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Evaluation of Tensile Strength of Friction-Welded Joints of Aluminium to Copper

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Abstract

The relationship between tensile strength and heat input or burn-off length was examined on the friction welding of industrial pure aluminium to copper. It was found that a stable tensile strength was obtained when the unit deformation heat input in the upset stage or the upset burn-off length exceeded a certain value. However, the fracture mode in tensile testing could not be evaluated because of the intermetallic formation of Al-Cu at the weld interface. A satisfactory evaluation for tensile strength and fracture mode could be obtained by introducing a simple heat input formula.

1. Introduction

Friction welding is used in many fields. However, a non-destructive evaluation method has not been established yet, and there are still unresolved issues in this method; e. g. setting the appropriate welding conditions is difficult for some materials, the optimum welding conditions vary between friction welding machines, and so on. Recently, in order to establish the non-destructive evaluation method, the authors began research to examine the relationship between joint strength and heat input or burn-off length. Previously, the authors revealed that in friction-welded similar joints of 5056 [1] and 6061 aluminium alloys [2], and SUS304 stainless steel [3], joint strength could be evaluated by the unit deformation heat input in the upset stage or the upset burn-off length. In the present study, the authors examined whether the same evaluation method, using heat input and burn-off length, could apply to the dissimilar joint of industrial pure aluminium to copper. The joint of this combination is widely used in electrical wiring parts and the demand for this joint is increasing in many industrial fields.

2. Experimental Procedures

The materials used in the present study are 1050 industrial pure aluminium (A1050-JIS) with 109 MPa tensile strength and tough pitch copper (C1100-JIS) with 361 MPa tensile strength. A 16 mm diameter round bar of each metal was cut to 100 mm in length, and a 20 mm length of bar on the welding end was machined down to 14 mm in diameter. Friction welding was conducted using a brake-type friction welding machine. The friction welding factors used are shown in Table 1. The joint strength of friction-welded joints was evaluated by tensile testing using the test specimen without a burr.

Table 1: Friction-welding factors.

Factor	Time control	Burn-off control
Friction pressure P_1, MPa	5-20	5-20
Upset pressure P_2, MPa	15-140	15-140
Friction time t_1, s	1, 2, 4	-
Friction burn-off length δ_1, mm	-	1, 2
Friction speed N, s^{-1}	50.0	50.0
Stopping time t_B, s	0.1	0.1

The mechanical work (heat input) done during friction welding consists of friction heat input (by friction) [4] and deformation heat input (by deformation of the weld material) [1]-[3]. The friction heat input involves the heating of the friction surface, wile the deformation heat input aids in joining the welding surface and causes the junction to expand. The unit friction heat input per unit time q_f (J/s) is shown in Eq. (1), where the friction speed is N (s^{-1}), and the friction torque is T (Nm) [4].

$$q_f = 2\pi NT \qquad (1)$$

The unit deformation heat input per unit time q_d (J/s) is shown in Eq. (2), where the thrust is F (N), and burn-off speed is v_δ (m/s).

$$q_d = Fv_\delta \qquad (2)$$

Therefore, unit total heat input unit per time q_t (J/s) is shown in Eq. (3).

$$q_t = 2\pi NT + Fv_\delta \qquad (3)$$

The brake-type friction welding process consists of friction stage (initial stage) and upset stage (final stage). Unit friction heat input in the friction stage, upset stage and total stage showed q_{if}, q_{ff} and q_{tf}, respectively, unit deformation heat input in these stages showed q_{id}, q_{fd} and q_{td}, respectively, and unit total heat input in these stages showed q_i, q_f and q_t, respectively. In the present study, the relationship between tensile strength and each heat input was examined.

3. Results and Discussion

3.1 Evaluation of Tensile Strength by Heat Input.

The relationships between tensile strength and unit friction heat input in the friction stage, upset stage and total stage is shown in Figure 1. Solid circles in this figure represent joints fractured at the weld interface, and open circles represent joints fractured in the A1050 side. The data disperses and there is no the clear relation for tensile strength and unit friction heat input. The unit friction heat input in the total stage shows the similar distribution to that in the friction stage. This is because in the upset stage in deceleration area of the friction speed, the absolute value of the friction heat input is much small.

The relationships between tensile strength and unit deformation heat input in the friction stage, upset stage and total stage is shown in Figure 2. In the friction stage, although tensile strength tends to increase with a deformation heat input, the data disperses. In the upset stage, it is possible to obtain a stable tensile strength when the deformation heat input exceeds a certain value. The unit deformation heat input in the total stage shows the same distributions as that in the upset stage. This is because the absolute value of deformation heat input in the upset stage is much larger than that in the friction stage. It appears that the deformation heat input in the total stage could not evaluate joint strength purely.

The relationships between tensile strength and the unit total heat input in the friction stage, upset stage and total stage is shown in Figure 3. In the friction stage, the same distribution as Figure 1(a) is obtained.

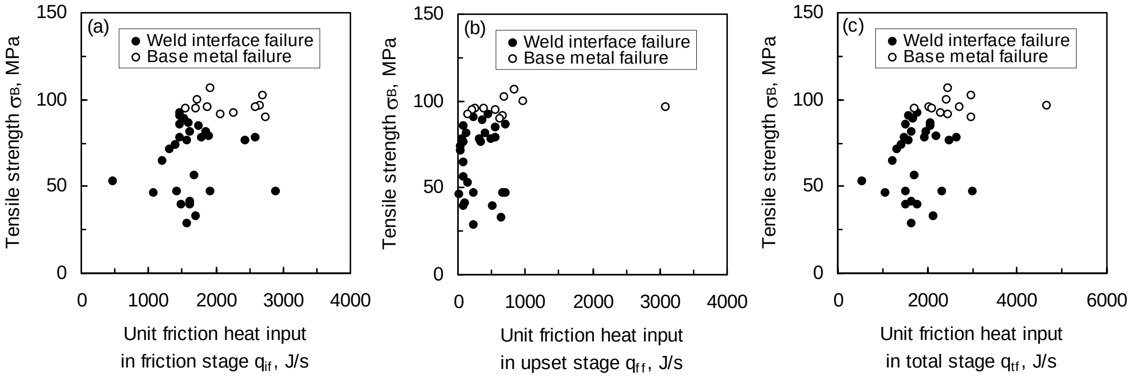

Figure 1: Relationships between tensile strength and unit friction heat input in the friction stage (a), upset stage (b) and total stage (c).

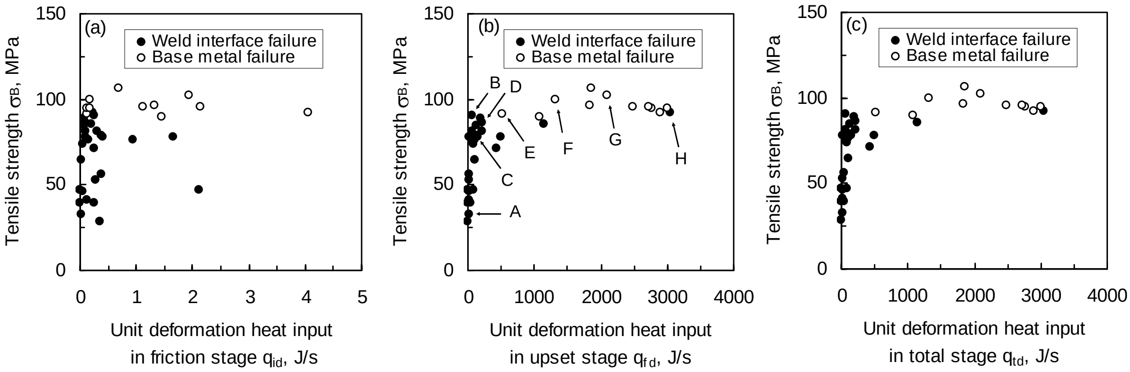

Figure 2: Relationship between tensile strength and unit deformation heat input in the friction stage (a), upset stage (b) and total stage (c).

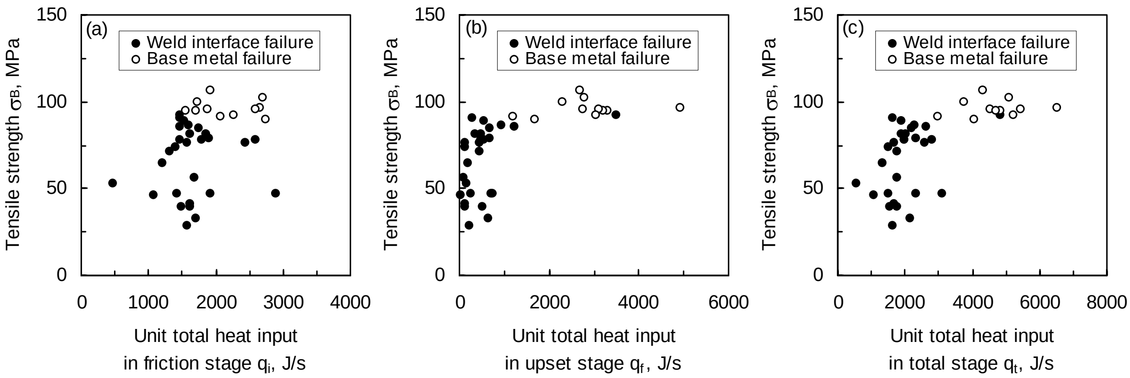

Figure 3: Relationship between tensile strength and the unit total heat input in the friction stage (a), upset stage (b) and total stage (c).

In the upset stage, the similar distribution to Figure 2(b) is obtained, though there is the dispersion in the region where the total heat input is low. This is because in the friction stage, the friction heat input is dominant further than the deformation heat input, while in the upset stage, the deformation heat input is dominant further than the friction heat input. In the total stage, although it is possible to obtain a stable tensile strength when the total heat input exceeds a certain value, the data disperses largely.

As mentioned above, the relationship between tensile strength and each heat input was examined. The result showed that the unit deformation heat input in the upset stage and the total stage, and the unit total hest input in the upset stage and the total stage could evaluate tensile strength. However, the unit deformation heat input in the upset stage seems to be suitable for the evaluation of the tensile strength because of little dispersion of the data and the easiness of the measurement.

3.2 Evaluation of Tensile Strength by Burn-Off Length.

It would be convenient in the welding field if joint strength could be evaluated in terms of burn-off length. The relationships between tensile strength and friction burn-off length, upset burn-off length and total loss is shown in Figure 4. It is possible to obtain a stable tensile strength when the upset burn-off length or the total loss exceeds a certain value, though the data disperses in case of the total loss. In the friction welding of similar metals, the authors revealed that the unit deformation heat input in the upset stage correlated with the upset burn-off length, and joint strength could also be evaluated by the upset burn-off length [1]-[3]. In the present study, the unit deformation heat input in the upset stage correlated with the upset burn-off length, too, as seen as Figure 5.

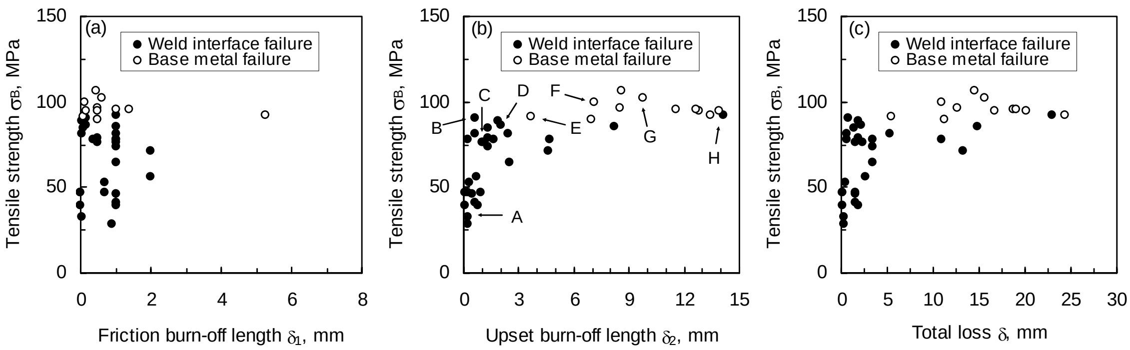

Figure 4: Relationship between tensile strength and friction burn-off length(a), upset burn-off length (b) and total loss (c).

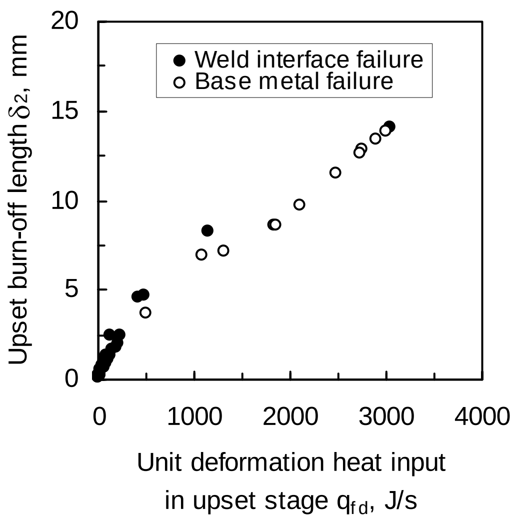

Figure 5: Relationship between unit deformation heat input in the upset stage and upset burn-off length.

3.3 Effect of Intermetallic Formation at the Weld Interface.

Although the tensile strength of joints could be evaluate, it was not possible to classify joints into the base metal failure and the weld interface failure in tensile testing by the unit heat input or burn-off length. So the weld interface layer of joints was observed. Appearance of typical joints A-H, represented in Figure 2(b) and Figure 4(b), is shown in Figure 6. The friction welding conditions and the unit deformation heat input in the upset stage of these joints is shown in Table 2. A burr was largely exhausted when the unit deformation heat input in the upset stage was raised. Macrostructure of joints A-H is shown in Figure 7. A layer seen darkly formed A1050 side at the weld interface in all joints.

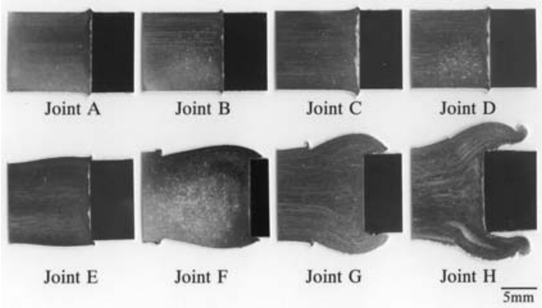

Figure 6: Appearance of the weld interface

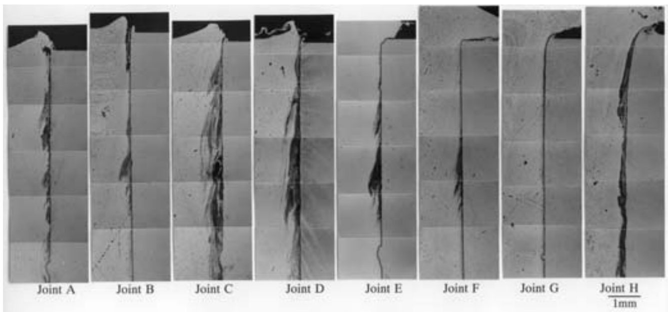

Figure 7: Macrostructure of the weld interface.

Table 2: Friction welding condition and unit deformation heat input of joints.

Joint	Friction pressure P_1 ,MPa	Upset pressure P_2 ,MPa	Friction time t_1 ,s	Friction burn-off length δ_1, mm	Unit deformation heat input q_{fd} ,J/s
A	10	30	2	-	12
B	10	60	1	-	59
C	10	60	2	-	120
D	7.5	67.5	2	-	212
E	10	90	1	-	510
F	10	120	1	-	1312
G	20	140	1	-	2106
H	10	140	(6.4)	1	3045

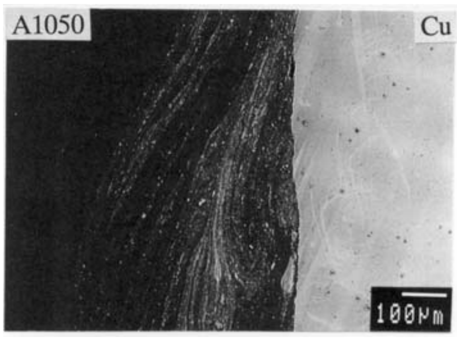

Figure 8: SEM image of the interface layer.

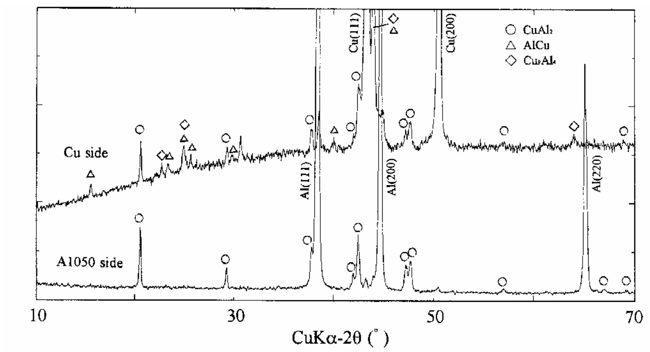

Figure 9: X-ray diffraction pattern of the fracture surface.

SEM image at the welded interface and X-ray diffraction pattern of the fracture surface of joint D are shown in Figs.8 and 9, respectively. It is clear that intermetallic compounds of $CuAl_2$, AlCu and Cu_9Al_4 formed at the weld interface, and the dark layer in Figure 7 is the mixing layer interpolated copper and these intermetallic compounds into A1050. As seen in Figure 7, joints A-D fractured at the weld interface have thick mixing layer. In joints E-G fractured in A1050 side, the mixing layer decreases with an increase in upset pressure and unit deformation heat input in the upset stage. It appears that the mixing layer was exhausted with burr under action of upset pressure.

However, joint H have thick mixing layer and fractured at the weld interface in spite of high upset pressure and large unit deformation heat input in the upset stage. This is because the intermetallic formation in the friction stage was too much to exhaust it satisfactorily due to the long friction time 6.4 s. It appears that the friction heat input in the friction stage is concerned in this intermetallic formation.

These facts show that in order to evaluate both tensile strength and fracture mode, it is necessary to introduce new heat input formula which the friction heat input in the friction stage is added to the unit deformation heat input in the upset stage. A heat input ratio Q_r (s^{-1}) was calculated by Eq. (4), where total friction heat input in the friction stage (the integrated value of the friction heat input in the friction stage) is Q_{if} (J).

$$Q_r = q_{fd} / Q_{if} \tag{4}$$

The relationship between tensile strength and heat input ratio is shown in Figure 10. Sound joints having a stable tensile strength and fractured in A1050 side could be obtained when the heat input ratio exceeds a certain value. That is, it is possible to classify joints into sound and defect by this heat input ratio.

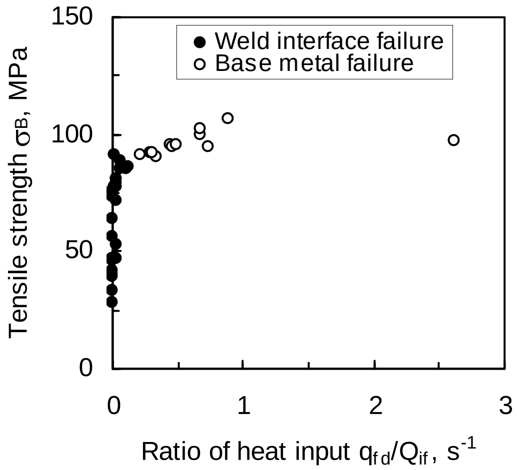

Figure 10: Relationship between tensile strength and the heat input ratio.

4. Conclusions

Industrial pure aluminium to copper was friction welded, and tensile strength of these joints was evaluated by heat input and burn-off length. The results are as follows:

(1) The unit deformation heat input in the upset stage or the upset burn-off length correlated well with tensile strength, and a stable tensile strength was obtained when the unit deformation heat input in the upset stage or the upset burn-off length exceeded a certain value.
(2) However, it was not possible to classify joints into the base metal failure and the weld interface failure in tensile testing by the unit heat input or burn-off length because the thick mixing layer interpolated copper and intermetallic compounds of Al-Cu into aluminium formed at the weld interface in joints with long friction time.
(3) The heat input formula, which the friction heat input in the friction stage is added to the unit deformation heat input in the upset stage, is useful to evaluate both tensile strength and fracture mode.

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