Microstructure and properties of solid state joints of titanium sheets produced by ultrasonic welding

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Abstract. The results of the study on the microstructure and properties of solid state joints of titanium sheets obtained by ultrasonic welding (USW) with frequency 20 kHz and vibration amplitude 20 µm during 2 and 3 s under a 6 kN clamping force are presented. The thermomechanically affected zone is observed along the defect-free weld line (joint). It was found that the length and width of this zone increased with the welding time. In the thermomechanically affected zone, a significant grain growth takes place, a change in the texture is observed and maxima near 60° and 90° in the grain boundary misorientation distributions appear. The maximum lap shear failure load of the joints obtained by USW of 2 and 3 s durations are 1998±122 and 2506±226 N, respectively. There is a change in the failure mode from interface debonding after 2 s USW to nugget pull-out for the welding time of 3 s.

1. Introduction
Ultra sonic welding (USW) is widely used in the electrical, automotive, aerospace, instrument-making and medical industries to obtain joints between thin plates, tapes, foils, and wires. The USW has a number of advantages over other types of welding, the main of which is a low heat generation. The temperature in the welding zone depends on the material used and welding parameters, but, as a rule, it is below the melting temperature of the metals to be joined [1]. In addition, this method of joining metals requires two orders of magnitude less energy in comparison to the resistance spot welding [2]. Due to high-frequency vibrations in the process of USW, the surfaces to be welded are cleaned of dirt and oxide films, therefore, in most cases, preliminary cleaning of the surfaces is not required. Another advantage of the USW is its high productivity: the formation of a joint normally occurs in less than a couple of seconds [1]. As shown in [3], almost any metal and most of their combinations can be welded with ultrasound. Nevertheless, the greatest experience has been accumulated in welding soft metals and alloys with high thermal conductivity based on aluminum or copper [1-3]. The structure and properties of compounds of stronger metals, in particular, titanium and its alloys, obtained by USW, are practically not studied today. To the authors’ knowledge, there is only one work in the literature devoted to the USW of titanium [4].

This paper presents the results of studies on the structure and properties of titanium solid state joints of titanium produced by USW.

2. Material and methods
Commercially pure titanium sheet with the thickness of 0.5 mm in the annealed condition was used in
this work. Coupons for welding, 20 mm wide and 40 mm long, were cut along the rolling direction (RD) of the sheet, ground and washed with alcohol. USW was carried out with a frequency of 20 kHz and an amplitude of 20 μm. The static load of 6 kN was applied and the duration of ultrasound exposure was equal to 2 and 3 s. The sonotrode tip with dimensions of 5 mm × 6 mm had a serrated surface comprised of seven parallel teeth and its vibrations occurred in the plane of the sheets perpendicular to the rolling direction.

The welded joints were cross sectioned across their center, parallel to the direction of the vibrations. For structural studies, the samples were mechanically ground and polished, and the structure was characterized using optical and scanning electron microscopy on a TESCAN MIRA 3 LMH FEG microscope using orientation analysis (EBSD).

The welded samples were subjected to lap shear tests at room temperature with a crosshead speed of 1 mm / min on an Instron 5982 machine. The results were averaged over three tests with the peak load measured.

3. Results and discussion

3.1 Structure observations

Images of the macrostructure of the resulting joints are shown in figure 1. The microstructure at the periphery and central zones of the welds are shown in figure 2.

![Figure 1](image1.png)

**Figure 1.** Optical images of the macrostructure of the cross-sections of USW joints produced with welding times 2 s (a) and 3 s (b) (polarized light).

As one can see from the figures, joints of a satisfactory quality were formed under the selected processing conditions. The relative lengths of the defect-free weld joints are respectively 46 and 86% after ultrasonic welding in time intervals 2 and 3 s. Narrow unbonded regions were observed only along the perimeters of the joints. In addition, along the perimeters of the weld nugget, there was a significant reduction in the thickness of the upper sheet. The highest compression deformation was 20% and 35% after USW for 2 and 3 s, respectively.

In these narrow peripheral regions of the welded joints, deformed grains elongated in the direction of vibrations of the weld tip were observed. In areas adjacent to the anvil and the weld tip, the microstructure of the sheets is very close to that of the original sheet. In the central defect-free zone of joints, the microstructure has changed dramatically.

Figures 3 and 4 show the results of EBSD analysis of samples obtained from cross-sections of the initial sheet and from the centers of the weld spots of the welded samples. The microstructure of the alloy in the initial state consisted of equiaxed grains about 7 μm in size (figure 3a). The misorientation spectrum of high-angle boundaries did not have any pronounced maxima (figure 3b). The texture is typical for titanium subjected to rolling and subsequent annealing [5]: the basal planes (0001) are
rotated by 20-40° relative to the plane of the sheet around the RD direction, and therefore on the IPF from the sheet plane, an increase in the intensity of reflections in the directions \( <01\overline{1}3 > \) and \( <\overline{1}2\overline{4} > \) occurred (figure 4a).

![Figure 2. Microstructure of the USW joints produced with welding times 2 s (a,b) and 3 s (c,d); periphery (edge) (a,c) and centre (b,d) of the joints (BSE images).](image)

![Figure 3. IPF orientation maps of the initial sheet (a) and joints obtained by USW in time intervals 2 s (c) and 3 s (d) and misorientation distribution of high-angle grain boundaries (b).](image)

![Figure 4. IPFs of the initial sheet (a) and weld joints obtained by USW in 2 s (b) and 3 s (c).](image)
During USW, due to the combined action of high-frequency shear vibrations and static compression force, local heating occurred in the joint zone, and zones of thermo-mechanical influence were formed. In these zones, mainly large grains with a size of 40-80 µm containing a developed substructure were observed (figure 3 b, c). In the misorientation spectra of high-angle boundaries, maxima appeared in the vicinity of the angles 60° and 90° (figure 3d). The texture of the material changed (figure 4 b, c): there is a strong maximum in the <0001> direction on the IPF and less intense maxima were observed in the directions <0323>, <0212>, and <1010>. The texture in the thermo-mechanically affected zone changed little with an increase in the USW time from 2 to 3 s (some enhancement of the component <1010> can be noted). An increase in the duration of USW led to a two-fold increase in the width of the zone of thermo-mechanical influence, which is maximal in the center of the welded joint and decreases towards its periphery.

The changes in the microstructure described above are observed in titanium after β-α transition [6]. Probably, during the welding process at the interface of the surfaces to be joined, the material experiences deformation in the β-phase field and the final structure in the welded zone is produced via β-to-α phase transformation during the cooling cycle. Note that the microstructural changes occurring during USW of titanium differ from the data obtained during similar processing of Al and Cu, where a thin layer with a fine-grained structure was observed in the welded joint zone [2, 7-9].

3.2 Mechanical properties

Typical force vs. crosshead displacement curves obtained during lap shear tests of welded specimens and the appearance of ruptured specimens are shown in figure 5.

![Figure 5](image-url)

**Figure 5.** Typical lap shear test curves for USW-processed samples (a) and typical appearances of ruptured samples b).

It can be seen that an increase in the duration of the USW from 2 to 3 s (all other conditions being equal) led to an approximately 20% increase in the breaking force (figure 5a), an almost 3 times increase in the fracture work and a change in the fracture mode of the welded joint: fracture occurred at the interface after processing within 2 s, and for longer welding time of 3 s full nugget pull-out took place (figure 5 b). We assume that the main reason for the change in the fracture mode is a significant increase in the area of a defect-free joint and a decrease in the thickness of the top sheet in a narrow region along the perimeter of the welded point.

It should be noted that similar values of the breaking force (maximum lap shear force 1940 N) were obtained during lap shear tests of the joints of sheets of Ti-6Al-4V alloy obtained by roller USW [10]. However, this comparison is not entirely correct, since the true area of the welded joint has not been reliably determined.

4. Conclusions

A comparison of the microstructure and properties of the joints of titanium sheets with a thickness of
0.5 mm obtained by ultrasonic welding with a frequency of 20 kHz and an amplitude of 20 µm under the action of a constant static load of 6 kN for 2 and 3 s has been carried out. It is shown that a defect-free joint is formed in the thermo-mechanically affected zone, the length and width of which increases with the duration of welding. In the thermo-mechanically affected zone, a significant increase in the grain size, a change in texture is observed; in the misorientation spectra of high-angle grain boundaries, maxima appear in the vicinity of angles 60° and 90°. The fracture of the joints obtained with 2 s USW occurs in the interface mode under the action of a force of 1998 ± 122 N. After ultrasonic welding for 3 s, fracture occurs in the weld nugget pull-out mode and the fracture force increases to 2506 ± 226 N.

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