**Rare Metal Materials and Engineering**
Volume 48, Issue 1, January 2019
Available online at www.rmme.ac.cn

Science Press

**Cite this article as:** Rare Metal Materials and Engineering, 2019, 48(1): 0063-0070

ARTICLE

# Effect of Tool Offset on Weld Formation and Tensile Strength of Friction Stir Welded Ti/Al Dissimilar Metal Joints

**Chen Yuhua, Cao Wenming, Zhou Xingwen, Li Shuhan, GeJunwei**

*Nanchang Hangkong University, Nangchang 330063, China*

**Abstract:** 3 mm-thick TC4 titanium alloy and 2A14-T4 aluminum alloy were well joined by friction stir welding (FSW), and the influence of tool offset on weld formation and tensile property of the joints was investigated. The results show that tool offset to the Al side has significant influence on ultimate tensile strength (UTS) of the joints. With the increase of tool offset, the UTS increases gradually. When the tool offset is 2.0 mm, the UTS of the joint decreases with increasing the tool rotation speed from 400 to 700 r/min. However, when the tool offset is increased to 2.5 mm, the UTS of the joint increases with the increase of tool rotation speed. A tool rotation speed of 700 r/min and a welding speed of 60 mm/min are matched, the highest UST of 347 MPa of the joint is obtained, which reaches to about 83% of that of Al base metal. The tensile results prove that the fracture location and tensile strength of the joints mainly depend on microstructure and intermetallic phases. For the joint with the highest strength, the fracture occurs in the heat affected zone (HAZ) of Al base metal due to brittle TiAl phase formed in the joint.

**Key words:** Ti/Al dissimilar metal; friction stir welding; tool offset; tensile strength; fracture location

Weight reduction, cost efficiency and performance improvement have become more and more important in many applications of aerospace, aircraft, automobile and other fields. Hybrid structure of dissimilar materials is one of effective solutions because one can take advantage of the properties of both the materials[1-3]. For example, hybrid structure of Ti/Al dissimilar alloys is an attractive design in aerospace. However, the welding of Ti and Al alloy is of challenge as the performances of Ti and Al alloy have great differences in crystal microstructure, melting point, heat conductivity, coefficient of linear expansion, etc. So the welding of Ti and Al alloy is very difficult. In order to obtain good joints between Ti and Al alloy, many methods are conducted such as laser welding-brazing[4], gas tungsten arc welding-brazing[5], diffusion welding[6], brazing[7], friction welding[8], laser roll welding[9], ultrasonic welding[10] and pulsed gas metal arc welding[11]. However, it is difficult to obtain sound dissimilar joints of these two types of alloys because the continuous distribution of the intermetallic compound layer is easily formed and the oxidation film is difficult to clean up.

As a solid–state joining process, friction stir welding (FSW) is extensively studied to dissimilar material joining in recent years, for example Al to Cu[12,13], Al to Mg[14], Steel to Al[15], Steel to Ti[16]. More recently, there are several reports on FSW of Ti and Al alloy dissimilar metals. Chen et al. [17] joined Al-Si alloy and pure titanium using FSW, the maximum failure load of the joints reached 62% of Al-Si alloy base metal with the joints fractured at the interface, and new phase of $TiAl_3$ was found at the interface. Ulrike et al. [18] joined Ti-6Al-4V alloy and 2024-T3 aluminum alloy, and the weld nugget exhibited a mixture of fine recrystallized grains of aluminum alloy and titanium particles, and the ultimate tensile strength of the joint reached 73% of AA2024-T3 base material strength. In 2014, Li et al. [19] used a modified butt joint configuration into the

Received date: January 08, 2018
Foundation item: National Natural Science Foundation of China (51265042); Special Plan Project for the Construction of Jiangxi Advantageous Scientific and Technological Innovation Team (20171BCB24007); Natural Science Foundation of Jiangxi Province (20114BAB206006)
Corresponding author: Chen Yuhua, Ph. D., Professor, School of Aerospace Manufacturing Engineering, Nanchang Hangkong University, Nangchang 330063, P. R. China, E-mail: Yuhua-chen@nchu.edu.cn

FSW of Ti-6Al-4V alloy to Al-6Mg alloy with a special pin plunge setup, the tensile strength of the joint can reach more than 92% of Al-6Mg alloy, but this method is only for special structure such as lap structure. However, few works are reported on the FSW butt dissimilar Ti and Al alloy, and the tensile strength of the joint is unsatisfactory which can not meet the need of aerospace industry.

Therefore, in this research, we focus our efforts on the FSW butt of TC4 titanium alloy and 2A14 aluminum with 3 mm in thickness. The effects of the tool offset and tool rotation speed on weld formation and tensile strength are systematically investigated in order to obtain superior joints.

## 1 Experiment

The base metals used for FSW in the present study were 3 mm-thick rolled and annealed plates of Ti-6Al-4V titanium alloy (TC4) and 2A14-T4 aluminum alloy (AA2A14). Their chemical composition is listed in Table 1. The plates were cut and machined into rectangular welding specimens with a desired size of 200 mm (length) × 80 mm (width). The ultimate tensile strength (UTS) of TC4 and AA2A14 alloys were measured about 1100 and 420 MPa, respectively.

The welding setup is schematically shown in Fig.1. In this setup, both the Al alloy and Ti alloy were rigidly clamped to minimize vibration and distortion during FSW. In order to study the effects of tool offsetting on morphology, structure, and mechanical properties of the welds, different tool positions were tested with offsetting values ranging from 0 to 2.5 mm. Following the work of Nandan et al.[20], harder material (TC4 alloy) was placed on the advancing side (AS) while 2A14 alloy was on the retreating side (RS).

Tool offset ($\delta$), which was corresponding to the distance from the base metal interface to the tool axis, was placed towards the aluminum alloy side. Thus, the welds were denoted as $\delta_0$, $\delta_{1.0}$, $\delta_{2.0}$ and $\delta_{2.5}$ referring to the tool offset of 0, 1, 2, 2.5 mm, respectively. FSW experiment was performed using a tool with the shoulder diameter, pin diameter and pin length of 18, 6 and 2.6 mm, respectively. The tool was made of directionally solidified superalloy and with left-hand thread on the cylindrical pin surface. A 2° tilt opposite the traveling direction was applied to the pin tool for all the processing.

The sizes of the tensile test specimens and the locations where the welded joints were extracted are shown in Fig.2. The tensile tests were carried out according to GB/T2651-2008 for all the welds under as-welded condition using a WDW-50 electromechanical universal testing machine, and the cross-head movement speed was 10 mm/min. Three specimens of the joints were tested and the average tensile strength was reported. Metallographic specimens were cut from the transverse cross-section of the welds. After standard grinding and polishing procedures and etching with mixed solution (1 mL HF + 1.5 mL HCl + 2.5 mL $HNO_3$ + 24 mL $H_2O$), the as-welded macro- and micro- structural characteristics of the transverse cross-sections of the weld were inspected by optical microscopy (OM) and field emission scanning electron microscope (FE-SEM) using a Nova Nano SEM 450 microscope equipped with an energy-dispersive X-ray spectrometer (EDS). To identify the intermetallic compounds in the weld, micro area XRD was conducted using an Empyrean X-ray diffractometer.

## 2 Results and Discussion

During our research, the weld surface was very poor and there were obvious weld defects such as connected tunnel and cracks for most of the welds produced without tool offset ($\delta_0$), so the tensile test was not conducted. When the tool offset was 1 mm, the weld surface was better than that of 0 mm, but the weld was also easy to crack during the welding. When the tool offset was increased to 2.0 or 2.5 mm, the welds with best surface were produced in the same welding condition.

In FSW, the joint is formed by the frictional heat generated by the tool and the materials. In the FSW of Ti/Al alloy dissimilar metals, the amount of frictional heat is different when the tool offset is changed because of different friction coefficients between Ti alloy and Al alloy, so the formation of the joint is various. Fig.3 shows surface appearances of the joints at different offsets when the tool rotation speed was 600 r/min and welding speed was 60 mm/min. As seen from Fig.3, there are obvious macroscopic cracks on the top surface of $\delta_0$ and $\delta_{1.0}$. When the offset is increased to 2 and 2.5 mm, much better appearances of the joints are obtained, there are no significant weld defects on the surface.

**Table 1 Chemical composition of base metals of TC4 and 2A14 alloys (wt%)**

| Alloy | Al | Ti | Mn | Mg | Fe | Zn | Si | Ni | Cu | V | N | C | H | O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2A14 Al | Bal. | 0.02 | 0.73 | 0.55 | 0.3 | 0.08 | 1.0 | 0.02 | 4.3 | - | - | - | - | - |
| TC4 Ti | 6.0 | Bal. | - | - | 0.026 | - | - | - | - | 4.0 | 0.008 | 0.015 | 0.007 | 0.06 |

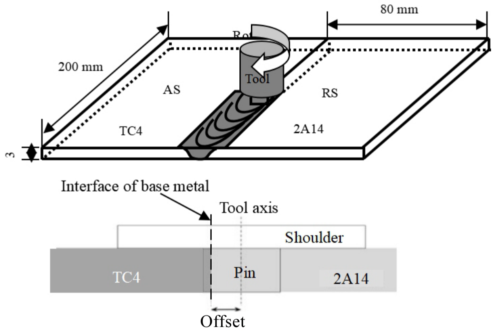


Fig.1 Schematic illustration of the joint arrangement and tool offset in FSW

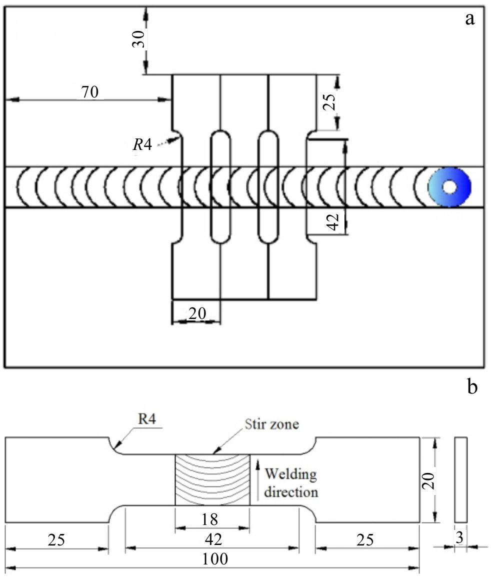


Fig.2 Configuration of the tensile specimens and the location in the welded joint: (a) the location of the specimens and (b) the size of the specimens (mm)

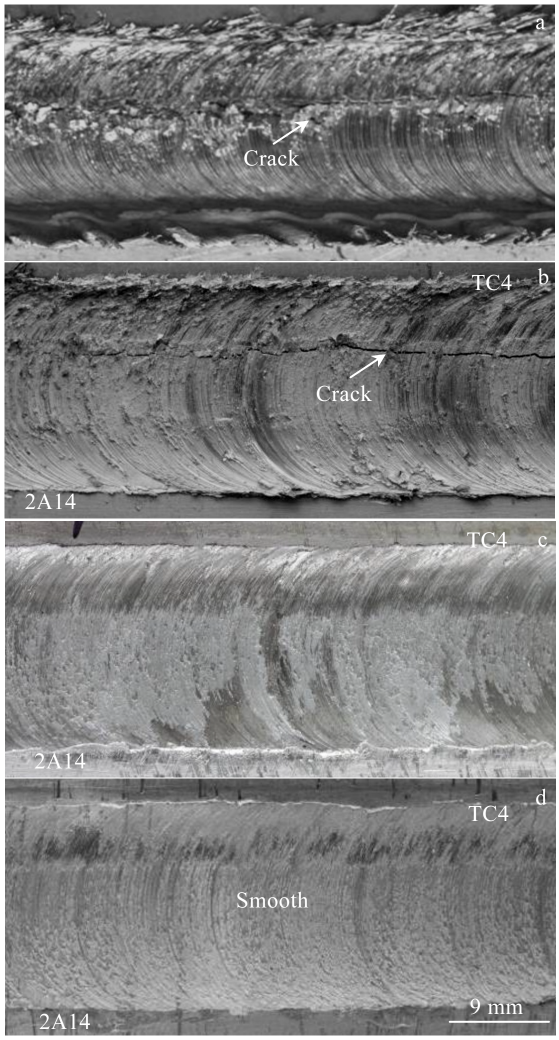


Fig.3 Surface appearances of the joints at different tool offsets: (a) 0 mm, (b) 1 mm, (c) 2 mm, and (d) 2.5 mm

In a word, smaller offset will increase the weld defects for the FSW of Ti/Al alloy which reduces the tensile strength. The reason for this can be explained as follows: TC4 alloy has higher friction coefficient than 2A14 Al alloy, more frictional heat is generated from TC4 alloy than from 2A14 alloy for the same friction area. Decreasing the offset can increase the contact area between the tool and TC4 alloy which can increase the amount of frictional heat. In addition, this will raise the interface temperature between the plasticized TC4 and 2A14 alloy. More brittle phases may be produced in the joint, so the joint is easy to crack under low welding stress.

When tool offset was fixed at 1.0 mm and the welding speed was fixed at 60 mm/min, tool rotation speed has an obvious effect on surface morphology, as shown in Fig.4. Crack appeared when the tool rotation speed was 600r/min. The XRD results show that there is about 5.9% brittle $TiAl_3$ in the joint produced at 400 r/min while it is 10.2% at 700 r/min. Therefore, as shown in Fig.5, $TiO_2$ is also produced in the joint at 700 r/min, the reason for which is that the temperature of TC4 alloy is high and Ti element reacts with the $O_2$ in the air. Both $TiAl_3$ and $TiO_2$ are brittle phase which can induce the cracking of the joint at low welding stress.

As stated above, increasing tool rotation speed will produce more brittle phases and hence reduce the strength of joint. However, the law is reversed when the tool offset is fixed at 2.5 mm. Fig.6 shows the surface appearances of the joints with the tool rotation speed varying from 400 r/min to 700 r/min when the tool offset is fixed at 2.5 mm. The surface appearances of the joints are different at various tool rotation speeds. There is an obvious interface between TC4 alloy and 2A14 alloy on the weld surface when the tool rotation speed is 400 r/min (Fig.6a). With increasing the rota-

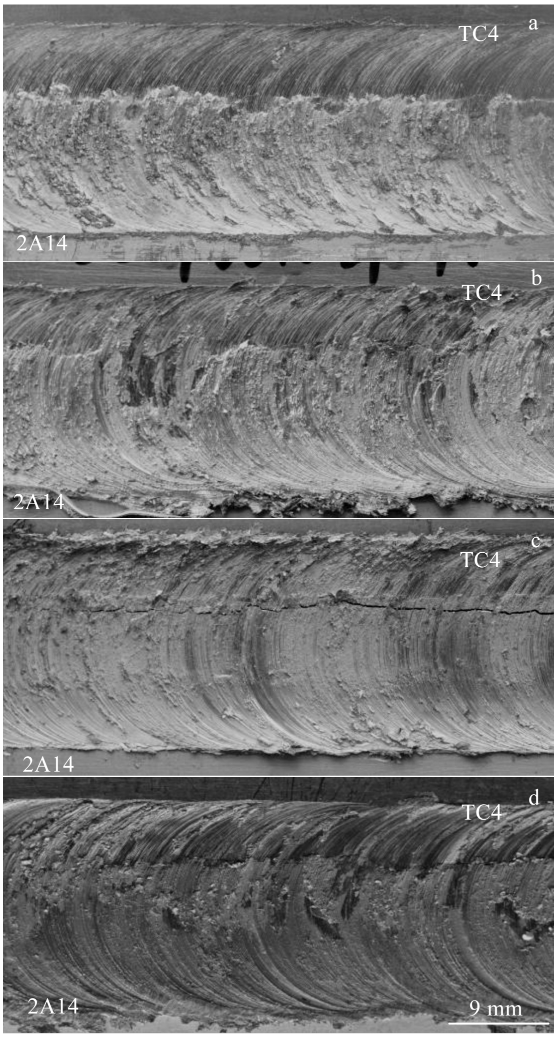


Fig.4 Surface appearances of the joints at different tool rotation speeds: (a) 400 r/min, (b) 500 r/min, (c) 600 r/min, and (d) 700 r/min

tion speed, the interface becomes more and more vague. When the tool rotation speed is increased to 700 r/min, the interface disappears. There are no weld defects such as cracks on the surface of all the four rotation speeds, despite the top surface quality is poor when the tool rotation speed is low.

Fig.7 shows the UTS of the Ti/Al joints at different tool offsets of 1.0, 2.0 and 2.5 mm ($\delta_{1.0}$, $\delta_{2.0}$ and $\delta_{2.5}$) for a tool rotation speed between 400 and 700 r/min, when the welding speed is fixed at 60 mm/min.

The UTS of the joint increases with increasing the tool offset. When the tool offset is fixed at 1.0 mm, the UTS of the joint decreases with the increasing of the tool rotation speed. The trend is the same for $\delta_2$. However, the changing trend of the UTS is opposite when the tool offset is fixed at 2.5 mm. The UTS of the joint increases with the increasing of the tool rotation speed. The highest strength of 347 MPa

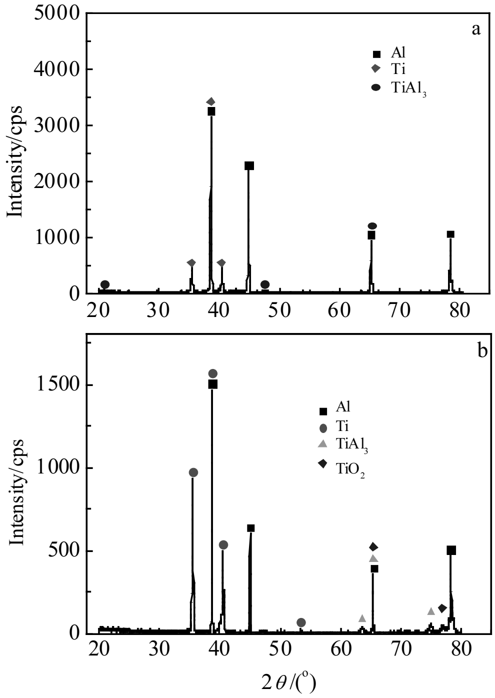


Fig. 5 XRD patterns of the joints at different tool rotation speeds: (a) 400 r/min and (b) 700 r/min

of the joint is obtained which is about 83% of that of 2A14-T4 base metal when a tool rotation speed of 700 r/min and a welding speed of 60 mm/min are matched. With respect to the tensile results, there is an indication that the tool offset has a significant influence on the UTS of the joint, and the tool offset of 2.5 mm is suitable for achieving sound joints between TC4 alloy and 2A14 alloy.

The fraction location of the joint at various tool rotation speeds is different in the tensile test, despite the surfaces of the four rotation speeds are all good and have no defects. There are three kinds of fraction locations as a whole listed in Table 2, such as nugget zone, interface between TC4 and nugget, heat affected zone (HAZ) of Al base metal. The tensile strength is low when the tensile sample is fractured in the nugget zone and the tensile strength is high when the tensile sample is fractured in the HAZ of Al base metal. The tensile strength is between the two when the tensile sample is fractured in the interface between TC4 and nugget.

The surface morphologies and cross sections for different samples are shown in Fig.8. When the tensile sample fractures at the HAZ of base metal, there is an apparent necking around the fraction area. The fraction location is about 8 mm apart from the interface, the crack originates from the bottom surface and extends to the top surface along the thickness direction. When the tensile sample fractures at the nugget, the crack originates from the area with a lot of Ti particles which are the result of material flow from the TC4 base metal into the nugget, and there is no necking around the fraction area. When the tensile sample fractures at the interface between

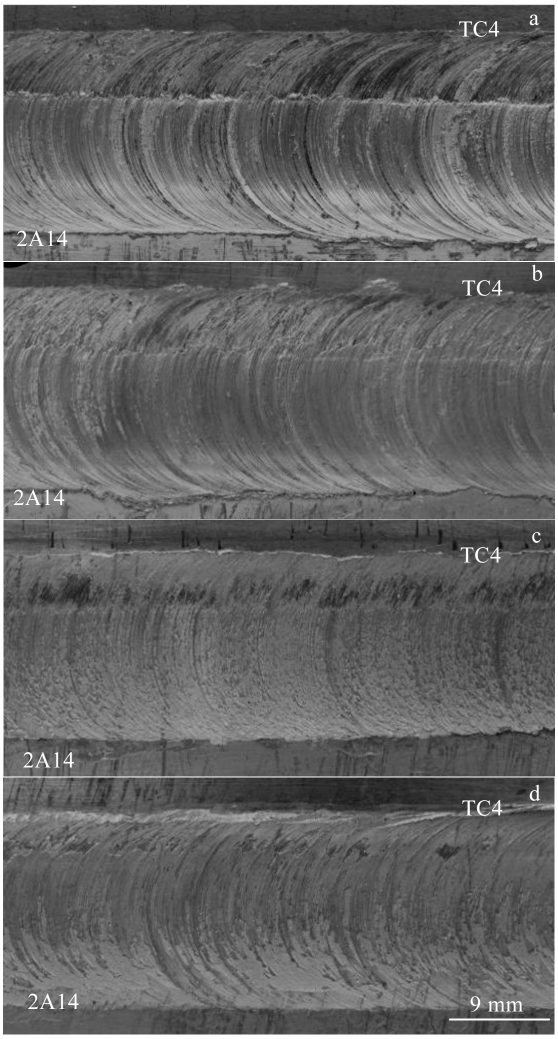


Fig.6 Surface appearances of the joints at different tool rotation speeds: (a) 400 r/min, (b) 500 r/min, (c) 600 r/min, and (d) 700 r/min

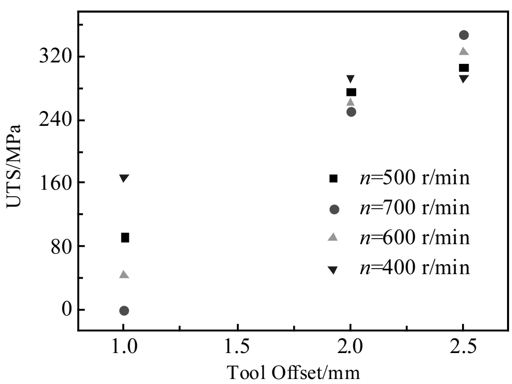


Fig.7 Effects of the tool offset and rotation speed on the UTS of the joints

**Table 2 Tensile properties of the joints at various tool rotation speeds**

| No. | Tool rotation speed/r·min$^{-1}$ | UTS /MPa | Fraction location |
|---|---|---|---|
| 1 | 400 | 293 | Nugget zone |
| 2 | 500 | 306 | Interface between TC4 and nugget |
| 3 | 600 | 324 | Interface between TC4 and nugget |
| 4 | 700 | 347 | HAZ of Al base metal |

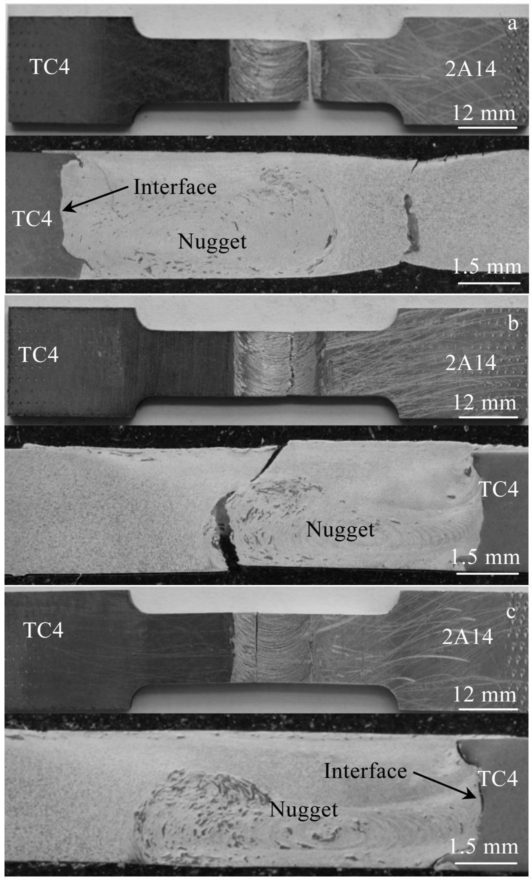


Fig.8 Surface morphologies and cross sections of the joints for different fraction locations: (a) HAZ of Al base metal, (b) nugget zone, and (c) interface between TC4 and nugget

TC4 alloy and the nugget, the crack originates from the interface and fracture occurs along the interface, and there is also no necking around the fraction area, which indicates a brittle fracture model.

Fig.9 shows the microstructure in the nugget zone of the joint produced at a welding parameter of 400r/min-60 mm/min with a tool offset of 2.5 mm. Fig. 9b consists of a mixture of the Al matrix and big Ti particles, and many voids are observed around the Ti particles. Therefore, the welding crack initiates from the boundary between the Ti particles and Al matrix, which makes the joint fracture at

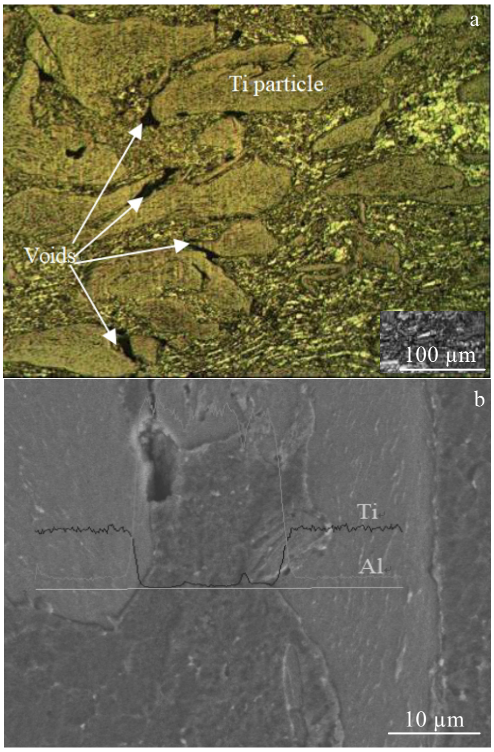


Fig.9 Microstructure in the nugget zone of the joint: (a) microstructure and (b) element distribution through Al matrix and Ti particle

the nugget zone during the tensile testing. The formation of the voids should be related to the insufficient friction heat which induces the plasticization of the Ti particles and combination with the Al matrix in the nugget at a lower tool rotation speed.

At a higher rotation speed of 500, 600 and 700 r/min, the temperature in the nugget zone is higher due to stronger stirring and more friction between the tool and the alloys compared to that at a lower rotation speed. More sufficient plasticization induces Ti particles combining well with the Al matrix, and no defects are observed in the nugget zone, as shown in Fig.10.

But, the interface between TC4 base metal and the nugget is different for different joints with various tool rotation speeds. Fig.11 gives SEM images of the interface between Ti base metal and the nugget at 500 and 600 r/min. When the tool rotation speed is 500 r/min, there are many obvious micro-voids and cracks between Ti base metal and the nugget, and there is no obvious reaction layer at the interface, as shown in Fig.11a. Therefore, the location of the joint at the interface is the weakest between Ti base metal and the nugget although there are no defects in the nugget. However, when the tool rotation speed is increased to 600 r/min, there is a very thin interface (Fig.11b).

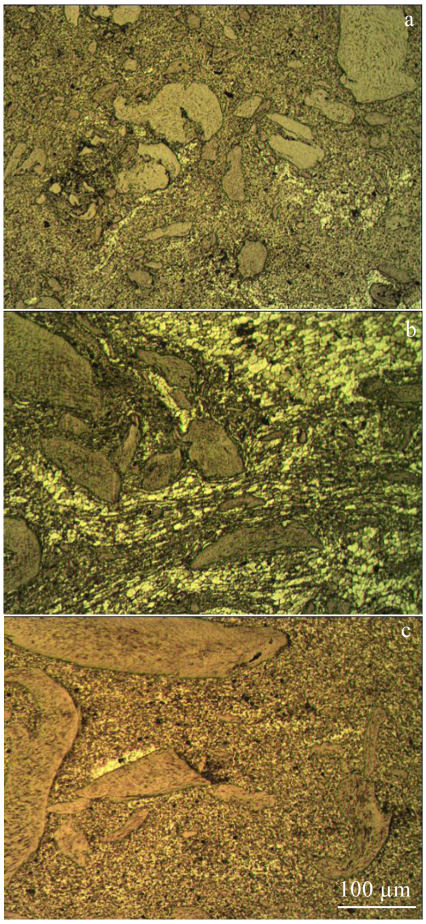


Fig.10 Microstructures in the nugget zone of the joints obtained at different tool rotation speeds: (a) 500 r/min, (b) 600 r/min, and (c) 700 r/min

Fig.12 shows SEM image of the interface at 700 r/min and EDS spectra including the main element content in special regions obtained by EDS. Under this process condition, an intermetallic layer of about 8 μm in thickness is formed, and a multi-layer structure characteristic is found in this layer. The EDS results of main elements and their contents in the intermetallic layer are shown in Fig.12b. The EDS results show that the intermetallic layer constitutes an Ti-Al reaction typed as-welded interface zone, which have a unique structure in comparison with that in Fig.11. Between the intermetallic layer and the nugget, there are intermittent white region shown in Fig. 12a. The main elements and the content at the point "N" are shown in Fig.12c. The result shows that the atom ratio of titanium and aluminum element is about 1:1, which indicates that it is TiAl phase.

Therefore, a metallurgical bonding occurs between Ti base metal and the nugget through the intermetallic layer and TiAl intermetallic in the joint. Because the thickness of the inter

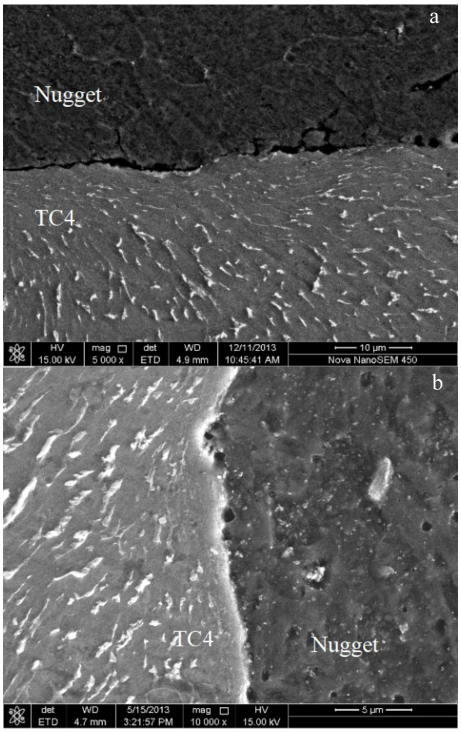


Fig.11 SEM images of the interface between Ti base metal and the nugget of the joints produced at 500 r/min (a) and 600 r/min (b)

metallic layer and TiAl intermetallic are very thin which is helpful to improve the strength of the joint[21]. In the meantime, there are no defects in the nugget and plasticized Ti particles in the nugget which can enhance the strength of the nugget. As far as the FSW of heat-treatable aluminum alloys are concerned, it is pointed out that the metastable precipitates, i.e. the main strengthening phases of the alloys, can be coarsened, and then transformed to stable state or dissolved into the matrix during the welding. Furthermore, if the weld is performed at a relatively large power, the reprecipitation of meta-stable phases may occur during the cooling[22]. Therefore, the weakest location of the joint is such a place that it experiences the greatest precipitate deterioration but does not achieve a cooling rate that is low enough to reprecipitate the metastable phases. From this standpoint of view, the cooling rate of FSW is high relatively, softening may occur in the HAZ of the Al side. Therefore, the strength of the nugget and interface is higher than the HAZ, and the fracture occurs at the HAZ of the Al side during the tensile testing.

According to the binary phase diagram of Ti-Al[23], Ti and Al can produce TiAl, $TiAl_2$, $TiAl_3$ and $Ti_3Al$ intermetallic-under different conditions. But among these kinds of intermetallic, $TiAl_2$ can not be produced by Ti and Al directly, but be produced through TiAl as an intermediate product. In FSW joints, only TiAl, $TiAl_3$ and $Ti_3Al$ can be produced by Ti and Al directly among these three kinds of intermetallic,

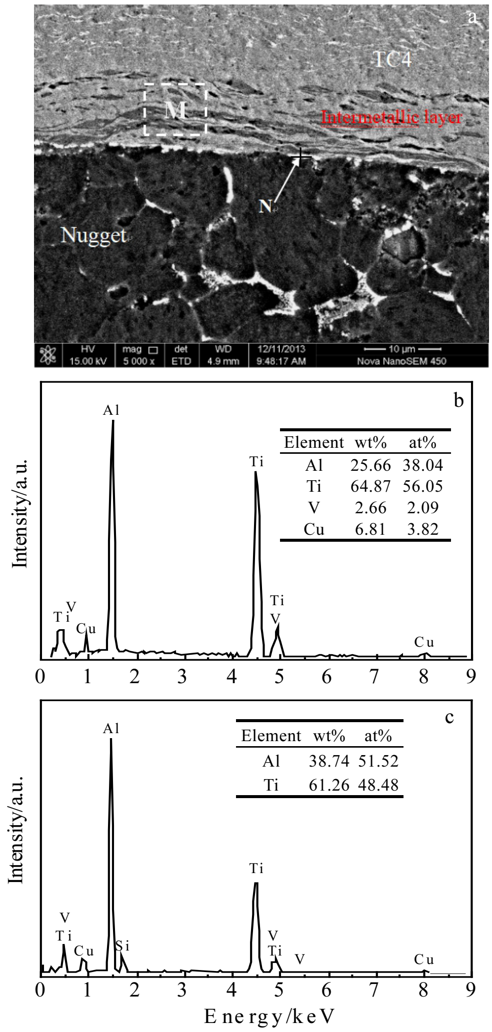


Fig.12 SEM images of the interface between Ti base metal and the nugget of the joint at 700 r/min: (a) interface morphology, (b) EDS result of M region, and (c) EDS result of N point

therefore $TiAl_3$ is easier to produce on the interface of Ti/Al in FSW joint, and then is TiAl. $Ti_3Al$ has the maximum enthalpy of formation and it is hard to produce during FSW.

The valence electron structure factors of all the three kinds of intermetallic are listed in Table 3 which can represent the me-

**Table 3 Valence electron structure factors of Ti-Al intermetallic[24]**

| Phase | $Ti_3Al$ | TiAl | $TiAl_2$ | $TiAl_3$ |
|---|---|---|---|---|
| $\rho_v^c$ /nm$^{-3}$ | 171.0301 | 169.0839 | 167.1995 | 165.957 |
| $\overline{E}$ /kJ·mol$^{-1}$ | 411.91 | 406.78 | 384.99 | 379.25 |
| $\rho_v^l$ /nm$^{-3}$ | 52.1012 | 45.3768 | 40.5404 | 37.9965 |
| $I$ | 0.25 | 0.1667 | 0.2162 | 0.1667 |
| $N_c$ | 0.7163 | 0.9079 | 0.5884 | 0.9145 |
| $S$ | 9.33001 | 6.86765 | 5.15723 | 5.79247 |
| $\overline{F}$ | 6.2590 | 5.9945 | 5.5243 | 5.3793 |

chanical properties of intermetallic. The plasticity factor $S$ of TiAl is bigger than that of $TiAl_3$ which indicates that TiAl is more plastic than $TiAl_3$ (Table 3). Therefore, the joint with a thin TiAl layer in the interface should not fracture at the interface.

## 3 Conclusions

1) Tool offset has a significant influence on weld surface appearance and tensile strength for FSW Ti/Al dissimilar metals. When the tool offset is 0 and 1.0 mm, the surface of the joints is easy to crack. However, with increasing the tool offset to 2.0 or 2.5 mm, the formation quality of the welds is improved well, and the tensile strength increases obviously with the increasing of the tool offset.

2) When the tool offset is fixed at 1.0 or 2.0 mm, the tensile strength of the joint decreases with increasing the tool rotation speed. But, when the tool offset is fixed at 2.5 mm, the tensile strength of the joint increases with the increasing of the tool rotation speed. The highest strength of 347 MPa of the joint is obtained which is about 83% of 2A14-T4 Al base metal when a tool rotation speed of 700r/min and a welding speed of 60 mm/min are matched.

3) The fracture location and the tensile strength of the joint have a relationship with microstructure and intermetallic phase formed in the joint. For the joint with higher strength, it fractures in the heat affected zone of Al base metal as TiAl phase formed in the interface between Ti base metal and the nugget in addition to $TiAl_3$ phase which offers a better plasticity. When there are defects or no TiAl in the interface, the joints fracture at the interface. When the tool rotation speed is low, there are many voids in the nugget due to the insufficient friction where the joint fractures.

## References


1 Chen Y H, Ni Q, Ke L M. *Trans Nonferrous Met Soc*[J], 2012, 22: 299

2 Zhang X, Chen Y H, Wang S L. *Rare Metal Materials and Engineering*[J], 2017, 46(1): 247 (in Chinese)

3 Zhang X, Chen Y H, Wang S L. *Rare Metal Materials and Engineering*[J], 2016, 45(5): 1290 (in Chinese)

4 Ren J W, Li Y J, Feng T. *Mater Lett*[J], 2002, 56(5): 647

5 Chen Y B, Chen S H, Li L Q. *Int J Adv Manuf Tech*[J], 2009, 44: 265

6 Lv S X, Jing X J, Huang Y X *et al. Sci Technol Weld Joi*[J], 2012, 17(7): 519

7 Yao W, Wu A P, Zou G S. *Mat Sci Eng A*[J], 2008, 480: 456

8 Sohn H W, Bong H H, Hong S H. *Mat Sci Eng A*[J], 2003, 355: 231

9 Kimura M, Nakamura S, Kusaka M *et al. Sci Technol Weld Joi*[J], 2005, 10(6): 666

10 Ozaki H, Hayashi S, Kutsuna M. *Weld Int*[J], 2009, 23(7): 501

11 Zhu Z Q, Lee K Y, Wang X L. *Int J Adv Manuf Tech*[J], 2012, 59: 569

12 Xue P, Xiao B L, Ni D R *et al. Mat Sci Eng A*[J], 2010, 527: 5723

13 Xue P, Ni D R, Wang D *et al. Mat Sci Eng A*[J], 2011, 528: 4683

14 Venkateswaran P, Reynolds A P. *Mat Sci Eng A*[J], 2012, 545: 26

15 Lee W B, Schmuecker M, Mercardo U A *et al. Scripta Mater*[J], 2006, 55: 355

16 Li S H, Chen Y H, Zhou X W *et al. Mater Lett*[J], 2019, 234: 155

17 Chen Y C, Nakata K. *Mater Des*[J], 2009, 30: 469

18 Ulrike D, Gerhard B, Ulises A M. *Mat Sci Eng A*[J], 2009, 526: 113

19 Li B, Zhang Z H, Shen Y F *et al. Mater Des*[J], 2014, 53: 838

20 Nandan R, DebRoy T, Bhadeshia H K. *Prog Mater Sci*[J], 2008, 53: 980

21 Li S H, Chen Y H, Kang J D *et al. Metals*[J], 2018, 8(11): 925

22 Upadhyay P, Reynolds A P. *Mat Sci Eng A*[J], 2010, 527: 1537

23 Rahmel A, Spencer P J. *Oxidation of Metals*[J], 1991, 35(1-2): 53

24 Jiang S Y. *Thesis for Doctorate*[D]. Qingdao: China University of Petroleum, 2010 (in Chinese)


# 搅拌头偏移对 Ti/Al 异种金属搅拌摩擦焊接头成形及拉伸强度的影响


陈玉华，曹文明，周兴汶，李树寒，戈军委

(南昌航空大学，江西 南昌 330063)



**摘　要**：采用搅拌摩擦焊(FSW)完成了 3 mm 厚 TC4 钛合金和 2A14-T14 铝合金的连接，研究了搅拌头偏移对接头的成形及拉伸性能的影响。结果表明在搅拌头向铝合金侧的偏移对接头的最大抗拉强度有显著的影响。接头最大抗拉强度随搅拌头的偏移量的增加逐渐升高。在偏移量为 2.0 mm、搅拌头转速从 400 r/min 增加到 700 r/min 时，接头的最大抗拉强度逐渐降低。在偏移量为 2.5 mm、接头的最大抗拉强度随转速的增加逐渐升高。当在搅拌头转速为 700 r/min, 焊接速度为 60 mm/min 时，所得接头强度最高，约 347 MPa，为铝合金母材的 83%。接头的断裂位置和拉伸强度均取决于微观组织和金属间化合物。对于强度最高的接头，由于 TiAl 相的生成，接头于铝合金侧热影响区发生断裂。



**关键词**：Ti/Al异种金属；搅拌摩擦焊；搅拌头偏移；抗拉强度；断裂位置



作者简介：陈玉华，男，1979 年生，博士，教授，南昌航空大学航空制造工程学院，江西 南昌 330063，E-mail: Yuhua-chen@nchu.edu.cn