Effect of welding parameters on mechanical properties of friction stir welded T-lap dissimilar metal joints between 7075 and 5083 aluminum alloys

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Abstract
Dissimilar T-lap joint between aluminum alloy 7075-T651 and 5083-H116 was fabricated by friction stir welding. Special focus was paid to the defect formation and mechanical properties which were significantly affected by the welding parameters. The results showed that four typical types of defects were detected in the T-lap joint; tunnel, kissing bond, hook, and bonding line defects. The tunnel and bonding line defects could be avoidable by decreasing the welding rate. At low welding rate, however, the hook defect was formed and reduced the skin effective thickness. The kissing bond defect was too hard to be eliminated by using one welding pass only by changing the welding parameters. Among these defects, the hook defect played the important role in the mechanical properties of T-lap joint. It is a special finding that there was the optimum welding rate by which the maximum joint efficiency was attained. These findings were summarized into the table and map which can optimize the joint properties.

Keywords : Dissimilar friction stir welding, T-lap joint, Welding parameters, Aluminum alloys, Defect formation, Mechanical properties

1. Introduction
Non-heat treatable aluminum alloy 5083 (denoted as AA5083) possesses an excellent corrosion resistance (Davis, 2001) while heat treatable aluminum alloy 7075 (denoted as AA7075) possesses a high strength and light density (Davis, 2001; Dursun and Soutis, 2014; Zhang et al., 2018). A combination of the two alloys must be useful to develop structural components with multiple functions; e.g. high durability and good corrosion resistance. The T-joints of aluminum alloy have been frequently used for many frames and structural panels of shipbuilding, aerospace, transportation, etc. To reduce the weight of the structure and save material, they are often manufactured with variations in both the thickness plates and material properties. However, the weldability of them has not been well achieved by riveting and traditional welding methods such as Metal Inert Gas (MIG) and laser welding (Manes et al., 2011; Costa et al., 2014; Oliveira et al., 2015). For instance, the riveting not only increases the weight of structure but also the source of stress concentration. Meanwhile, the limitation of conventional fusion welding is induced by solidification shrinkage, high residual stress, significant distortions, porosity defects, and the coarsening of microstructure in weld joints (Dursun and Soutis, 2014; Costa et al., 2014; Meng et al., 2014). In particular, AA7xxx is one of the representative aluminum alloys that the fusion welding technique is rarely applied due to solidification cracking during the welding process (Lu et al., 1996; Kim and Nam, 1996). These factors might lead to the bigger challenge of joining dissimilar AA5083 and AA7075. Friction Stir Welding (FSW) has been developing as a strategic technology to solve
these difficulties (Thomas et al., 1991; Tokisue et al., 2005; Sato et al., 2005). As evidence, some previous studies have
successfully fabricated the FSWs of dissimilar AA5083 and AA7075 (Ahmed et al., 2017; Kalemba-Rec et al., 2017).
However, these works have only focused on butt-joints, which are considered to be easier to employ with the FSW
technique than lap-joints and T-joints (Mishra et al., 2005; Tokisue et al., 2005).

The weldability of FSW T-joint has been discussed in the literatures with respect to three methods (Tokisue et al.,
2005; Martin et al., 2011; Cui et al., 2012; Hou et al., 2014; Zhao et al., 2014; Jesus et al., 2018; Suna et al., 2019).
These researches covered T-lap joint, T-butt joint, and stationary shoulder. The results reported that the T-lap joint was
more useful for the strength of skin than stringer. In contrast, the pulling along stringer was improved due to using
T-butt joint but it is harmful to skin plates. Reason for these results was attributed to the formation of tunnel, oxide line,
and kissing bond defects those were affected by the asymmetric material flows during the FSW process (Cui et al.,
2012; Hou et al., 2014; Zhao et al., 2014; Jesus et al., 2018). Use of two passes with stationary shoulder to insert the
tool pin into two corner fillets of the T-joint seems to be effective to eliminate the kissing bond defect (Martin et al.,
2011; Suna et al., 2019). However, this method is difficult to be widely applied for T-joint, especially with the thin skin
and thick stringer plates.

The similar FSW T-joint have been performed from different aspects; they are exploring the influences of the
welding parameters, welding tools on defect formation, mechanical properties, and residual stress distribution (Cui et
al., 2012, 2013; Hou et al., 2014; Zhao et al., 2014; Jesus et al., 2018; Suna et al., 2019). However, the dissimilar metal
FSW T-joint which have difference in both material properties and significant thickness has been still a limitation,
especially when the thickness of stringer is much larger compared to skin plates. These variations would lead to
difficulty in fabricating successful T-lap joint. Moreover, the role of some defects in the failure behavior in both the
global and local strengths of T-joint has not been well understood.

The primary aim of this work is to try to fabricate the dissimilar FSW T-lap joint between AA5083 and AA7075.
As is case in literatures by other researchers, some types of undesirable defects were formed as well as in this work.
Those were tunnel, hook, kissing bond, and bonding line defects. In this work, hence, special focus was put on how to
minimize or eliminate the formation of these defects by controlling the welding conditions, and how to enhance the
mechanical properties of dissimilar T-lap joint.

2. Experimental procedures

The materials used in this work were two aluminum alloys: one is AA7075-T651 for the stringer and the other is
AA5083-H116 for the skin plate with the dimensions of 300×100×8.2 mm and 300×150×3.0 mm, respectively. The
chemical compositions of them are shown in Table 1. The ultimate tensile strengths of base metal AA5083-H116 and
AA7075-T651 were nearly 320 and 570 MPa, respectively. The T-lap mode was applied to fabricate T-joint (Fig. 1a).
The contact surface of two plates was polished by abrasive SiC paper to limit the influence of oxide layers. Welding
conditions and tool geometry employed in this study is summarized in Table 2. The welding rate is the ratio of the tool
welding speed (v) to the tool rotational speed (ω). Here the welding speed was in range from 50 mm/min to 200
mm/min and the rotational speed was kept constant at 400 rpm. A simple conical pin with 28.0 mm of the tool shoulder
diameter was used. The pin geometry was non-thread body with 3.0 mm in length of which diameter is tapered from
11.0 mm at the root to 8.0 mm at the top (Fig. 1b). The pin axis alignment was kept at a constant with the tilt angle of
2.0° and the tool shoulder penetrated into the surface of skin plate was 0.2 mm in the depth during the welding process.

Optical microscope and a scanning electron microscope (SEM) were used to observe the shapes of defects and the
microstructures of the joint that was cut perpendicular to welding direction. Then, all of samples were ground and
polished by water abrasive SiC paper and alumina, respectively to achieve mirror surfaces, and finally etched with
Kroll’s reagent (2%HF, 6%HNO₃(30%), 92% water) for 10s.

The hardness profiles for both skin and stringer plates were measured along the centerline of the cross section by the
means of a micro Vickers indenter under 0.2 kgf load for 10 s. To evaluate the local bonding strength along the
interface, some small specimens were extracted from the different locations of original sample. Specimen geometry and
loading process are shown in Fig. 2a and Fig. 2b, respectively with the support of a jig made of steel material. Two
types of tests were carried out to evaluate the mechanical properties of T-lap joint. One is the tensile test along the skin
part (see Fig. 3a, denoted by “skin test”) and the other is along the stringer part (see Fig. 3b, denoted by “stringer test”).
Here the tensile specimens were prepared via ASTM E08 standards (ASTM E08, 2004) where a part of stringer is still
remaining by 8.0 mm of length in the specimen of skin (Fig. 3a). These tests were performed under a rate of 1.0
mm/min at room temperature.

| Compositions   | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Al  |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| AA5083-H116   | 0.4 | 0.4 | 0.1 | 0.4-1.0 | 4.0-4.9 | 0.05-0.25 | 0.25 | 0.15 | Bal. |
| AA7075-T651   | 0.5 | 0.7 | 1.2-2.0 | 0.3 | 2.1-2.9 | 0.18-0.40 | 6.1 | 0.2  | Bal. |

Table 2  Welding conditions and tool geometry.

| Welding rates (mm/rev) | Tool geometry (mm) |
|------------------------|--------------------|
|                        | Ø Shoulder | Ø Root pin | Ø Top pin | Pin length |
| 0.13                   | 28.0        | 11.0       | 8.0        | 3.0        |
| 0.19                   |             |            |            |            |
| 0.25                   |             |            |            |            |
| 0.38                   |             |            |            |            |
| 0.50                   |             |            |            |            |

3. Results and Discussion

3.1 Defects formed in T-lap joint

Figure 4 displays the representative macrostructures on the cross-section of current specimens under the welding rates of 0.13 and 0.50 mm/rev. Four typical types of defects were found, depending on the welding conditions: tunnel, kissing bond, hook, and bonding line defects. The change in the microstructure of the T-lap joint, that was significantly affected by welding rate, is also presented in Fig. 5. Hereinafter, the characteristics and mechanisms of these defect formations are given.
3.1.1 Tunnel defect

Figure 6a shows a representative tunnel defect, which was viewed as a cavity or wormhole. This defect was originated by non-filling during the welding process. This type of defect was pronounced in the advancing side (AS), and located at the transition zone between thermo-mechanically affected zone (TMAZ) and stir zone (SZ). It is worthy to note from Figs. 5a-c that the tunnel defects were absent at the low welding rate (from 0.13 to 0.25 mm/rev) but appeared at the higher welding rate of 0.38 and 0.50 mm/rev (Figs. 5d,e). This result might be related to the low flow of plasticized metal that was affected by heat input during the FSW process (Cheng et al., 2006; Zhao et al., 2014; Khan et al., 2017; Jesus et al., 2018).

3.1.2 Hook defect

The hook defect that was observed along the joint line uplifted seems to be a feature in the FSW lap-joint. It predominantly initiated in the retreating side (RS) and had tendency towards the weld center of joint (Fig. 6b). It is worth noting that a small dark line was formed around the hook defect as oxide film (as shown in Fig. 6c). Figures 5a,b
show that the hook defect was produced under the low welding rate of 0.13 and 0.19 mm/rev, respectively. This type of defect in FSW T-lap joint was minimized by advancing the welding rate. A good weld without the tunnel and hook defects was found at 0.25 mm/rev (Fig. 5c).

The formation mechanism of the hook defect can be understood by metal flow induced by stirring as follows. As indicated in Fig. 7, the noteworthy conjunction of two metal flows was found: one is shoulder-driven material and the other is pin-driven material. This morphology was also detected by Liu et al. (2018) and Meng et al. (2018). Herein, the shoulder-driven material flow was induced by the rotation of tool shoulder to fill in trench that was arisen by the forward movement of tool pin. As an undesirable result, the original interface at the RS was deeply lugged into the welding center. Moreover, the formation of this type of defect was drastically supported by the pin-driven material flow. It means that the initial interface was significantly pushed upward due to the vertical material flow which was enhanced at the low welding rate with growing heat input. Consequently, the hook defect remarkably increased both the height and length.

3.1.3 Kissing bond defect

The kissing bond defect was formed at two corner fillets at both the RS and AS sides under all the welding rates. It is a typical type of defect with little or no metallic bonding. This defect often occurs outside the stirred zone where the materials are in close touch although they have not formed a chemical or mechanical bond. Figure 5 displays the geometries of the kissing bond at the various welding conditions, which was no symmetry under all welding conditions. It is worthy to note from this figure that the bonding angle, $\theta$, between 7075/5083 alloys and the lengths of bonding line at the RS and AS were significantly changed by the welding rate (Fig. 5(a-1) through Fig. 5(e-1) and Fig. 5(a-2) through Fig. 5(e-2), respectively). These features may be driven by the asymmetric material flows during the FSW process. A large dark line was detected along the kissing bond defect.

Figure 8 covers the analytical result around the dark line due to analyzing Energy Dispersive X-Ray Spectroscopy (EDS), which clearly shows a large amount of oxygen concentrated along the kissing bond at both the RS and AS sides. This result means that oxide layer has hardly been extruded in this work, as case by some researchers (Oosterkamp et al., 2004; Sato et al., 2005; Kadlec et al., 2015; Khan et al., 2017). The lack of stirred action during the welding process might be reason for forming this defect. Actually, the positions at corner fillets beyond tool pin (see Fig. 7) did not get stirring action, resulting in the kissing bond defect formation.

Fig. 7  The hook and kissing bond defects formation in T-lap joint at 0.13 mm/rev.

Fig. 8 Distribution of oxygen along kissing bond measuring at (a) RS and (b) AS (as marked in Figs. 5(e-1,2), respectively).
3.1.4 Bonding line defect

Differently from the kissing bond, the bonding line defect was formed along the bonding interface in the stir zone (Fig. 4), where experienced severely plastic deformation during the welding process. The stir efficiency of pin might be reason for this defect formation. Compared to the kissing bond (Figs. 9a,e), the oxide film around the bonding line defect (Figs. 9b-d) seems to be discontinuous and thinner (compare between Fig. 8 and Fig. 10). Furthermore, the formation of oxide film along bonding interface was heterogeneous and seems to be more dominant at the AS. This might affect the erratic distribution of the local bonding strength along interface, as will be documented in the next section.

The background of the formation of the bonding line defect might be closely related to heat input between the two joining materials, induced by stirring action of welding tool (Tokisue et al., 2005). This may be significant under such a condition that the horizontal oxide layer in original interface is not easy to be removed from weld joint. As shown in Fig. 11, the bonding line defect appears more common at the high welding rate that generated low heat input. This reason might lead to the low efficiency in breaking the oxide film on the surfaces of interface.

Fig. 9  Image of (b-d) bonding line defect along bonding interface compared to (a,e) kissing bond defect at welding rate of 0.25 mm/rev.

Fig. 10  Analysis of bonding line defect. (a) SEM image and (b) EDS spectrum with inserting oxygen mapping around the bonding line defect.

Fig. 11  Images of (a) a cross-section of T-lap joint and (b-f) bonding line defect produced under various welding rates measured at center bonding interface, as illustrated in Fig. 11a.
3.2 Effect of welding parameter on the formation of four kinds of defects

The findings in the previous sections are summarized in Table 3. In order to understand more quantitatively, the influence of welding rate on the formation of four types of defects in T-lap joint is summarized in Fig. 12. Here the defect sizes were measured on the cross-section of samples by means of optical microscope and SEM. These findings clearly demonstrate that the change in welding rate would lead to various effects on the defect formation (as clearly shown by Fig. 12a). The kissing bond defect, which formed under all welding conditions, was insensitive to welding rate when the stirring pin given in Fig. 1b was always used under the same rotation speed. It is worth noting that the presence of the hook defect significantly decreased the bonding width that affected the strength of T-lap joint (Fig. 12b). Differently from the size of kissing bond defect, the tunnel and bonding line defect sizes were drastically changed by controlling welding rate. To minimize the size of the tunnel and bonding line defects, decreasing the welding rate is effective. On the contrary, increase in the welding rate is useful to reduce hook defect size.

![Table 3](image)

| Type of defects          | Kissing bond defect | Hook defect | Tunnel defect | Bonding line defect |
|--------------------------|--------------------|-------------|---------------|---------------------|
| Predominant locations    | Two corner fillets | Retreating side | Advancing side | Interface in stirred zone |
| Identifications          | Continuous dark line of oxide layer | Joint line uplifting originated from the RS to weld center | Cavity or wormhole | Discontinuous dark line of oxide layer |
| Mechanisms               | Lack of stirred action | Strong material flow according to horizontal and vertical directions | Low heat input | Low heat input |
| Features                 | No metallic bonding | Weak metallic bonding | Decreasing cross-section area | Reducing strength of bonding interface |
| Solutions                | Using reasonable pin geometry and clamping fixture | Increasing the welding rate | Decreasing the welding rate | Decreasing the welding rate |

![Fig. 12](image)  Influence of welding rate on the formation of (a) each type of defect and (b) bonding width in T-lap joint.

3.3 Mechanical properties of T-lap joint

The measurements in the previous sections are more or less qualitative. In order to get more quantitative knowledge, the mechanical properties of T-lap joint are evaluated in this section.

3.3.1 Hardness profiles

The effects of the welding rate on the hardness profile of T-lap joint along skin plate are illustrated in Fig. 13a. The results showed that there is little significant difference in hardness value in various welding conditions. Note the experimental data in Fig. 13 are given in terms of the ratio of welding rate to rotation speed \((v/\omega)\), which is a good measure to represent specific heat input during stirring process. It can be seen that the soft zone with lower hardness was formed around the jointed area. The width of soft zone tended to be narrowed down with increasing the ratio of \(v/\omega\). The longitudinal hardness profile along the stringer is depicted in Fig.13b. The lowest hardness value of 95 HV was found on the AA7075 side at area apart from 10.0 mm the upper surface of the skin plate. The type of heat affected zone (HAZ) was more pronounced with decreasing the welding rate, or specific heat input.
3.3.2 Local bonding strength in T-lap joint

The local bonding strength along interface of T-lap joint by the welding rate of 0.13 mm/rev is evaluated in Fig. 14, where the testing process is demonstrated in Fig. 2. It is clear that the ultimate tensile strength was heterogeneous. The strength at position [E] with the presence of the kissing bond defect was nearly zero. The bonding strength at hook position (as denoted [A]) was higher than that at the kissing bond site. However, it was much lower than the strength of [B]-[C] sites. These results showed that the effect of the kissing bond and hook defects on bonding strength was the most harmful. Furthermore, the local bonding strength at the RS (denoted [C]) was more dominant than that at other sites, which location fracture was detected at the HAZ with lowest value hardness, as shown in Fig. 13b. This result might be caused by the asymmetry of metal flow during the FSW process. The influence of welding parameters on the bonding strength of the sample extracted from the site [C] is presented in Fig. 15. It is found that the condition which could minimize the bonding ling defect took the highest tensile strength, compare Fig. 15 with Fig. 11; it was taken by the welding rate of 0.13 mm/rev.

Fig. 13  Effects of welding rate on hardness profile on (a) skin and (b) stringer plates.

Fig. 14  The local bonding strengths along interface with insert of fracture locations at 0.13 mm/rev.

Fig. 15  Effect of welding parameters on the bonding strength measured at centre interface.
3.3.3 Effect of welding parameters on tensile properties of full size T-lap joint

(a) Tensile strength: Figure 16a displays the comparison of the different stress-strain curves in the skin test of the full size T-lap joint specimen under various welding rates. It is worthy to note that all of curves almost overlapped each other in elastic deformation regime. However, there are significant differences after the yielding. As presented in Fig. 16b, the increased with growing the welding rate from 0.13 to 0.25 mm/rev, and then decreased at 0.50 mm/rev. The highest tensile strength and rupture strain of the skin specimen was approximate 290 MPa and 12%, respectively, which was attained at the welding rate of 0.25 mm/rev. Here the joint efficiency was about 90% compared to the base metal. These results might relate to defects formation during the FSW process.

Similarly to the stress-strain curve in the skin test, the load-displacement curves were significantly affected by welding rate (Fig. 17). Noting that there was an optimum welding rate by which the maximum stringer strength was attained; it was by 0.25 mm/rev.

(b) Role of defects on mechanical properties of T-lap joint: Figure 18 presents the fracture location and fractography of samples in the skin test. Three typical modes of failure were observed; those were denoted by FT1, FT2, and FT3, respectively. In the FT1 mode, the fracture was from the hook defect region, that was pronounced in the joint at the low welding rates of 0.13 and 0.19 mm/rev associating with smooth fracture surface (Figs. 18d,g). The joint failed by this mode showed the low strength (see Fig. 16b). In the FT2 mode, on the other hand, the fracture was nucleated from the HAZ area (Fig. 18b) where the hardness value is the lowest as shown in Fig. 13a. Consequently, the highest strength was found with fracture surface associated with the ductile dimples mode as shown in Figs. 18e,h. This mode was realized at the welding rate of 0.25 mm/rev. In the FT3 mode, the role of tunnel defect was clear; these were significant under the high welding rate (Fig. 18c). It is worthy to note that in all cases the bonding line defect seems to have insignificant effect in the skin test.

In the stringer test, two main modes; denoted by FT4 and FT5, were observed as shown in Figs. 19a and 20a, respectively. The mode FT4 that was found in the welding rate of 0.13 and 0.19 mm/rev was stimulated not only by the
hook defect but also by the kissing bond defect. This was the reason for degrading the strength and increasing displacement, as shown in Fig. 17. Based on local bonding strength along interface shown in Fig. 14, this failure can be initiated at the kissing bond in both the AS and RS sides in which the bonding strength was the lowest, and then propagated along hook defect before rupture. From the microscopic aspect shown in Figs. 19b-e, the fracture morphologies were heterogeneous with some of them revealed ductile fracture, the others did brittle fracture. Meanwhile, the bonding line defects were considered as main reason for the failure of FT5 mode that cracked along interface (Fig. 20a). They were found at the higher welding rate. Figs. 20c-o show the difference in fracture surface at various positions, as marked in Fig. 20b. Some trench-likes with a large of oxygen were more dominant at the AS compared to the RS. This might lead to the lower bonding strength at the AS in comparison with the RS, as indicated in Fig. 14. A large of dimple on fracture surface indicated ductile failure in this mode.

Based on these observations, the role of each type of defect on the mechanical properties of T-lap joint is summarized in Table 4. Since the welding rate of 0.25 mm/rev took the highest strength, the selection of the welding condition which can minimize the hook defect size must be the most effective.

| Welding rates (mm/rev) | 0.13; 0.19 | 0.25 | 0.38; 0.50 |
|------------------------|------------|------|------------|
| Mode of failure        | AS FT 1    | AS FT 2 | AS FT 3   |
| Macro-fractography     | Hook defect | Tunnel defect | View direction |
| view direction         |            |        |            |
| Micro-fractography     |            |        |            |

Fig. 18  Failure behaviour of skin test in the T-lap joint. (a-c) fracture location and (d-i) corresponding fractographies.

Fig. 19  (a) Fracture location and (b-e) fractography of FT4 at welding rate of 0.13 mm/rev.

Fig. 20  (a) Fracture location and (b-o) fractography of FT5 at welding rate of 0.25 mm/rev.
Table 4  Summary effect of defects on failure of T-lap joint.

| Type of test | Skin test | Stringer test |
|--------------|-----------|---------------|
| Modes of failure | FT1 | FT2 | FT3 | FT4 | FT5 |
| Tunnel defect | ☒ | ☒ | ☐ | ☒ | ☒ |
| Hook defect | ☐ | ☒ | ☒ | ☒ | ☒ |
| Kissing bond defect | △ | ☒ | ☒ | △ | △ |
| Bonding line defect | ☒ | ☒ | ☒ | ☒ | ☐ |

- ☒ No effect
- ☐ Major effect
- △ Minor effect

4. Conclusions

The dissimilar FSW T-lap joints between AA5083 and AA7075 were fabricated, focusing on the formation and the role of the defects in the mechanical properties. The following conclusions were reached:

1. The welding rate was one of the important variables to have higher performance of the FSW T-lap joint. Here, the increase in the welding rate could contribute to decrease the hook defect size which played the most significant role in the mechanical properties. At high welding rate, however, the tunnel and bonding line defects were formed and reduced the joint efficiency.

2. The kissing bond defect was formed at the two corner fillets under all the welding conditions. It was too hard to be eliminated in this work. However, this type of defect was secondary in the mechanical properties of T-lap joint.

3. The local bonding strength along the interface is heterogeneous. It seems to be higher at the RS than that at the AS. This strength was decreased with advancing the welding rate.

4. There was an optimum welding rate which could minimize the defect size and make the T-lap joint strength higher; it was 0.25 mm/rev in this work. Here the joint efficiency was reached 90%.

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