Mechanical properties of Ti-6Al-4V titanium alloy and Al-Mg aluminium alloy (AA5052) friction welded joint

M. Kimura, S. Nakamura, M. Kusaka, K. Seo and A. Fuji

This paper describes the mechanical properties of a friction welded joint of Ti-6Al-4V titanium alloy and Al-Mg aluminium alloy (AA5052). The Ti-6Al-4V/AA5052-H112 joint, made at friction speed of 27.5 s^{-1}, friction pressure of 30 MPa, friction time of 3.0 s and forge pressure of 60 MPa, had 100% joint efficiency and it fractured at the AA5052-H112 base metal. The Ti-6Al-4V/AA5052-H34 joint, made under the same friction welding conditions, did not achieve 100% joint efficiency and it fractured at the AA5052-H34 base metal because the AA5052-H34 base metal had softened under friction heat. The joints made at low friction speed or short friction time were fractured at the welded interface because sufficient heat quantity could not be produced for welding. On the other hand, the joints made at high friction speed or long friction time were fractured at the welded interface. In this case, the welded interface also had an intermetallic compound layer consisting of $Ti_2Mg_3Al_{18}$. The Ti-6Al-4V/AA5052-H34 joint, it made at friction speed of 27.5 s^{-1}, friction pressure of 150 MPa, friction time of 0.5 s and forge pressure of 275 MPa, had 100% joint efficiency and it fractured at the AA5052-H34 base metal although the AA5052-H34 side slightly softened. In conclusion, the Ti-6Al-4V/ AA5052-H112 joint and Ti-6Al-4V/AA5052-H34 joint had 100% joint efficiency and it fractured at the AA5052 base metal when made under the above friction welding conditions.

Keywords: Friction welding, Titanium alloy, aluminium alloy, Joint efficiency, Softening, Intermetallic compound layer

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INTRODUCTION

Titanium (Ti) and its alloys have highly attractive characteristics in terms of mechanical and metallurgical properties, e.g., high tensile strength and excellent corrosion resistance. They are widely used for important structural components in architecture, automobiles, aerospace, and so on.[1] Furthermore, Ti is also used in biomedical materials because of its low allergenic effect on the human body.[2] However, it is expensive and this limits its application. Moreover, the fusion weld between Ti and other metals such as aluminium (Al), copper (Cu) or stainless steel, has poor mechanical properties due to the brittle intermetallic compound layer produced at the joint interface.[3] A welding process of dissimilar joint with Ti that will give less damage to the mechanical and metallurgical properties of a joint is therefore strongly required. The solid state joining methods such as diffusion welding, friction welding and so on, can be applied to join Ti and other metals. Many researchers have reported that the mechanical and metallurgical properties of a friction welded joint of Ti or its alloys show good characteristics.[4-20]

Al is another of the most important non-ferrous metals. Al and its alloys are also widely used for structural components such as automobiles, aerospace, and so on, because they have good mechanical and metallurgical properties, e.g., high specific strength and excellent corrosion resistance. A dissimilar welded joint of Ti and Al has more advantages than that of Ti alone, e.g., low cost, less weight and high performance. A typical Ti alloy, e.g., Ti-6Al-4V, has highest tensile strength. On the other hand, a typical Al alloy, e.g., AA5052, is typical one that is weldable and is widely used in industry, such as in the manufacture of transportation machines. Clearly, a joint welded using a Ti/Al system is very valuable to industry. Meanwhile, basic research into pure Ti and pure Al is useful for establishing Ti/Al system welding, and for evaluating metals basic mechanical and metallurgical properties. One of the authors has investigated the mechanical and metallurgical properties of a friction welded joint of commercially pure Ti and some Al alloys (pure Al, Al-Mg alloy and Al-Zn-Mg alloy).[16-20] The weldability of those combinations was good, and the welded joints had good mechanical properties. However, clarification is required concerning the weldability of a Ti alloy with other metals because expansion in the use of Ti alloys can be expected.

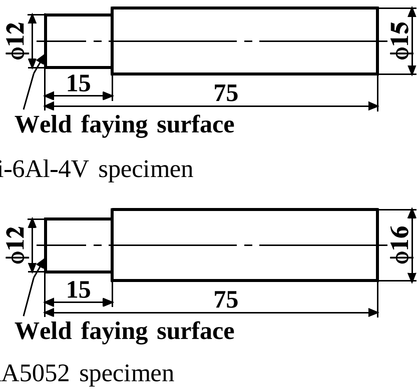
The authors have been carrying out research to clarify the weldability of a friction welded joint of a Ti alloy and an Al alloy. In this study, we present the weldability of the Ti-6Al-4V titanium alloy (from now on, it is referred to as Ti-6Al-4V) and Al-Mg aluminium alloy (from now on, it is referred to as AA5052). We also present their mechanical properties under various friction welding conditions, especially, the effect of friction speed, friction time and forge pressure on the tensile strength of the welded joint.

EXPERIMENTAL PROCEDURE

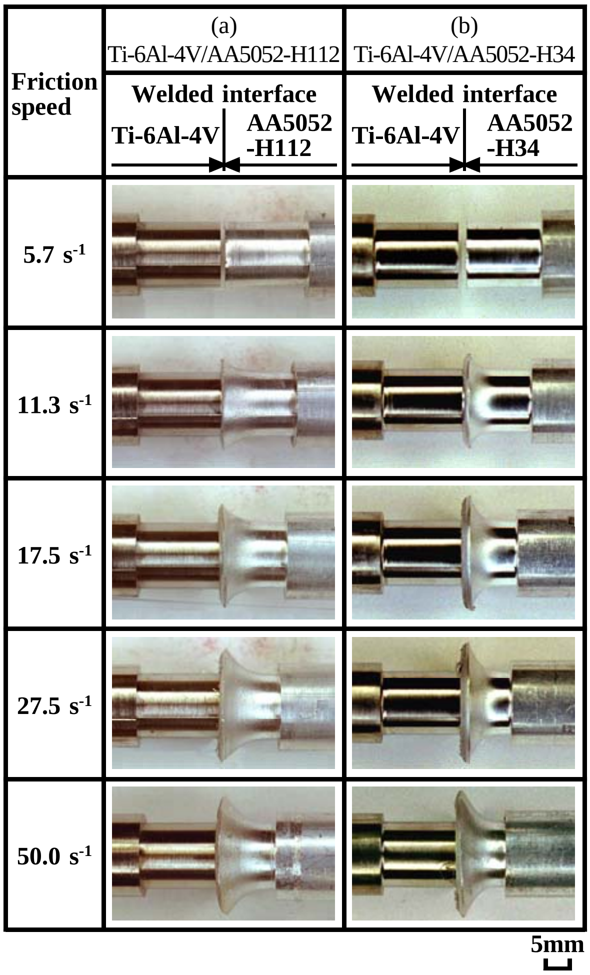
The materials used were Ti-6Al-4V with diameter of 15 mm

Table 1 Chemical compositions and tensile properties of materials used

Chemical compositions, mass-%														T.S.,	0.2%Y.S.,	El,	Vickers
C	H	O	N	Fe	Ti	Mn	Si	Cr	Cu	V	Al	Mg	Zn	MPa	MPa	%	hardness
Ti-6Al-4V																	
0.015	0.006	0.170	0.005	0.22	Bal.	-	-	-	-	4.30	6.21	-	-	1050	970	19	354
AA5052-H112																	
-	-	-	-	0.19	-	0.03	0.12	0.18	0.05	-	Bal.	2.50	0.02	194	73	35	56
AA5052-H34																	
-	-	-	-	0.11	-	0.04	0.07	0.23	0.01	-	Bal.	2.50	0.01	275	250	14	86



1 Shapes and dimensions of friction welding specimens



2 Appearances of welded joints after welding: friction pressure of 30 MPa, friction time of 3.0 s, forge pressure of 60 MPa and forge time of 6.0 s

and AA5052 in rods with diameter of 16 mm. Two types of A5052 with different tensile properties by work hardening treatment as given symbol of H112 and H34 (from now on, its are referred to as H112 and H34, respectively) were used. The chemical compositions and tensile properties of those materials are given in Table 1.[21-23] Those materials were machined to 12 mm in diameter of the weld faying (contacting) surface, as shown in Figs.1(a) and (b). The measuring portion was 1 mm from the weld faying surface at half-radius. All weld faying surfaces of the specimens were polished with buff before joining because surface roughness influences the mechanical properties of a dissimilar materials joint.[15,16] The average height of weld faying surface roughness was approximately 0.07 μm.

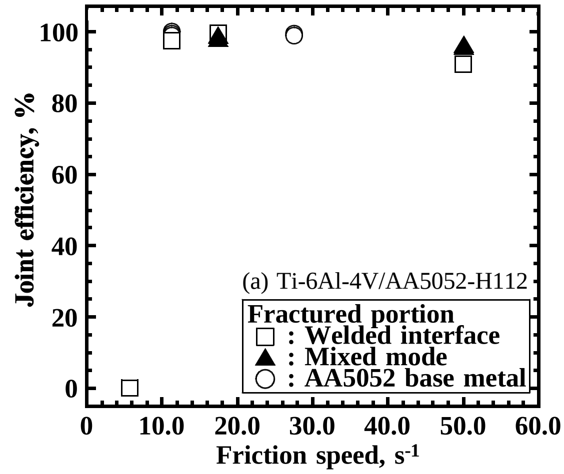
The Ti-6Al-4V/AA5052-H112 and Ti-6Al-4V/AA5052-H34 joints (from now on, its are referred to as Ti-6Al-4V/H112 and Ti-6Al-4V/H34, respectively) were made by a continuous (direct) drive friction welding machine. The braking time of the friction welding machine was approximately 0.4 s. From now on, this welding method will be referred to as the conventional method. During friction welding operations, the parameters of the friction welding condition were as follows: friction pressure of 30 MPa, friction time of 3.0 s, forge pressure of 60 MPa and forge time of 6.0 s. The friction speed was set to 5.7, 11.3, 17.5, 27.5, and 50.0 revolutions per second (s^{-1}). The Ti-6Al-4V specimen was set on a fixed side and the AA5052 specimen was on a rotating side. The friction torque during the friction stage was measured with a load-cell and recorded with a personal computer through an A/D converter at a sampling time of 0.015 s. The effect of friction time on joint properties was also investigated. In this case, the specimens were joined by the LHI method,[24-32] which used an electromagnetic clutch in order to prevent braking deformation during rotation stop. When the clutch was released, the relative speed between both specimens instantly decreased to zero. The detailed characteristics of the LHI method have been described in previous reports.[24-32]

Joint tensile and Vickers hardness tests were carried out in the as-welded condition. The joint tensile test specimen was machined to 10 mm in diameter and 60 mm in length. Vickers hardness distribution at the half-radius location of the welded interface region on the Ti-6Al-4V side was measured with a load of 1 kgf and that of the AA5052 side was measured with a load of 0.5 kgf. The measuring range was 8 mm from the welded interface and the measuring interval was 200 μm. The fractured surface of the welded joint after joint tensile testing was analysed with the X-ray diffraction analysis system.

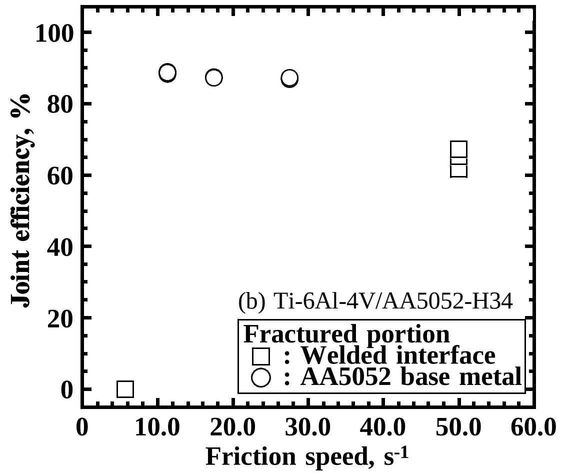
RESULTS

Appearances and axial shortening of welded joint

Figure 2 shows the appearances of welded joints. Those joints were made by the conventional method under the following conditions: friction pressure of 30 MPa, friction time of 3.0 s, forge pressure of 60 MPa and forge time of 6.0 s. When friction speed was 5.7 s^{-1}, Ti-6Al-4V and AA5052 were not joined because sufficient heat quantity could not be produced for welding during a friction time of

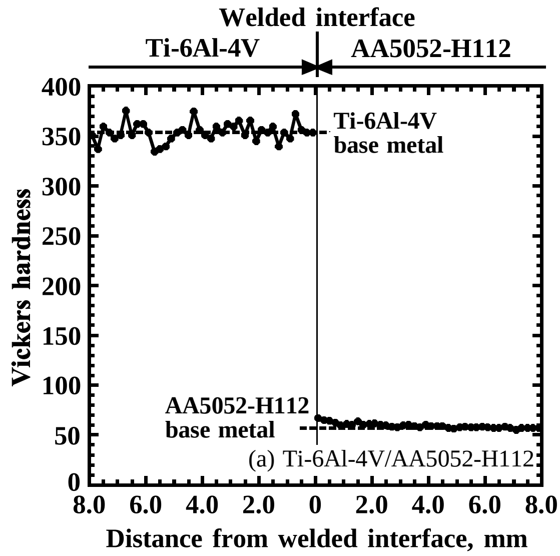


(a) Ti-6Al-4V/AA5052-H112 joint

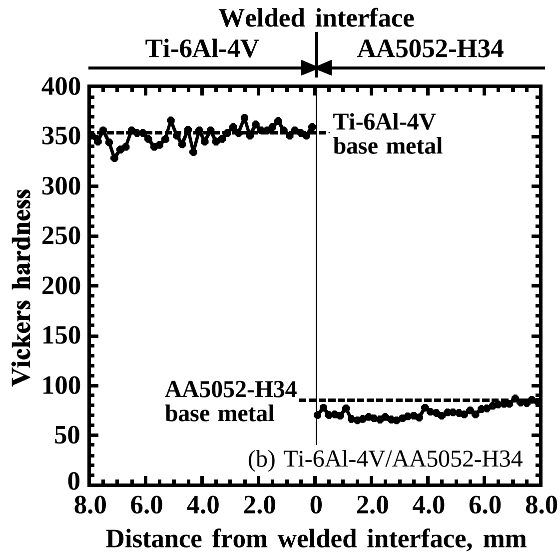


(b) Ti-6Al-4V/AA5052-H34 joint

3 Relationship between friction speed and joint efficiency of welded joint: friction pressure of 30 MPa, friction time of 3.0 s, forge pressure of 60 MPa and forge time of 6.0 s



(a) Ti-6Al-4V/AA5052-H112 joint



(b) Ti-6Al-4V/AA5052-H34 joint

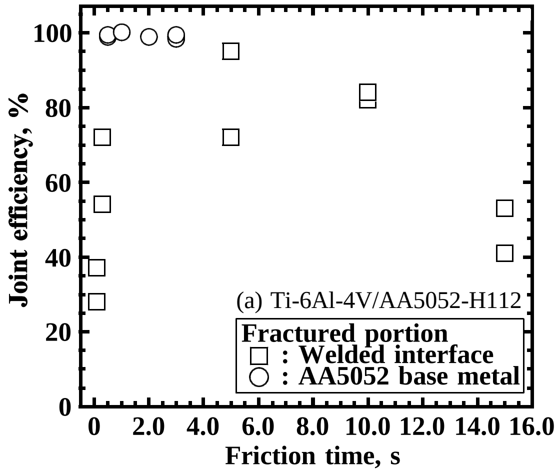
4 Vickers hardness distribution across welded interface: friction speed of 27.5 s^{-1}, friction pressure of 30 MPa, friction time of 3.0 s, forge pressure of 60 MPa and forge time of 6.0 s

3.0 s. The symmetrical flash (burr or collar) of AA5052 was uniformly formed around the whole welded interface when friction speed was 11.3 s^{-1} or over. The flash increased with increasing friction speed, while Ti-6Al-4V side was not deformed. The flash height in the radius direction of the Ti-6Al-4V/H34 joint (Fig.2(b)) was larger than that of the Ti-6Al-4V/H112 joint (Fig.2(a)). In addition, the axial shortening increased with increasing friction speed. The axial shortening of the Ti-6Al-4V/H112 joint was shorter than that of the Ti-6Al-4V/H34 joint.

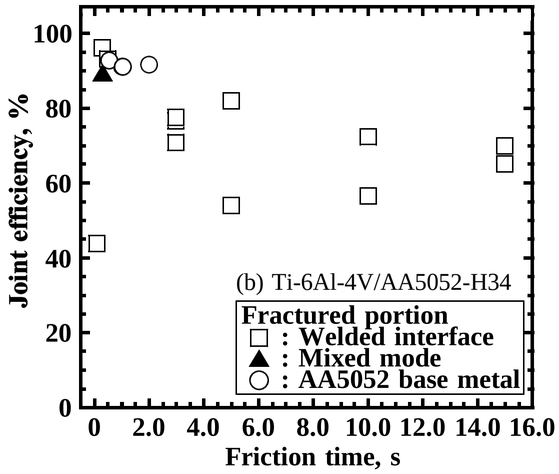
Relationship between friction speed and joint efficiency of welded joint

Figure 3 shows the relationship between the friction speed and joint efficiency of the welded joint by the conventional method: friction pressure of 30 MPa, friction time of 3.0 s, forge pressure of 60 MPa and forge time of 6.0 s. The joint efficiency was based on the ratio of joint tensile strength to the ultimate tensile strength of each of the AA5052 base metals. The joint efficiency of the Ti-6Al-4V/H112 joint was approximately 100% when friction speed was 11.3, 17.5 and 27.5 s^{-1} (Fig.3(a)). At a friction speed of 50.0 s^{-1}, the joint efficiency decreased and the joint fractured at the welded interface and H112 base metal (mixed mode fracture) or the welded interface. On the other hand, the joint efficiency of the Ti-6Al-4V/H34 joint was approximately 90% when friction speed was from 11.3 to 27.5 s^{-1} (Fig.3(b)). In this case, all joint tensile specimens fractured at the H34 base metal. The joint efficiency decreased and the joint fractured at the welded interface when friction speed was 50.0 s^{-1}. The joint efficiency and the fracture mode of the Ti-6Al-4V/H34 joint differed from the Ti-6Al-4V/H112 joint made under the same friction welding conditions.

Figure 4 shows the Vickers hardness distribution across the welded interface at a friction speed of 27.5 s^{-1}. The Ti-6Al-4V/H112 joint had not softened (Fig.4(a)). However, the Ti-6Al-4V/H34 joint softened at about 7 mm from the welded interface in the longitudinal direction on the H34 side (Fig.4(b)). The softened region of this joint was approximately 76% of the hardness of the base metal. The joint made by another friction speed also softened. This result occurred because the H34 base metal has a tendency to soften more than the H112 base metal.



(a) Ti-6Al-4V/AA5052-H112 joint



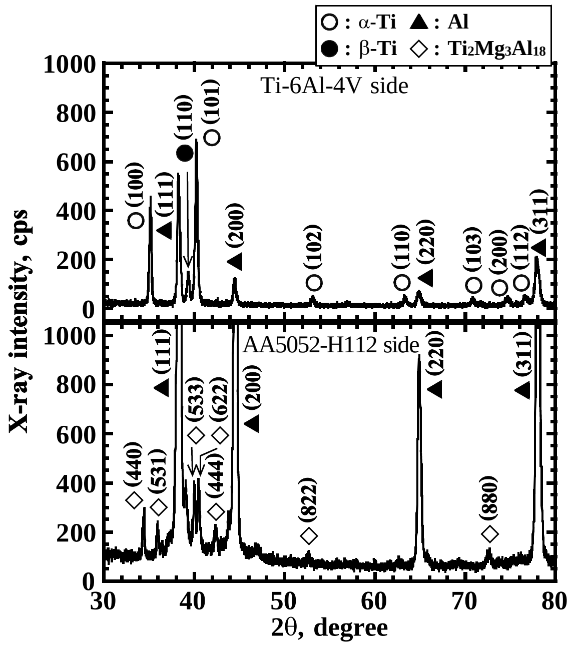
(b) Ti-6Al-4V/AA5052-H34 joint

5 Relationship between friction time and joint efficiency of welded joints: friction speed of 27.5 s^{-1}, friction pressure of 30 MPa, forge pressure of 60 MPa and forge time of 6.0 s

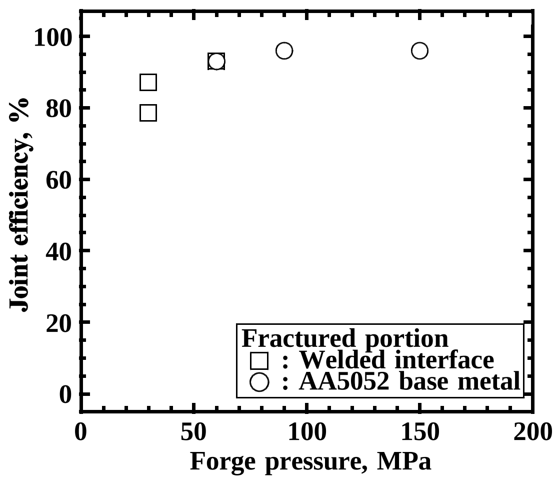
Relationship between friction time and joint efficiency of welded joint

Figure 5 shows the relationship between friction time and joint efficiency by the LHI method: friction speed of 27.5 s^{-1}, friction pressure of 30 MPa, forge pressure of 60 MPa and forge time of 6.0 s. When friction time was 0.1 and 0.3 s, both joints did not achieve 100% joint efficiency and the fracture occurred at the welded interface. Those joints did not produce a sufficient heat quantity for welding. When friction time was from 0.5 to 3.0 s, the Ti-6Al-4V/H112 joint had 100% joint efficiency and the fracture occurred at the H112 base metal. On the other hand, the Ti-6Al-4V/H34 joint made at the same friction time had approximately 95% joint efficiency and the fracture occurred at the H34 base metal. The joint efficiency of the Ti-6Al-4V/H112 joint decreased with increasing friction time, that is, 5.0 s or longer. That of the Ti-6Al-4V/H34 joint decreased with increasing friction time at 3.0 s or longer. Those of the joints made at long friction time were fractured at the welded interface. This fracture was due to the occurrence of an intermetallic compound layer the reason for which is described later.

Figure 6 shows the results of the X-ray diffraction analysis of the fractured surface of the Ti-6Al-4V/H112 joint at a friction time of 5.0 s. Al and $Ti_2Mg_3A_{18}$ peaks were observed on the fractured surface on the H112 side.



6 X-ray diffraction analysis of fractured surface of Ti-6Al-4V/AA5052-H112 joint: friction speed of 27.5 s^{-1}, friction pressure of 30 MPa, friction time of 5.0 s, forge pressure of 60 MPa and forge time of 6.0 s



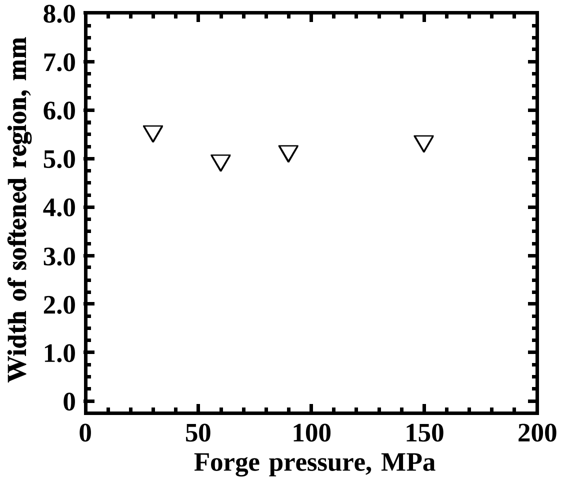
7 Relationship between forge pressure and joint efficiency of Ti-6Al-4V/AA5052-H34 joint: friction speed of 27.5 s^{-1}, friction pressure of 30 MPa, friction time of 0.5 s and forge time of 6.0 s

$Ti_2Mg_3A_{18}$ peaks were also observed on the fractured surface on the H34 side of the Ti-6Al-4V/H34 joint when friction time was 3.0 s or longer. However, the peak was not observed on the fractured surface when friction time was 0.1 and 0.3 s. $Ti_2Mg_3A_{18}$ peaks were also observed on the fractured surface of the dissimilar joint of pure-Ti to AA5083 or AA7075-T6 aluminium alloys at long friction time.[18-20] Thus, the fracture occurred at the interface between Ti-6Al-4V and AA5052.

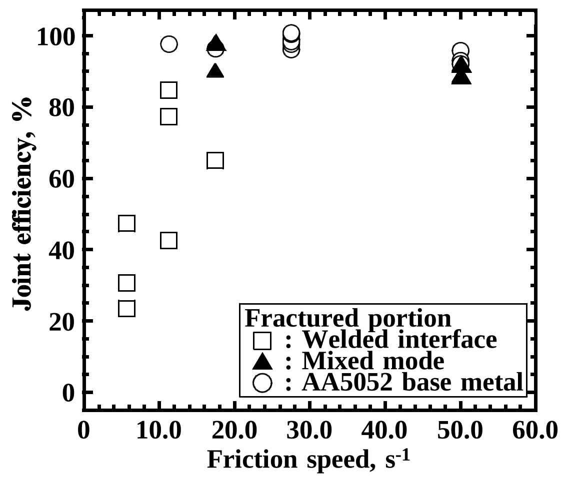
DISCUSSION

Relationship between forge pressure and joint efficiency of Ti-6Al-4V/AA5052-H34 joint

To reduce the softened region at the H34 base metal, the effect of forge pressure on joint properties was investigated.



8 Relationship between forge pressure and width of softend region from welded interface on AA5052-H34 side of Ti-6Al-4V/AA5052-H34 joint: friction pressure of 150 MPa, friction time of 0.5 s, forge pressure of 275 MPa and forge time of 6.0 s



9 Relationship between friction speed and joint efficiency of Ti-6Al-4V/AA5052-H34 joint: friction pressure of 150 MPa, friction time of 0.5 s, forge pressure of 275 MPa and forge time of 6.0 s

Figure 7 shows the relationship between forge pressure and joint efficiency for the Ti-6Al-4V/H34 joint by the LHI method: friction speed of 27.5 s^{-1}, friction pressure of 30MPa and friction time of 0.5 s. The joint efficiency increased with increasing forge pressure, but it did not achieve 100% joint efficiency. A fracture occurred at the H34 base metal when forge pressure was 90 and 150 MPa (approximately 95% joint efficiency). Figure 8 shows the relationship between forge pressure and the width of softened region from the welded interface in the longitudinal direction on the H34 side. The width of the softened region was similar for all joints, regardless of forge pressure. However, the axial shortening of those joints increased with increasing forge pressure. According to those results, it was considered that the H34 base metal was softened after the friction stage, i.e., during the forging stage, by the friction heat that was stored in the Ti-6Al-4V side.

Improving joint efficiency of Ti-6Al-4V/AA5052-H34 joint

To improve the joint tensile strength of the Ti-6Al-4V/H34 joint, a joint was made by the conventional method with higher forge pressure. Friction welding conditions were as follows: friction pressure of 150 MPa, friction time of 0.5 s, forge pressure of 275 MPa and forge time of 6.0 s. Figure 9 shows the relationship between friction speed and joint efficiency. The joint efficiency increased with increasing friction speed. The joint had 100% joint efficiency and fractured at the H34 base metal when friction speed was 27.5 s^{-1}. However, the joint efficiency decreased at 50.0 s^{-1} and the joint fractured at the H34 base metal or the welded interface (mixed mode fracture). The adjacent region to the welded interface on the H34 side slightly softened. However, this joint had 100% joint efficiency and fractured at the H34 base metal. The softened region of this joint was approximately 87% of the hardness of the base metal. As a result, Ti-6Al-4V/AA5052 friction welded joint with sufficient mechanical properties was able to be made with scarce intermetallic compound layer at the interface and little softening of the AA5052 base metal by selecting suitable parameters in friction welding condition. That is, the joint made with high friction pressure, short friction time and high forge pressure has good mechanical and metallurgical properties.

CONCLUSIONS

This paper described the mechanical properties of a Ti-6Al-4V titanium alloy and Al-Mg aluminium alloy (AA5052) friction welded joint. The following conclusions are presented.

1. The symmetrical flash of AA5052 was uniformly formed around the whole welded interface on the Ti-6Al-4V side. The axial shortening of the Ti-6Al-4V/AA5052-H112 joint was shorter than that of the Ti-6Al-4V/AA5052-H34 joint even under the same friction welding condition.
2. The Ti-6Al-4V/AA5052-H112 joint had 100% joint efficiency at friction speeds from 11.3 to 27.5 s^{-1}, friction pressure of 30 MPa, friction time of 3.0 s and forge pressure of 60 MPa.
3. The welded interface of both joints had an intermetallic compound layer ($Ti_2Mg_3Al_{18}$) when friction time was longer. In addition, those joints were fractured at the welded interface.
4. It was considered that the H34 base metal was softened after the friction stage, i.e., during the forging stage, by the friction heat that was stored in the Ti-6Al-4V side.
5. Although the AA5052-H34 side slightly softened, the joint had 100% joint efficiency and the fracture occurred at the AA5052-H34 base metal. This joint was made at a friction speed of 27.5 s^{-1}, friction pressure of 150 MPa, friction time of 0.5 s and forge pressure of 275 MPa.
6. The joint made with high friction pressure, short friction time and high forge pressure has good mechanical and metallurgical properties.

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