Ultrasonic Assisted Friction Stir Welding of Ti-Al Bimetals

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Abstract. High performance and reduced weight and cost are gaining importance in the aviation industry. There are different approaches to meet these requirements. In this study, titanium and aluminum alloys were welded using friction stir welding. The samples were divided into two groups, one of which was welded using ultrasound. Studies have shown that the strength of samples is influenced by many factors that are usually not taken into account. For example, the complexity of the interface between dissimilar materials and its roughness. It was found that the application of ultrasound during welding often increases the complexity of the interface and decreases its roughness, which generally leads to strengthening. This effect can neutralize the increase in the volume fraction of intermetallic compounds during the intensification of the welding process. The final strength consists of the number of defects, the volume fraction of intermetallics and the complexity of the interface.

1. Introduction

High performance and simultaneous weight and cost reductions are becoming increasingly important in the aviation industry. There are various approaches to meet these requirements. For example, the welding of cladding elements is gradually replacing riveted fuselage structures. Another effective option is the use of hybrid designs. Components from different materials can be adapted to local requirements. Modern industry needs a reliable welding method for joining dissimilar materials such as titanium and aluminum alloys. However, it is difficult to produce dissimilar welds from these alloys because of significant differences in their characteristics, including microstructure, melting point, thermal conductivity, coefficient of thermal expansion, etc. [1]. Brittle intermetallides and high stresses at the interface of dissimilar layers are formed in the produced welds [2]. One of the possibilities of titanium-aluminum bimetals producing is friction stir welding (FSW), which occurs without material melting. FSW allows the successful welding of most traditional structural materials.

Titanium-aluminum welds produced by FSW overlapping through aluminum have been previously investigated [3]. A layer of intermetallides is formed at the interface, but of lower thickness than in fusion welding, and the joint is a mechanical mixture. In this case, the more developed the interface, the stronger the joint [4]. In terms of interface development, lap welding through titanium may be more successful. When welding through aluminum, a small feed rate can cause the aluminum to overheat, causing it to be removed from the weld. Also, a low feed rate can lead to thickening of the intermetallide layer, which unstrengthen the joint [5]. When welding through titanium, these problems can be avoided due to its lower thermal conductivity. The development of the interface is possible by varying the process parameters, which is difficult because selecting the optimal welding mode is very time-consuming. In a previous study [6], it was found that a decrease in feed rate led to a decrease in defects...
and interface development. These effects together contributed to an increase in the strength of the joint as a whole. Reducing the feed rate did not result in an increase in intermetallide growth.

One possible modification used to improve the quality of the FSW weld is ultrasonic assisted friction stir welding. Ultrasonic vibrations reduce the yield strength of the metal during plastic deformation. In this case the input of additional energy does not lead to significant heating of material during deformation. The introduction of ultrasonic vibration during FSW can intensify the plastic flow of the material around the welding tool and improve the quality of the joint, as well as reduce welding stresses. These effects allowed the intermetallide layer at FSW Al/Mg to be broken into smaller layers and increased the strength of the joint [7]. Nevertheless, at material plasticization temperature, diffusion between dissimilar materials occurs inevitably, that is, the intermetallide layer cannot be removed at all, and its minimization does not always lead to increased joint strength. First of all, the FSW joint is a mechanical mixture, so the most important for dissimilar materials is the development of the interface, which can be facilitated by ultrasound. This work is aimed at developing and confirming these notions.

2. Experimental section

Bimetals were made by friction stir welding from 2.5 mm thick aluminum alloy 5056 and 2.5 mm thick commercially pure titanium. Friction stir welding in argon atmosphere was performed from the side of the titanium sheet, overlapped on the aluminum sheet. A tool from the heat-resistant alloy ZhS6U (Ni-10W-10Co-9Cr-6Al-2Ti-2Mo-1Fe-1Nb) with a pin length of 2.8 mm was used for welding. Based on the previous study [6], different parameters of the welding process in the samples were changed. The ultrasonic influence was imposed on the workpiece by rigid fixing of the magnetostrictive transducer on the free edge of the titanium alloy workpiece. The ultrasonic frequency was 21.6 kHz. Power of ultrasonic influence was 0.9 KW. Parameters of the technological process of welding are given in Table 1.

| №  | Rotation rate, RPM | Feed rate, mm/min | Axial force, kg | US |
|----|--------------------|--------------------|----------------|----|
| 1  | 950                | 100                | 800            | -  |
| 2  | 950                | 100                | 900            | -  |
| 3  | 950                | 90                 | 800            | -  |
| 4  | 1100               | 100                | 800            | -  |
| 5  | 950                | 100                | 800            | +  |
| 6  | 950                | 100                | 900            | +  |
| 7  | 950                | 90                 | 800            | +  |
| 8  | 1100               | 100                | 800            | +  |

The structure of the weld was studied using optical light and scanning electron microscopy. Mechanical tensile tests were performed to reveal the mechanical properties of the obtained joints. In fact, the tests were carried out on a shear, i.e. in the direction parallel to the plane of the interface.

To study the microstructure of the obtained bimetals, samples were cut in the cross-section transverse to the welding direction. Plane-parallel polished thin sections were prepared. A Microtrac SM-3000 scanning electron microscope was used to identify the phase structure. A metallographic microscope Altami MET-1S was used to reveal the grain structure; the samples were chemically etched beforehand. X-ray diffraction analysis was performed using a Dron-7 diffractometer.

3. Results

The obtained joints have a typical structure of the stir zone, which repeats the geometry of the welding tool. Stir zone is strongly recrystallized, which is typical for this alloy under severe plastic deformation
Zones of thermomechanical affect and thermal affect are almost absent visually, which is also typical for friction stir welding of titanium.

The criteria for macrostructure evaluation in this paper are the weld width, the plunge depth of the upper plate into the lower one, the interface complexity, the total area of defects in the cross section, the interface roughness, and the strength. Roughness in this case refers to the root-mean-square deviation of the interface profile. The interface complexity was estimated as the ratio of the interface length to the length of the joint width. The results of measuring these characteristics and the results of mechanical tests are shown in Table 2. The strength of the original material is given as #0.

Ultrasonic exposure during the welding process increases the complexity of the interface and reduces its roughness, which often leads to hardening. Also, ultrasound often results in minimized defects and a slight increase in weld width.

| #  | Weld width, mm | Plunge depth, mm | Interface complexity | Defect’s area, mm² | Rq, µm | Tensile strength, N |
|----|----------------|------------------|----------------------|-------------------|-------|-------------------|
| 0  | -              | -                | -                    | -                 | -     | 4579              |
| 1  | 3.6±0.1        | 0.34±0.03        | 1.87                 | 0.37              | 125   | 2580              |
| 2  | 3.84±0.1       | 0.32±0.05        | 1.36                 | 0.58              | 140   | 3000              |
| 3  | 4.1±0.1        | 0.7±0.04         | 1.71                 | 0.43              | 198   | 3580              |
| 4  | 4.3±0.1        | 0.57±0.03        | 1.66                 | 0.55              | 167   | 3030              |
| 5  | 4.4±0.1        | 0.42±0.04        | 1.98                 | 0.55              | 135   | 3220              |
| 6  | 4.47±0.1       | 0.28±0.05        | 1.38                 | 0.3               | 134   | 3900              |
| 7  | 4.3±0.1        | 0.54±0.03        | 1.91                 | 0.17              | 190   | 3170              |
| 8  | 4.34±0.1       | 0.57±0.05        | 2.06                 | 0.42              | 141   | 3250              |
Figure 2. Load-displacement diagram of titanium-aluminum bimetals: #2 – FSW, #6 – UAFSW.

Figure 2 shows a mechanical tensile test diagram in load-displacement coordinates. Since the bimetals are a composite and the tests are actually performed on shear, the plots cannot be reduced to stress-strain coordinates. However, the specimens were of equal width with an error of less than 0.01 mm, so a comparison in the units given is appropriate. The figure shows specimen #2 and specimen #6 with ultrasonic exposure. The strength of sample #6 was 85% of the strength of the original material.

Figure 3. Interface’s microstructure of samples #2 – FSW, #6 – UAFSW.

Using a scanning electron microscope (Fig. 3) in the backscattered electron mode, images of the joint microstructure in the interface area were obtained. As can be seen from the images, the joint is a mechanical mixture. No extended intermetallide layers were detected. Intermetallic layers are observed in some areas of strong titanium fragmentation. Similar structures are typical for lap welding of dissimilar materials under high loads and great penetration depths. For example, this was observed for copper and zinc alloys [9].
A fractographic analysis was performed (figure 4). The fracture surface, which was on the aluminum part of the joint, was analyzed. The fracture surface is very heterogeneous. The fractogram showed areas of aluminum (shown in dark gray), areas of titanium (shown in light gray), and intermetallics. Fracture occurs mostly in aluminum. Thus, the strength of the weld will strongly depend on the strength of the aluminum. The strength is also affected by the amount of intermetallics and the geometry of the weld joint.

X-ray diffractometer analysis was carried out and volumetric fraction of intermetallic content on the fracture surface of the samples was calculated (Table 3). The following intermetallics were found in the compounds: AlTi₃, AlTi₂, Ti₅₃Al, Ti₁₁Al₂₃, Al₃Ti. Figure 5 shows an X-ray diagram of sample #3 because the greatest number of phases were detected in this sample. Ultrasonic exposure during welding on average reduced the amount of intermetallics. The exception was sample #8, the amount of intermetallics was significantly higher than in sample #4, which was welded with the same parameters but without ultrasonic. This can be explained by the high heat input during welding. It was shown earlier that, depending on the thermal mode, ultrasound can both decrease the number of secondary particles and increase them [10]. Because of this, the strength #8 of the sample was also lower.
Table 3. Results of X-ray diffraction analysis.

| #  | Fraction of intermetallic, % |
|----|------------------------------|
| 1  | 0.47                         |
| 2  | 3.05                         |
| 3  | 28.96                        |
| 4  | 4.57                         |
| 5  | 0.2                          |
| 6  | 1.09                         |
| 7  | 3.57                         |
| 8  | 16.08                        |

4. Conclusion
As studies have shown, the strength of samples is influenced by a lot of factors that are usually not taken into account. For example, the complexity of the interface of dissimilar materials and its roughness. It was found that the ultrasonic use in the welding process often increases the complexity of the interface and reduces its roughness, which generally leads to hardening. The strength of sample #6 was 85% of the strength of the original material. Also, ultrasound often led to a decrease in the volume fraction of intermetallics. No continuous interlayer of intermetallics was observed between the dissimilar materials. Fracture occurred in aluminum, titanium and intermetallics. The final strength is a function of the number of defects, the volume fraction of intermetallics and the complexity of the interface.

Acknowledgments
The reported study was funded by RFBR according to the research project № 20-32-90194.

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