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ARTICLE

# Surface Nanocrystallization of 7A52 Aluminum Alloy Welded Joint by Aging and Ultrasonic Impact Compound Treatment

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**Abstract:** Welding joint of 7A52 aluminum was treated by ultrasonic impact technology (UIT) and a combined treatment of aging and ultrasonic impact (A-UIT). The effects of different treatments on the microstructure and properties of the welded joint were compared and analyzed, especially the effects of A-UIT on microstructure and the mechanism of surface hardening of welded joint. The results show that the nanometer grain layer can be successfully prepared by UIT and A-UIT on the surface of aluminum alloy welded joint. From the comparison, it can be found that the surface grain size, surface microhardness and matrix microhardness of the welded joint after A-UIT are significantly higher than those of the welded joint after UIT, which exhibits a better reinforcement. The surface hardening mechanism of welded joints after UIT is fine-grained strengthening, while that of welded joints after A-UIT is fine-grained and precipitated strengthening, which is different from that of UIT.

**Key words:** A-UIT; 7A52 aluminum alloy; welded joint; nanocrystallization

Aluminum and aluminum alloys have been widely applied in the field of space, ships, automotive, military and other areas by their relatively high electric conductivity, good workability, corrosion resistance and toughness. 7A52 aluminum alloy developed by China has obvious aging strengthening effect. After aging, mechanical properties of 7A52 aluminum alloy such as hardness and intensity have been evidently improved [1]. Welding is one of the main connection techniques for 7A52 aluminum alloy in practical application. Tungsten inert gas (TIG) and metal inert gas protection (MIG) of 7A52 aluminum alloy have been extensively used in production[2,3]. With the development of laser technology, laser welding of aluminum alloy develops rapidly and the quality of welded joint is better than that of the traditional welded joint [4,5]. But the low intensity and residual tensile stress of aluminum alloy joint affect the popularization and application of them. Therefore, some scholars have used surface self-nanocrystallization technology in welded joint surface, which can improve the residual stress distribution, wear resistance, hardness and life of the welded joint [6,7].

The common methods of surface self-nanocrystallization for metal are ultrasonic shot peening (USP), high energy shot peening (HESP), surface mechanical attrition treatment (SMAT) and ultrasonic impact treatment (UIT) [8-11]. Compared with other surface self-nanocrystallization technology, UIT is much simpler in operation and more convenient to use. A nano-crystal layer of aluminum alloy welded joints surface was generated whose microstructure and property have been improved after the UIT [12-14].

Although UIT has been successfully applied to aluminum alloy welded joint, the interaction influence between the aluminum alloy aging characteristics and welded joint surface microstructure and property after UIT was rarely investigated. So, we present a new compound treating method in this paper, which is called aging and ultrasonic impact compound treatment (A-UIT), and its schematic diagram is shown in Fig.1. Firstly aluminium alloy welded joint is tread by aging treatment under proper aging parameters. Secondly aging treatment of aluminium alloy

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welded joint is performed by UIT and finally a nano-crystal layer of weld joints surface was prepared.

In this paper, we compared the microstructure and properties of 7A52 aluminum alloy welded joint after A-UIT and UIT. The study focuses on the surface hardening mechanism and surface nanocrystallization process of aluminum alloy welding joint in different treatment processes. And it will provide the theoretical foundation for the further study of A-UIT in the future.

## 1 Experiment

The base material was 7A52 aluminum alloy with chemical composition (wt%) of Zn 4.2066, Mg 2.2642, Cu 0.1287, Mn 0.3113, Zr 0.12445, Cr 0.2278, Fe 0.2954, Si 0.2352 and balance Al. Plate samples 300 mm×50 mm×6 mm in size were cut from the hot rolled plate. The specimens were welded by IPG YLS-6000 fiber laser with welding power of 5.2 kW, welding speed of 40 mm/s, focal distance of 0 mm and weld shield gas flow of 15 L/min. Its welding process is shown in Fig. 1.

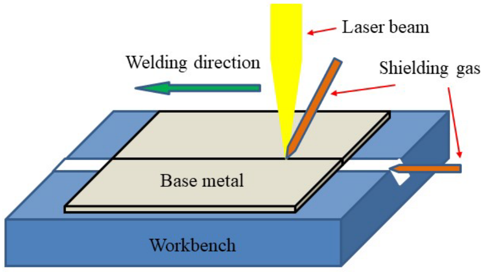


Fig. 1 Basic working schematic of welding

The welded joint was halved by wire cutting electrical technique and the cutting line was perpendicular to the direction of welding. One welded joint was aged in a resistance furnace (120 °C, 24 h) and the other was not aged. UIT was adopted to treat the welded joint surface of non-aging and aging specimens. The basic principle and working schematic of A-UIT is shown in Fig. 2. The UIT parameters are three impact needles with diameter of 4 mm, impact time of 15 min, processing welded joint area of 60 mm$^2$, and impact current of 2.5 A.

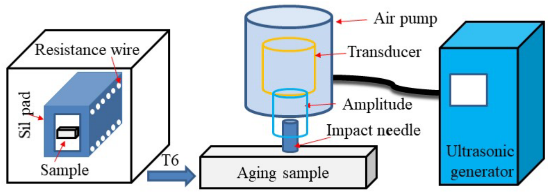


Fig. 2 Basic principle and working schematic of A-UIT

The microstructures and properties of 7A52 aluminum alloy welded joints were investigated. The macrostructure of welded joints was observed by the Zeiss microscope (OM). The variation of micro-hardness along the depth from the treated surface was measured by a HVS-30Z/LCD digital Vickers hardness machine, with a load of 50 g and loading time of 15 s. The different depths of microstructures of welded joint were observed by JEOL 2010 Transmission electron microscopy (TEM), which was operated at 200 kV. TEM specimens were cut off from three different regions in the UIT samples, which correspond to three different depth ranges: depth＜20 μm, depth＜40 μm, and 100~120 μm from the top surface.

## 2 Results and Discussion

### 2.1 Hardness test

Fig. 3 shows the surface deformation layer morphology and hardness change along the thickness direction of the weld joint after UIT and A-UIT. Fig. 3a shows the cross section of the weld, the deformation layer thickness of A-UIT weld is about 55 μm and the deformation layer thickness of UIT weld is about 70 μm. Since the hardness of the sample with aluminum alloy aging treatment is higher than that with aluminum alloy non-aging treatment, A-UIT weld need more high deformation energy than UIT weld if they get equal deformation of A-UIT weld. Therefore, the deformation layer of A-UIT weld is thinner than the deformation layer of UIT weld with the same UIT parameter (the same deformation energy). Fig. 3b shows the micro-hardness with distance from the UIT surface to the weld metal. It indicates that the micro-hardness of A-UIT weld and UIT weld dramatically decreases with increasing distance from the top surface. The top surface micro-hardness of the UIT weld is 1570 MPa and the thickness of the UIT weld deformation layer is 60~70 μm. The top surface micro-hardness of the A-UIT weld is 1750 MPa, which is better than that of the UIT weld. In addition, the thickness of the A-UIT weld deformation layer is 60~70 μm. Fig.3c shows the cross section of the weld, the deformation layer thickness of A-UIT base metal is 45 μm and the deformation layer thickness of No.4 base metal is 55 μm. Fig.3d shows micro-hardness with distance from the UIT surface to the base metal. The top surface micro-hardness of the A-UIT base metal is 1900 MPa and the UIT base metal is 1650 MPa.

The results show that the better surface micro-hardness of welded joint can be obtained by use of A-UIT. In the following sections, the surface hardening mechanism of welded joint during the A-UIT process will be discussed in detail.

### 2.2 Surface hardening mechanism of welded joint

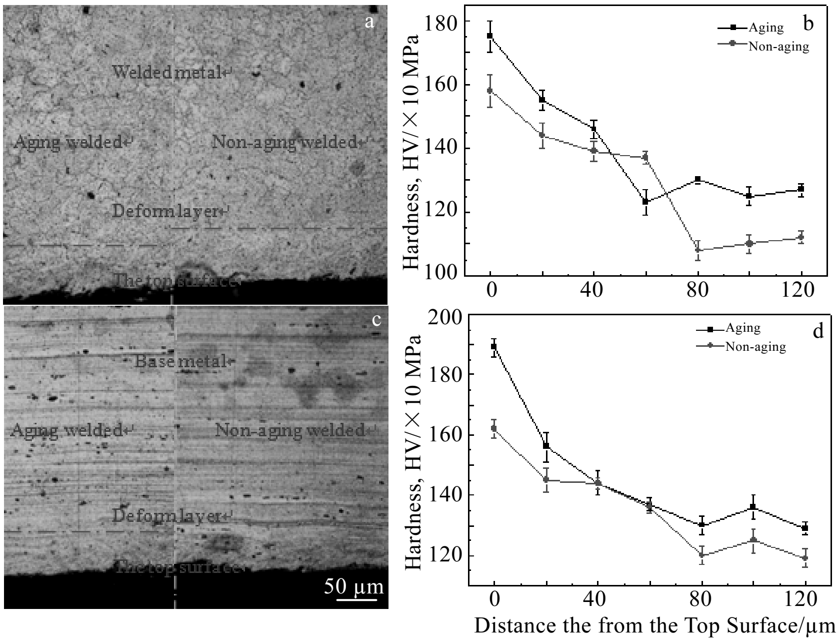


Fig. 3 Hardened layer morphologies (a, c) and hardness distribution (b, d) of the weld joint after UIT and A-UIT for weld (a, b) and base metal (c, d)

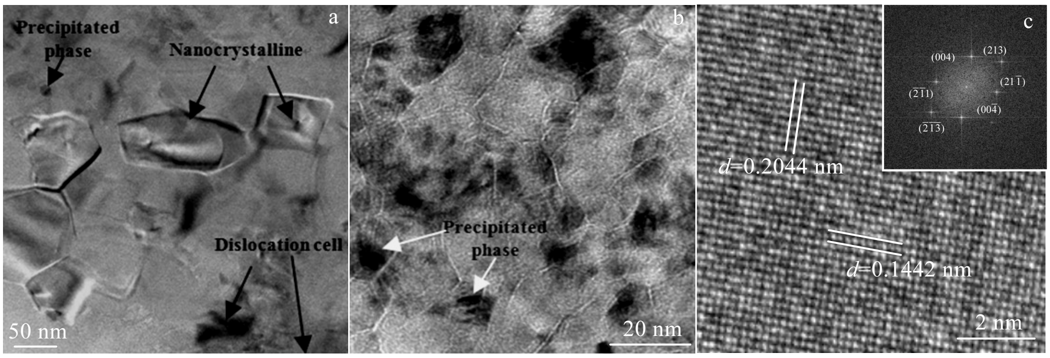


Fig. 4 TEM micrographs showing surface of 7A52 aluminum alloy weld center after UIT and A-UIT and precipitated phase characterization: (a) grain size ~100 nm, (b) grain size ~40 nm, and (c) $d$ = 0.1442 nm and $d$ = 0.2044 nm

Fig. 4 shows the surface region of 7A52 aluminum alloy weld center after UIT and A-UIT. The grain size of surface is ~100 nm, and there are a great amount of tiny precipitated phases and dislocation cells on the surface after UIT (Fig. 4a). The grain size of surface is ~40 nm, and there are lots of precipitated phases on the surface of weld after A-UIT (Fig. 4b). The above experimental results clearly illustrate that a nanostructured surface layer has been developed in the 7A52 aluminum alloy weld by UIT and A-UIT. But compared with UIT, the surface grain size of weld joint is smaller after A-UIT. In addition on the surface of weld there are a lot of precipitated phases after A-UIT, and the effect of aging strengthening is obvious, so the weld surface hardness increases more significantly than that of the UIT weld joints. The surface hardening mechanism of 7A52 aluminum alloy welded joints is fine grained strengthening and precipitated phase strengthening after the A-UIT. Fig. 4c is high resolution TEM and Fourier Transformation of precipitated phase. Two dimensional lattice fringes can be clearly seen. The spacing of two crystal planes is $d$ = 0.1442 nm and $d$ = 0.2044 nm, identical to the PDF standard card of $MgZn_2$ phase. It is known that the interfacial angle is about 90.6° through calculation, while the measured value is 88°. The calculated value is approximately the same to the measured value, which meets the requirements of calibration, so we can know that the crystal zone axis is [100]. The Fourier Transform image is shown at the top right corner in Fig. 4c.

Each set of diffraction spots corresponds to lattice plane of $MgZn_2$ along [100] crystal zone axis, and confirms to the interfacial angle formula.

### 2.3 A-UIT nanocrystallization mechanism of weld joint

As we know, aluminum alloy is a high stacking fault energy metal, so there are many slip directions in the plastic deformation process. The plastic deformation mechanism of aluminum alloy is mainly related to the dislocation motion. The slip system for aluminum alloy is slip plane of {111} and sliding direction of <110> at room temperature. Because this experiment was conducted at room temperature, and the surface temperature of the plate during UIT and A-UIT is low, the slip system of plastic deformation based on 7A52 aluminum alloy should be slip plane of {111} and sliding direction of <110>.

Fig. 5 are TEM micrographs showing the sub-grains of weld separated by dislocation pile-up and tangling after UIT (Fig. 5a) and A-UIT (Fig. 5b). Compared with Fig. 5a, it can be easy observed in Fig.5b that there is higher dislocation density and the size of sub-grains is smaller after A-UIT. This region corresponds to the one that is more than 100 μm below the top most surface and the microstructures of weld joints are not going to change under impact loading. Fig. 6 show microstructures of weld metal in the region 100 μm below the treated surface. In Fig.6a, few precipitated phases of weld metal are generated after UIT and in Fig. 6b, lots of precipitated phase of weld metal are generated after A-UIT. Studies have shown that the existence of the G.P, $\eta'$ and $\eta$ is the main reason that causes the obviously improved mechanical properties such as tensile strength, yield strength, elongation and electrical conductivity after appropriate aging treatment of 7A52 aluminum alloy. Therefore, not only the surface properties of 7A52 aluminum alloy weld joint after A-UIT are better than the one after UIT, but the base materials properties after A-UIT are also better than those of the one after UIT.

Based on the above discussions, the process and mechanism of surface nanocrystallization of 7A52 alloy weld joint during the UIT and A-UIT can be clarified. The plastic deformation of the weld joint can occur under impact loading, which gradually produces the high density of dislocations. Firstly, the grains of base materials are segmented and refined as a result of dislocation pile-up and tangling (Fig. 5). With the constant act of impact load and increase of deformation, the sub-structure of high density of dislocation walls and dislocation cells are generated in the interior of the original large grains and the grains of base materials are further segmented and refined gradually. Under impact load of high energy, the density of dislocations of surface grain increases dramatically and the sub-structures are rapidly generated because of the movement and inter-action of dislocation, which gradually turn to random direction of nano-crystals (Fig. 4a and Fig. 4b) with constant increase of dislocations.

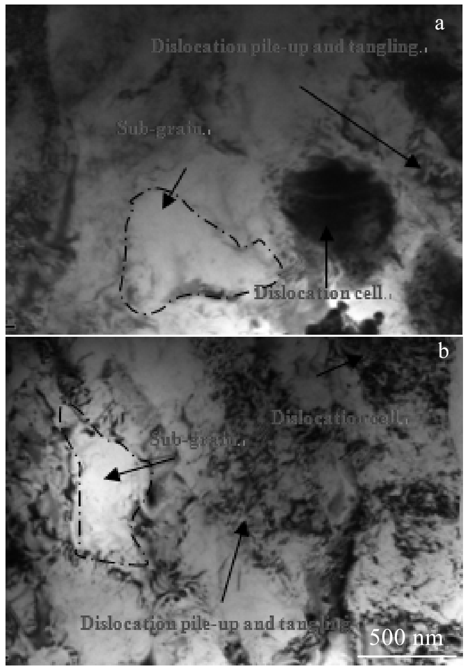


Fig. 5 TEM micrographs showing sub-grains in the region 40 μm below the treated surface after UIT (a) and A-UIT (b)

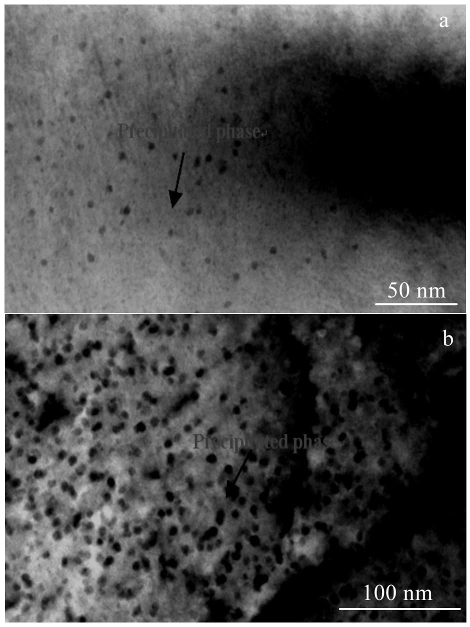


Fig. 6 TEM micrographs showing weld metal in the region 100 μm below the treated surface

## 3 Conclusions

1) The surface microhardness HV of base materials and weld after UIT are 1600 and 1570 MPa, respectively, the surface hardness of base materials and weld after A-UIT are 1600 and 1570 MPa, respectively; But the surface hardness of the weld joint after A-UIT increases significantly, compared with that of the weld joint after UIT.

2) A nano-crystal layer of weld joint surface is produced after the UIT and A-UIT process. The surface grain size is ~100 nm after UIT and the surface hardening mechanism is fine grained strengthening. The surface grain size is ~40 nm and there are lots of precipitated phases on the surface of weld after A-UIT, so the surface hardening mechanisms are fine grained strengthening and precipitated phase strengthening.

3) The surface nanocrystallization process of Aluminum alloy welded joint is divided into two phases. Firstly, a mass of dislocations form while some sub-structures form simultaneously because of the movement and inter-action of dislocation under impact loading; Secondly, with the gradual segmenting and thinning, the sub-structures finally become the nanocrystals during constant impact loading.

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# 时效及超声冲击复合处理 7A52 铝合金焊接接头表面纳米化研究


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**摘　要**：采用超声冲击处理（UIT）和一种新型的表面复合处理工艺-时效及超声冲击（A-UIT）复合工艺，对 7A52 铝合金激光焊接头进行了处理，对比分析了不同处理手段对接头组织性能的影响，重点研究了时效及超声冲击复合处理对焊接接头微观组织的影响并对其表面硬化机理进了讨论。结果表明，采用 2 种工艺均在铝合金焊接接头表面成功制备了纳米级晶粒层。通过对比发现，当采用时效及超声冲击复合工艺对焊接接头进行处理时，焊接接头的表面晶粒更加细小、表面硬度以及基体硬度均明显优于超声冲击处理后的焊接接头。超声冲击处理后的焊接接头表面硬化机理为细晶强化，时效及超声冲击复合工艺处理后的焊接接头表层硬化机理则与超声冲击处理有所不同，由细晶强化和析出相强化共同作用，强化效果更佳。



**关键词**: A-UIT；7A52 铝合金；焊接接头；纳米级晶



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