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# Formation of Weld Zones during Friction Stir Welding of Aluminium Alloys

Z.W. Chen and R. Maginness

*Department of Mechanical and Production Engineering,  
Auckland University of Technology, New Zealand*

A series of friction stir welding experiments was conducted examining the effects of tool shoulder size and tilt angle on the formation of weld zones. Our experiments have confirmed that the weld nugget formed solely due to the plastic flow of the material sheared by the rotating pin without a major influence from the shoulder. Smaller shoulder resulted in an insufficient flow in the upper weld zone and hence in the formation of a channel type defect. Our experiments have also shown that plastic flow by compression due to the forward motion of the shoulder contributed to the complete formation of the top weld zone without defect. Hence, a higher tilt angle resulted in a larger flow in the upper zone and hence the channel type defect size was less. Alloy 5083 was found to have a significantly lower weldability than alloy 6061 due to the lower hot workability of the alloy 5083 than alloy 6061.

## Introduction

A common feature observed in a cross section of a weld made by friction stir welding (FSW) is a weld nugget zone with a near-oval shape (depending on pin shape) from a small distance below the surface [1-5]. The width of the nugget zone is larger than the pin diameter. There is also an upper weld zone which is as wide as the tool shoulder and is primarily the result of the interaction between the workpiece and the tool shoulder [5].

The plastic flows resulting in the formation of the different zones during FSW are complex and have been the subject of a number of experimental studies recently, focusing on the structure and formation mechanism of lower weld (nugget/oval) zone [5-12]. Not only the mechanism of the formation of the patterns in weld nugget is not fully understood, the forming mechanism of the upper zone is yet to be fully determined [5] and the upper region is prone for lack of weld to be present [13,14].

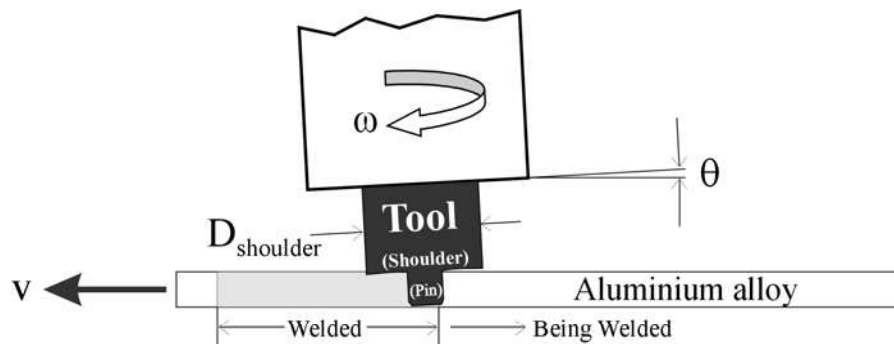
In this study, the upper zone formation affected by the size of the shoulder was first investigated, since the zone was thought to be primarily the result from the interaction of the workpiece with the tool shoulder [5]. Secondly, experiments were conducted by changing the tool tilt angle, since the degree of interaction must be affected by the tilt angle. Structure of the upper zone will be shown and the suggested flow will be given to explain the formation of the upper zone and to understand the mechanism of defect formation in that zone.

Aluminium alloy 5083 was used in the present experiments. Alloy 5083 is primarily the alloy used in boat building which has been one of the major industries considered for the application of FSW technology. The friction stir weldability of 5083 alloy is thus important for boat building application. FSW experiments and a brief examination of the welds were also conducted using 6061 aluminium alloy to illustrate the alloy effect on the weldability.

## Experimental procedures

For FSW, a Lagun milling machine was used and the relative movement of the tool and the workpiece (aluminium alloy plate) during FSW is illustrated in Fig. 1. During welding of an

alloy plate (250×100 mm), the ends of the plate were clamped onto the milling machine bed with a steel plate backing (not shown in Fig. 1). Fig. 1 also illustrates that the tool was allowed to tilt at different angles ( $\theta$ ) and the tool rotation speed ( $\omega$ ) could be adjusted.



**Fig. 1** Schematic illustrating friction stir welding and experimental parameters.

The thickness of the rolled 5083 alloy plate and 6061 alloy flat bar (Table 1) was 6 mm. Two FSW tools were machined using high speed steel and they only differed in shoulder diameter ( $D_{\text{shoulder}}$ ). One was 20 mm and the other 16 mm. Pin diameter 6 mm and pin length 5.5 mm were the same for both tools. For each pin, lefthand thread of 1.2 mm pitch and 0.8 mm depth was produced. The tool shoulder was machined to have the commonly used feature of slightly concavity.

**Table 1.** Nominal compositions (wt%) of 5083 and 6061 aluminium alloys.

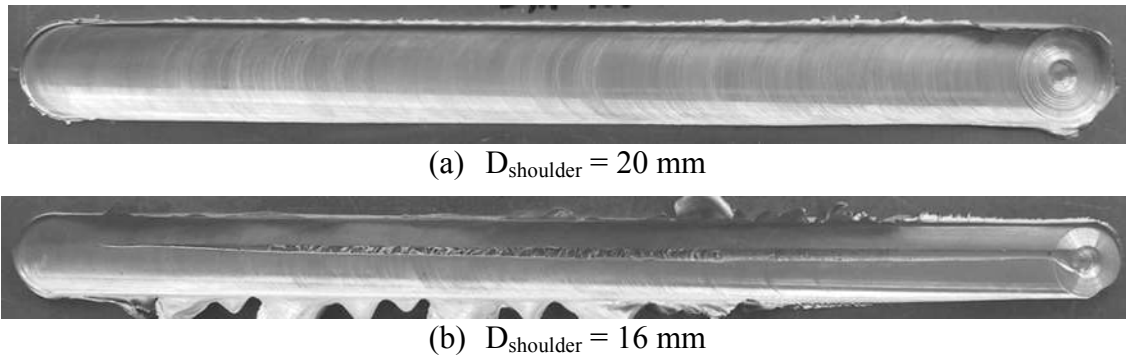
Alloy	Al	Mg	Si	Mn	Fe	Cr	Zn	Cu	Ti
5083	Bal.	4.2	0.2	0.6	0.15	0.09	0.09	0.06	0.02
6061	Bal.	0.9	0.6	0.1	0.33	0.17	0.02	0.28	0.02

A number of FSW conditions were used. Firstly, FSW experiments were conducted using  $D_{\text{shoulder}} = 20$  mm and 16 mm with  $\theta$  kept constant at  $2^\circ$ . Secondly,  $\theta$  started from zero and increased to  $4^\circ$ , while  $D_{\text{shoulder}} (= 16$  mm) was kept constant. In these two experiments, alloy 5083 was used. In the third experiment, alloy 6061 was used with the FSW conditions the same as that used in the second series of experiments. For all the experiments, weld travel speed was kept at 60 mm/min and  $\omega$  was 800 rpm.

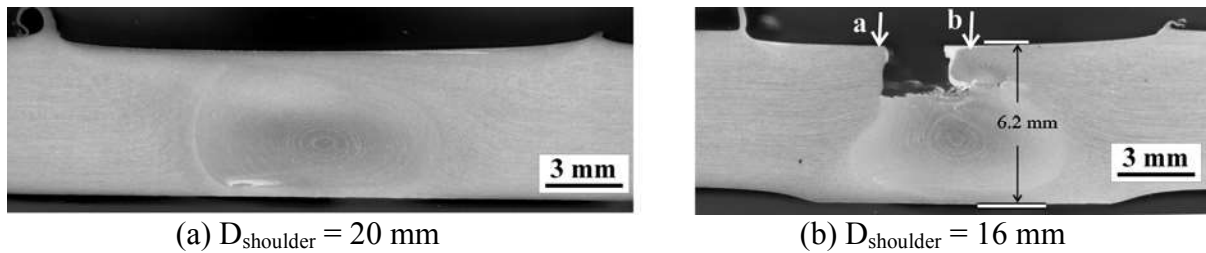
## Results and Discussion

### The effect of shoulder diameter

Welds of alloy 5083 made using tools of the two different shoulder diameters are shown in Fig. 2. Using the larger  $D_{\text{shoulder}}$  (20 mm) tool the weld was free of defect when the weld was observed from the surface of the weld (Fig. 2a). On the other hand, when the smaller  $D_{\text{shoulder}}$  (16 mm) tool was used, FSW resulted in a continuous lack of joint in a form of a channel along the weld, as is clearly seen in Fig. 2b. Cross sections ( $\sim 30$  mm from end of weld) of the welds are shown in Fig. 3. Consistent with the observation on the weld surface (as in Fig. 2a), the use of the larger  $D_{\text{shoulder}}$  tool resulted in a sound weld (no discontinuity) observed in the cross section (Fig. 3a). The commonly observed major weld nugget zone with an oval like shape can be identified.



**Fig. 2** Top view of alloy 5083 welds made using tile angle  $2^\circ$  and shoulder diameter as indicated. A channel defect in the weld is apparent in (b).



**Fig. 3** Cross sections ( $\sim 30 \text{ mm}$  from the ends of the welds as in Fig. 2) of alloy 5083 welds made using shoulder diameter as indicated and tile angle  $2^\circ$ .

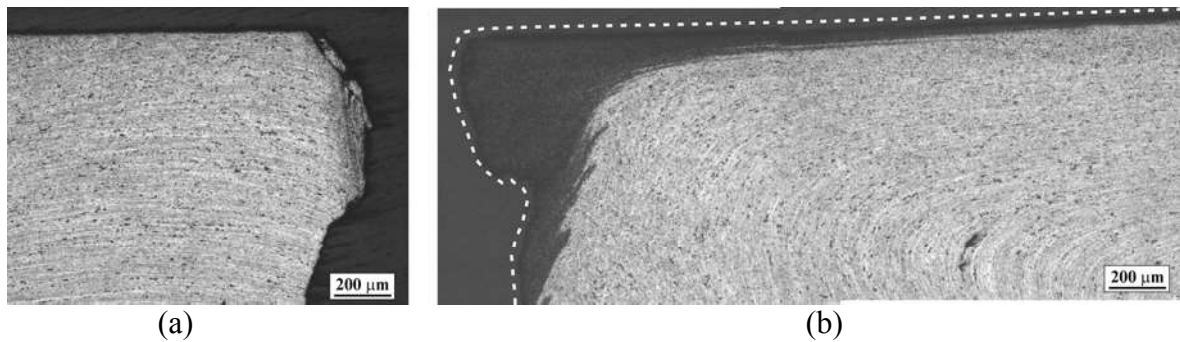
When the smaller  $D_{\text{shoulder}}$  tool was used, as can be seen in Fig. 3b, the weld nugget has become slightly bell shaped and there is a slight bulge of the plate at the bottom. Steel backing was used during FSW. Hence, the slightly bulge appearance when the smaller shoulder tool was used means that material in both sides of the weld (bulged area) had been driven up slightly. The weld nugget in bell shape also means that the lower portion of the weld nugget has enlarged but not the upper portion.

The flow induced bell shape is reasonable as the action of the pin thread is to shear and drive the material downward and hence spreading out in the lower part, causing slightly buckling in neighboring region (therefore bulge appearance). Such bulging could be prevented by more rigid clamping along and very close to the weld seam, but the present less rigid clamping is more helpful in regard to studying the flow during FSW. A large shoulder diameter serves to press on in a wider area and to increase the plasticity in a wider region to aid the upward flow, eliminating bulging at the bottom, reduces the need to severe clamping in practice.

Increase in  $D_{\text{shoulder}}$  from 16 to 20 mm, by 25%, increased the width of the nugget from 8.3 mm to 9.5 mm, by 15%. However, the significant effect was on the upper half of the nugget, changing from bell shape to oval, increasing the volume of the weld nugget significantly. This is reasonable as the use of a larger shoulder, and hence a larger frictional area, must have generated a larger amount of heat. This means that high temperatures and a high degree of plasticity could be obtained in a wider region. Hence, in TMAZ (next to the oval), the upward plastic flow/deformation became much higher and upward flow lines became more pronounced, as is evident in Fig. 3a. As a result, distortion and bottom bulging disappeared.

The channel defect (Fig. 2b) can be clearly seen in the upper weld zone (above the nugget) in the 16 mm shoulder weld in Fig. 3b. Typical microstructures of the upper region illustrating the flow are given in Fig. 4. The direction of this flow in the upper region is from the

retreating side to the advancing side with the material tending to fill the empty space behind the pin in the upper region. In the case of using the smaller  $D_{\text{shoulder}}$  tool, only about half the space was filled (Figs. 3b).

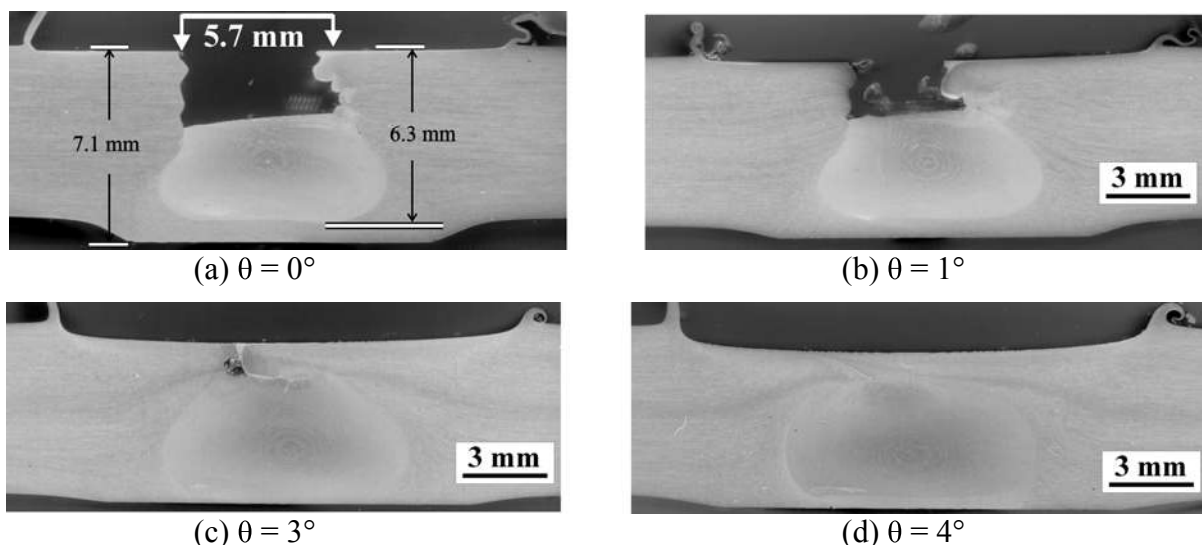


**Fig. 4** Microstructures of weld made using  $D_{\text{shoulder}} = 16 \text{ mm}$ ,  $\theta = 2^\circ$ . Micrographs were taken in locations of upper flow region **a** and **b** as in Fig. 3b.

The upper flow pattern as indicated in the micrograph in Fig. 4b suggests a barreling type of flow commonly found in forging. This suggests that, while friction by the rotating shoulder contributed to the increase in temperature and in a higher plasticity generally, the forging/compressing provided by the shoulder resulted in the flow to fill the channel left behind by the pin (and could not be filled by the nugget) in the upper region. A large shoulder, at the same tilt angle, providing a larger forged area, should then assist in the flow for the complete closure of the channel.

#### The effect of tool tilt angle

Cross sections of welds from experiments investigating the effect of tool tilt angle are shown in Fig. 5. With zero tilt angle (Fig. 5a), the weld nugget is clearly bell shaped and severe bulging at the bottom (and lifting of the weld plate) of weld took place. The bulged portion became thicker (than the original thickness). This is because, to have a zero tilt angle, the tool shoulder was held slightly above the plate. However, the relative motion of pin/plate resulted in lifting the plate up but material around the pin in the lower portion was driven down, causing severe bulging.



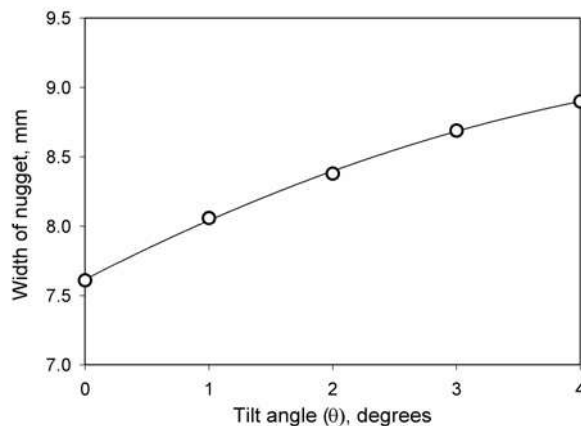
**Fig. 5** Cross section of alloy 5083 welds made using  $D_{\text{shoulder}} = 16 \text{ mm}$  and  $\theta$  as indicated.

There was little filling in the upper zone, resulting in a wide (~5.7 mm) channel (Fig. 5a). The shearing between the weld/plate and the shoulder should still exist (particularly for the plate to have been lifted up) but forging action should be absent in this experiment. This strongly suggests that shearing due to shoulder rotation did not contribute to the plastic flow to fill the channel as forging did. The fact that no forging action in this experiment must have resulted in very little plastic flow in the upper region and hence resulted in a channel as almost as wide as the size of the pin.

The width of the channel decreased as the tilt angle increased, as can be seen in the weld in Fig. 5 (for 0, 1, 3 and 4°) and Fig. 3b (for 2°). From a simple geometrical consideration, the increase in tilt angle increases the depth of the shoulder pressed downward and hence greater pushing/compressing of the material forward, meaning larger forging action. Hence, the volume of plastic flow to fill the channel is larger. This again strongly suggests that forging is the major mechanical action resulting in the plastic flow in the upper zone to close the channel.

The decrease in the channel width was accompanied by the weld nugget from more bell shaped to more oval shaped, when the tile angle increased. Increasing the forging action means an increase in the applied normal force and hence high frictional force and heat. Hence, high temperature and plasticity could be attained in the upper region and the nugget became more oval shape when a higher tile angle was used.

The well defined nugget zone formed even at 0° tilt angle (Fig. 5a) suggests that the tool shoulder had little influence on the actual weld nugget formation. The nugget formed due to the plastic flow induced solely by the shearing action of the tool pin. Increasing the tilt angle (from 0 to 4°) increased the width of the nugget (Fig. 6) from 7.6 mm to 8.9 mm ( $D_{\text{shoulder}} = 16$  mm). This, plus the fact that a more oval shape was obtained, means that the volume of nugget increased as the tile angle increased.

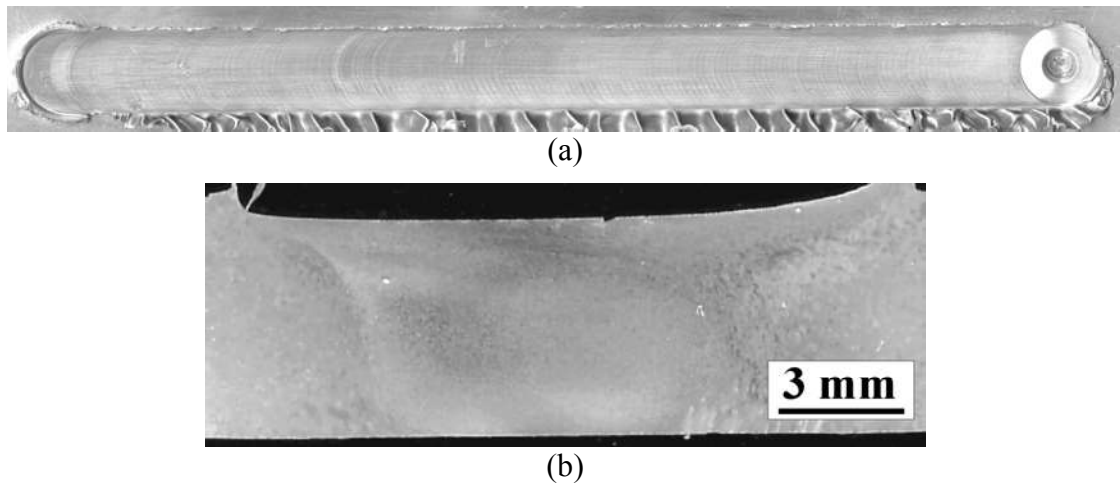


**Fig. 6** Width of weld nugget as a function of tool tile angle for alloy 5083 welds made using 16 mm shoulder diameter.

### The effect of alloy type

The appearance and cross section of a weld made using 6061 alloy with ( $D_{\text{shoulder}} = 16$  mm and  $\theta = 2^\circ$ ) are shown in Fig. 7. When the same welding condition and alloys 5083 were used, as described above, channel defect was present due to lack of plastic flow to fill the upper zone formed. The use of alloy 6061, with the same defect forming FSW condition as used in

FSW of alloy 5083, has resulted in the weld that the upper zone was completely filled and hence was free of channel defect.



**Fig. 7** Weld made using alloy 6061 using tile angle  $2^\circ$  and 16 mm shoulder diameter, (a) top view and (b) cross section.

It is well known that the intrinsic ability of alloy 5083 to resist deformation is significantly higher and hence hot extrudability of the alloy is significantly poorer than that of alloy 6061 [17]. Hence, under the similar FSW conditions, plastic deformation/flow is expected to be significantly more extensive for alloy 6061, assisting in the formation of oval shape nugget and the flow in the upper zone to close the channel.

## Conclusions

FSW weld nugget formed solely due to the plastic flow of the material sheared by the rotating pin and filled into the space behind the pin. But such flow was also in a downward direction, leaving the space in the upper region unfilled. A forged/compressive dominated flow contributed to the filling in the upper region. A small shoulder resulted in an insufficient flow in the upper weld zone and hence in the formation of a channel type defect. A higher tile angle resulted in a larger forging action and the flow in the upper zone was more extensive reducing the channel type defect size. The use of alloy 6061 with a better extrudability resulted in a larger plastic flow in the weld region and hence resulted in a more complete filling than the use of alloy 5083.

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## References

1. M.W. Mahoney, C.G. Rhodes, J.G. Flintoff, R.A. Spurling and W.H. Bingel, Metallurgical and Materials Transactions 29A (1998) 1955.
2. Y. Sato, H. Kokawa, M. Enomoto and S. Jogan, Metallurgical and Materials Transactions 30A (1999) 2429.
3. W.D. Lockwood and A.P. Reynolds, Materials Science and Engineering A339 (2003) 35.

4. H. Liu, H. Fujii, M. Maeda and K. Nogi, *Journal of Materials Science Letter* 22 (2003) 1061.
5. M. Guerra, C. Schmidt, J.C. McClure, L.E. Murr and A.C. Nunes, *Materials Characterization* 49 (2003) 95.
6. K. Colligan, *Welding Journal* (1999) 229s.
7. Y. Li, L.E. Murr and J.C. McClure, *Materials Science and Engineering A271* (1999) 213.
8. M.A. Sutton, B. Yang, A.P. Reynolds and R. Taylor, *Materials Science and Engineering A323* (2002) 160.
9. K.N. Krishnan, *Materials Science and Engineering A327* (2002) 246.
10. W.B. Lee, Y.M. Yeon and S.B. Jung, *Scripta Materialia* 49 (2003) 423.
11. J.A. Wert, *Scripta Materialia* 49 (2003) 607.
12. L. Ke, L. Xing and J.E. Indacohea, *Metallurgical and Materials Transactions* 35B (2004) 153.
13. B. Lee, Y.M. Yeon and S.B. Jung, *Materials Science and Engineering A355* (2003) 154.
14. A.L. Leonard and S.A. Lockyer, *Proceedings of the 4th International Symposium on Friction Stir Welding*, Park City, TWI.
15. T. Sheppard, "Extrusion of Aluminium Alloys", Kluwer Academic Publishers, Dordrecht, 1999.