve the fatigue performance of welded joints [3]. The surface condition of the friction stir welding joint had a significant influence on fatigue performance. Fatigue cracks were usually generated from the surface of the specimen, and the fatigue strength of the joint could be effectively improved by removing the flash and arc mark [4, 5]. The effect of ultrasonic peening treatment on the friction stir welding head fatigue behavior research is still not clear so far. Many vital manufacturing industries have been applied to aluminum alloys cumulatively, such as the automobile industry, aeronautics, and the military because of low density and excellent mechanical properties of aluminum alloy [6], and these applications also lead to deeper research. Rodopoulos [7] studied the influence of ultrasonic peening on the fatigue crack propagation...
characteristics of FSW joint in AA6061. The resistance of this surface treatment to fatigue cracks was considered to be observed only at low-stress intensity factor amplitude, which is mainly caused by the release of residual stress during cyclic loading. However, the effect mechanism of UPT on the long life fatigue of FSW joints has not been studied and discussed by relevant experiments. In this work, the ultrasonic fatigue experiment system is applied to the FSW joints of aluminum alloy 6061 after UPT, to study the difference of VHCF performance of joints before and after surface treatment. The fatigue crack initiation and failure mechanism were discussed based on the observation of a scanning electron microscope.

2. Experimental Methods

2.1. Material and Specimen

The present experimental material is aluminum alloy 6061 (AA 6061-T651), which is rolled as plates with a thickness of 10mm. Its composition of chemistry and properties of mechanics were showed respectively in Table 1 and Table 2. Geometric dimensions of the test piece for fatigue test are shown in figure 1. In the friction stir welding process, the diameters of stirring head at the root and top were 10mm and 7mm, respectively. The length of the stirring head was 9.2mm, while the diameter of the curved profile shoulder was 24 mm. The inclination angle of stirring head axis and plate normal was 2°, with the speed of rotation is 600r/min and the forward speed of welding is 400 mm/min. The specimen surface before and after UPT are shown in figure 2 [8].

| Cr | Cu | Fe | Si | Mn | Mg | Ti | Zn | Al |
|----|----|----|----|----|----|----|----|----|
| 0.04-0.35 | 0.15-0.40 | 0.70 | 0.40-0.80 | 0.15 | 0.80-1.2 | 0.15 | 0.25 | bal |

| Table 1. Chemical compositions of 6061-T651 in this test (wt.%). |
|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| p (g/cm³) | E (GPa) | σb (MPa) | σs (MPa) | δ (%) | Hardness (Vickers) |
| 2.62 | 68.9 | 310 | 276 | 12 | 102 |

**Figure 1.** Geometric dimensions diagram of specimen size
(a) Before UPT
(b) After UPT

**Figure 2.** Microstructure of the joint (a) and the morphology of specimen surface after UPT treatment (b).
2.2. Experimental Methods
For surface observation, the weld cross-sections of all tested specimens were first polished using different grades of emery paper and then subjected to electrolytic etching at 30 V for 90 s using perchloric acid/ethanol solution to reveal the microstructure. The ultrasonic fatigue test system test was carried out on SHIMADZU USF-2000 at the room temperature, and with the stress ratio of R=-1. The maximum cyclic load was applied to $10^9$ cycles unless the specimen failed beforehand. The specimens were sprayed with high-temperature black paint to understand the heat dissipation of the specimen under very high frequency loading, and the surface temperature field of the specimen under different loading stresses was recorded by an infrared camera. The results indicated that the temperature increase in this test was no more than 10 °C. After the fatigue failure, the fracture surface was observed by scanning electron microscope (SEM, JOEL-6510LV) and optical microscope to discuss the failure mechanism of fatigue and evaluate the effect of UPT on fatigue strength.

3. Experimental Results

3.1. S-N Curves
Fatigue data of aluminum alloy 6061 specimens after ultrasonic impact treatment are shown in figure 3, in which the fatigue strength before UPT from He et al. is also present for comparison. The arrows which represented data showed that specimens did not cause a failure until $10^9$ cycles. The fatigue life of the specimen after UPT was lower than untreated specimen at all levels of loading stress in the high-cycle region (life less than $10^7$ cycles), and this phenomenon indicated that the treatment method did not enhance the fatigue strength of the joints. Instead, it decreased to some extent. In the range of VHCF, with the decrease of loading stress, the specimen before and after the UPT treatment both showed a decreasing trend, in which fatigue failure still occurred in the range of $10^7$~$10^9$ cycles. That is to say, the traditional fatigue limit at $10^7$ cycles does not exist for friction stir welded joints in AA6061.

![Figure 3. S-N curves for aluminum alloy 6061 ultrasonic test after UPT](image)

In general, the study on the fatigue performance of ultrasonic peened welded joint found that the surface layer of the specimen is greatly refined, welding defects are reduced, microstructure becomes compact, and residual compressive stress could be introduced in the surface layer effectively at the same time. These factors make the specimen (after UPT) pose a greater improvement of fatigue strength, but this result in this test is opposite of above conclusions, the mechanism of friction stir welded joint in AA 6061 is probably different from the conventional fusion welded joints. The details are analyzed in the following parts via fracture analysis.

4. Fracture Analysis and Discussion
The failure specimen obtained the fracture morphology by using SEM. The mechanism information of fatigue crack initiation and propagation was investigated in studying the fracture morphology. In general, the resistances of fatigue crack initiation were deemed to play a predominant role on the mechanism of metallic fatigue failure in the VHCF regime [9]. The fatigue fracture morphology of
aluminum alloy 6061 after UPT is shown in figure 4. For most metal materials, high cycle fatigue cracks usually originated from the surface of the specimen, while very high cycle fatigue cracks originating from the interior [10]. But this figure (Fig.4) showed that the fatigue crack originates from the interior of the specimen and is composed of the relatively flat plane (facet). The width of the plane zone ranges from 300μm to 450μm, which is the same as the grain size of AA 6061 in the vertical direction of the plate, this phenomenon indicates that the facets plotted by arrows should be formed along specific slip plane of a grain. After UPT, the facet region of the crack source is completely determined by the grain size. Therefore, the formation of the facet is mainly caused by the sliding cracking of grains along the slipping plane. In addition, the intracrystalline slip plane is usually formed under high stress. The width of specimen is almost occupied by limited grains, which are located at the fatigue crack source of AA6061 joint after UPT, and the two ends of the grain are directly affected by the ultrasonic peening treatment. We can infer that the formation of the intracrystalline slip plane is associated with UPT process, and this is one of the main reason to cause the decrease of fatigue strength in this test as compared with that before UPT.

**Figure 4.** Fracture morphology of aluminum alloy 6061 impact specimen

In the process of ultrasonic peening, the impact head impinges on the surface of the sample at a very high speed and frequency, and strong plastic deformation is produced at specimen within a certain surface thickness range, which caused the formation of a strengthened layer at the same time. At the micro scale, dense dislocations and finer subgrains are formed in the strengthened layer [11]. The effect of UPT on the surface of the aluminum alloy 6061 joint fracture failure position in this test is shown in figure 4b. The strengthened layer is having a thickness of about 90 μm in this work. AA 6061 is presenting intracrystalline flat sliding plane in internal grain as shown in Fig. 4c, and its crack extension is mainly influenced by grain alignment and orientation. In the strengthening layer, the direction of crack growth is substantially perpendicular to the loading stress, and the two different crack propagation planes coalesced with the formation of dense river-like steps simultaneously.

For AA 6061 friction stir welded joint, fatigue crack is generated from local plastic slip band. UPT can refine the grains in the surface strengthening layer to the nanometer level. As a result, the surface slip band, grain boundary and the second phase interface increased accordingly. This phenomenon is beneficial to resist the initiation of fatigue cracks. Meanwhile, grain boundary can be used as an obstacle to the development of intra-grain slip dislocation. The reduction of grain size is conducive to the improvement of fatigue crack growth resistance at the initial stage [12]. Therefore, the UPT causes the fatigue crack initiation site of AA 6061 friction stir welded joint to transformed from the surface of the interior of specimens. The presence of the strengthened layer is beneficial to suppress the initiation and propagation of fatigue cracks. Besides, the residual compressive stress introduced at the surface can also reduce the maximum tensile stress on the surface of the specimen, thus reducing the possibility of fatigue cracks originating from the surface. In the meanwhile, due to the grain size of AA6061 is relatively large in this test, which individual length of one grain almost traverses the entire specimen, the fatigue cracks of the same grain are more likely to initiate from the sliding plane because the peening applied on both sides. Finally, the fatigue life of the specimens after UPT are reduced as compared with the untreated one.
5. Conclusion
In this paper, the ultrasonic fatigue test system is used to study the VHCF strength of AA6061 FSW joint after UPT, and the effect of surface strengthened layer on the fatigue crack initiation site and fatigue strength were analyzed and discussed. The results in this study can be summarized as follows:
(a) After UPT, the fatigue life of aluminum alloy 6061 joint is shortened than the untreated one.
(b) Fracture analysis found that the fatigue crack of specimens originated from large grains. The plane and impact treatment make the slip plane more susceptible to the occurrence of fatigue cracks, which is the main cause for the decrease of the fatigue strength of the AA6061 joint.
(c) UPT refines the grain at the surface of the specimen to form a dense strengthened layer, which can effectively improve resistance to the fatigue crack initiation and propagation. This is the main cause of the occurrence of fatigue cracks from the surface to the interior of specimen.

Acknowledgments
This work was financially supported by Chinese National Science Foundation (No.11572057) in Chengdu University.

References
[1] Mukhanov I, Golubev Y M. Strengthening Steel Components by Ultrasonically Vibrating Ball[J].Vestn. Mashin, 1966, 1152-53.
[2] Mordvintseva A. Ultrasonic treatment of welded joints[J]. Ultrasonic Applications in Welding Engineering, Moscow, TsINTIEngomash, Proc. of NE Bauman MVTU, ed, 1959, 35.
[3] Trufiakov V. Ultrasonic impact treatment of welded joints[M]. 1995.
[4] Magnusson L, Kallman L. Mechanical properties of friction stir welds in thin sheet of aluminium 2024, 6013 and 7475[A]. In Proceedings of the Second International Symposium on Friction Stir Welding, Paper[C], 2000.
[5] Bussu G, Irving P. The role of residual stress and heat affected zone properties on fatigue crack propagation in friction stir welded 2024-T351 aluminium joints[J]. International Journal of Fatigue, 2003, 25(1): 77-88.
[6] Wang QY, Li T, Zeng XG. Gigacycle fatigue behavior of high strength aluminum alloys. Fatigue 2010;2(1):65–70.
[7] Rodopoulos C, Pantelakis S G, Papadopoulos M. The effect of ultrasonic impact treatment on the fatigue resistance of friction stir welded panels[J]. J Mater Eng Perform, 2009, 18(9): 1248-1257.
[8] Chao He, Yongjie Liu, Jiangfeng Dong, Qingyuan Wang. Through thickness property variations in friction stir welded AA6061 joint fatigue in very high cycle fatigue regime[J]. International Journal of Fatigue, 2016, 82(3), 379-386.
[9] Wang QY et al. Effect of inclusion on subsurface crack initiation and gigacycle fatigue strength. Int J Fatigue 2002;24(12):1269–74.
[10] Huang Z Y, Wagner D, Wang Q Y, etc. Effect of carburizing treatment on the "fish eye" crack growth for a low alloyed chromium steel in very high cycle fatigue[J]. Mat Sci Eng a-Struct, 2013, 559790-797.
[11] Mordyuk B N, Prokopenko G I. Ultrasonic impact peening for the surface properties’ management[J]. Journal of Sound and Vibration, 2007, 308(3): 855-866.
[12] Masounave J, Baflon J-P. Effect of grain size on the threshold stress intensity factor in fatigue of a ferritic steel[J]. Scripta Metallurgica, 1976, 10(2): 165-170.