COMPRESSION RATIO EFFECTS IN BOBBIN FRICTION STIR WELDING

PREPRINT

M.K Sued, D. Pons, J. Lavroff

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M.K Sued, Mechanical Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand (Permanent Address: Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya 76100, Durian Tunggal, Melaka, Malaysia).
D. Pons, Mechanical Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand.
J. Lavroff, School of Engineering, university of Tasmania, private Bag 65, Hobart 7001, Tasmania, Australia.

SYNOPSIS

The mechanism for generating shoulder friction is dependent, in the bobbin case, on the interference (compression) between the substrate (plate thickness) and tool (shoulder gap). In the present work, the effects of different interference were evaluated. The substrate under evaluation in this work is thin plate aluminium. Results show that the interference affects the dynamic behaviour of the tool, the temperature, and the weld quality. Unstable force occurs because of minimum contact between shoulder and substrate hence material stirring is not efficient. Forces are more stable at high shoulder interference. Higher force and temperature are generated for higher interference, along with greater rind flash formation. Of the interferences examined here, the intermediate case (3.75% interference) is recommended, though the weld quality is improved by the provision of additional tool features such as flats. The paper develops a theory, based on empirical data, for the effects of shoulder interference. It also proposes a mechanism for slip-stick, which is given in terms of a dynamic interaction between an elastic tool and a viscoplastic substrate. The proposed casual relationships are summarised using a systems engineering approach. Implications for practitioners are that assembly tolerances and restraints used in BFSW need to be such that the parts are firmly held together, otherwise slip-stick behaviours result.

1 INTRODUCTION

The underlying mechanics of friction stir welding (FSW) involve a complex interaction of temperature, pressure and material flow (vertical and horizontal). These effects are caused by the rotating tool that travels through the material and creates a joint behind its passage. There are two types of FSW, differentiated by primary tool features, with single and double shoulders. The single shoulder case is conventional friction stir welding (CFSW), and double shoulder is bobbin friction stir welding (BFSW).

From the origins of FSW, the single shoulder case has been the main focus or research and application, and the bobbin case is less developed [1]. Though complex, the physics involved in CFSW are reasonable well-understood, but BFSW is more obscure [2]. The reason is the additional shoulder and full penetration of the pin in the BFSW process affects the mechanics of weld formation. This causes different sensitivities to tool features, process variables and parameter settings [3, 4]. In addition, several of the settings for CFSW are not relevant to the bobbin case, including the backing plate, axial load and tilt angle of the tool. The main source of heat generation is from the shoulder [5, 6]; hence intimate contact between shoulder and material is important. In the case of CFSW, the axial load parameter introduces vertical force to ensure full contact between tool and material [7]. In addition to axial force, certain tool features on the shoulder (tapered or convex features) may reduce the contact requirement [8, 9]. However in the BFSW process, the axial load is minimal or absent [10]. This is because of the full penetration of the tool into the material and the symmetrical arrangement of the shoulders.

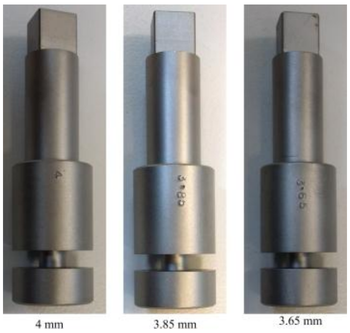
However this also means that the mechanism for generating shoulder friction is dependent, in the BFSW case, on the interference (compression) between the substrate (plate thickness) and tool (shoulder gap). Other work has examined shoulder features for bobbin tools [11] [1-3], but a comprehensive understanding of the interference effect is not yet available. In addition, it can be anticipated that the interference is unlikely to be static, but rather dependent on plate thickness variations, vibration due to equipment rigidity, and tool deflection. Hence the interference has the potential to alter the weld quality. In the present work, the effects of different interference (*compression ratios)* were evaluated. The substrate under evaluation in this work is thin plate aluminium.

2 PURPOSE AND METHOD

To assess the compression effects, three tools with different shoulder gap were fabricated. The tools had dimension of 18 mm and 6 mm for the shoulder and pin respectively. Shoulder gap at delta (δ) of 0 mm, 0.25 mm and 0.35 mm were selected to introduce different compression ratios on 4mm thick AA6082-T6. This extruded aluminium alloy was cut to 260 (length) mm x 130 mm (width) and set for a butt joint configuration. The tests were classified in cases of the interference present on each tool in percentage. The details are presented in Table 1. The selected welding parameters were based on prior trial and error. The trials were run using a manual milling machine, see Figure 1. Process responses based on force and temperatures were recorded during the welds. A force platform was designed and built in-house to measure forces in the plane of the substrate: axis Y is forward in the weld direction, and X is transverse. The tool axial force (Z) was not measured. The force platform consists of eight S-type load cells. Wired thermocouples were embedded at the half plate thickness to measure temperature. Data acquisition was achieved using conventional National Instrument (NI) equipment, and data were recorded using a program based on Labview.

The signals that were recorded were studied and characterized to reveal the compression effects. Weld features (recorded by photograph) were correlated to force episodes. The insights and heuristic findings from this empirical approach were then presented in a conceptual framework. This model used integration definition zero (IDEF0) notation which is used in systems engineering [12]. The outcome is a theory of the proposed causality whereby compression ratio affects the weld quality. This is an extension of a previous causality model [2].

Table 1: BFSW tools and process parameters

Tools Type	Tool Features	Spindle Speed (rpm)	Travel Speed (mm/min)	Case
Single piece tools with various shoulder gaps.  4 mm 3.85 mm 3.65 mm	Shoulder: Flat and concave (7°). Pin: Cylinder. Shoulder gap: 4 mm, 3.85mm and 3.65mm (Shoulder edges had been modified to include 1.5mm of 15° chamfer)	650	60	1.1 Single piece tool (cylindrical) built to 4mm gap (0% interference)
				1.2 Single piece tool (cylindrical) built to 3.85 mm gap (3.75 % interference)
				1.3 Single piece tool (cylindrical) built to 3.65 mm gap (8.75 % interference)

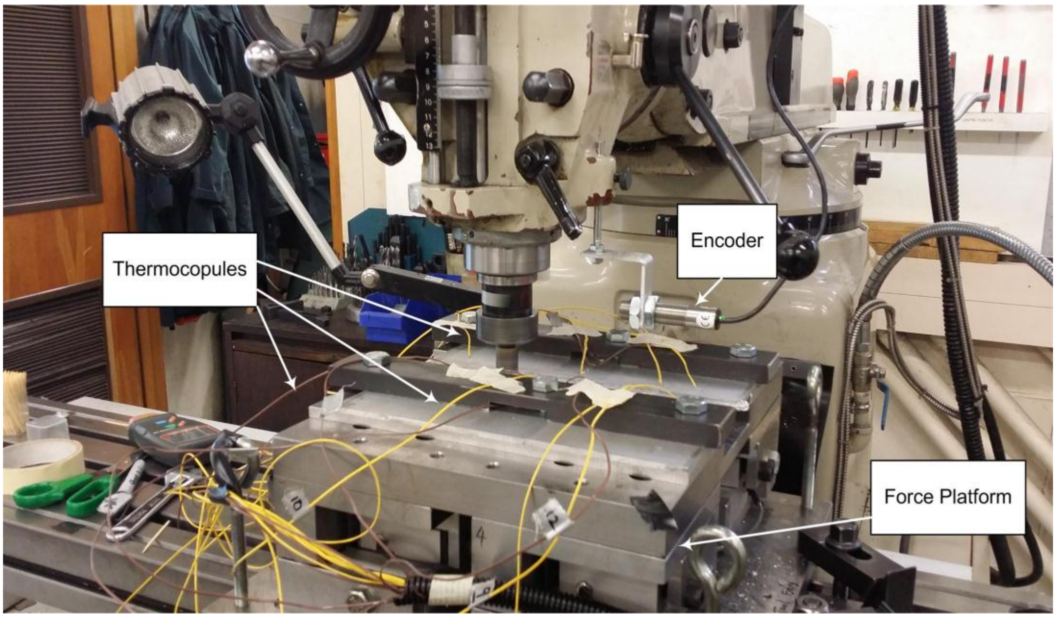


Figure 1: Manual milling machine with welding instrumentation

3 RESULTS

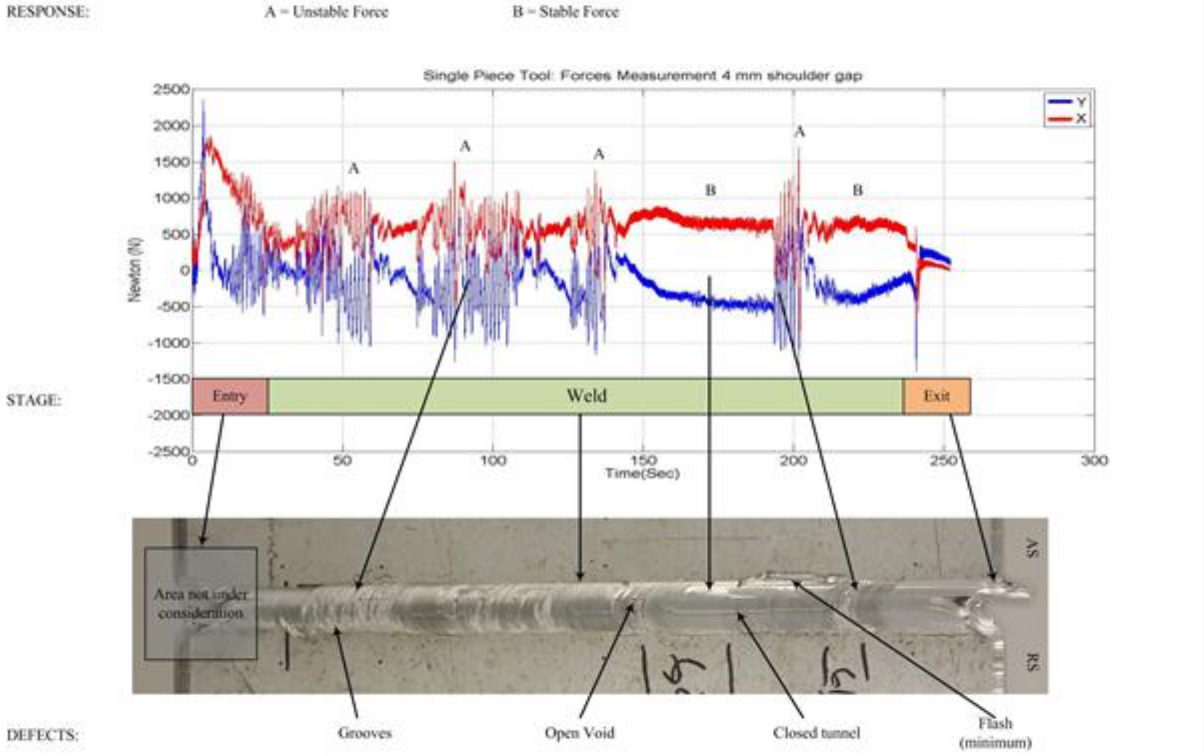
Surprisingly, no good welds were able to be produced. The most presentable weld was when 0% interference tool shoulder was used. Anyhow, the compression effects were presented based on visual inspection and instrumentation data.

Based on the built force platform, Y (F_y) is the force measured at travel direction and X (F_x) is the transverse force perpendicular to the travel direction. In general, three stages of forces responses can be identified: entry, welding and exit. The *entry* can be characterised as sudden high force which decreases over time before becoming stable as the tool travels completely into the plates. The *exit* phase is when the tool starts to leave the plate, and the force decreases steadily with a sudden last drop of the forces. The *weld* stage is located in between entry and exit. This study revealed that the weld stage can be divided to two types which are unstable force (fluctuating) and stable force. The fluctuation force at post-entry stage has a similar characteristic which appears to indicate heat build-up at the substrate-tool interface. It should be noted that for this study, manual feed for initiation was used at early stage of the tool entry before the auto feed was applied. Hence the magnitude at this time may not be exact. Nevertheless, the welds and exit stage forces magnitude is consider accurate to ± 5%.

3.1 EFFECT OF INTERFERENCE

(a) Case 1.1: 0% Interference.

Minimum flash was produced but period of groves (rough) surface finished were found. The force response is superimposed with the visual inspection, sees Figure 2, and permits a direct association to be seen between the fluctuating force and the groove defect. Other defects that were also present were open void and lines of closed tunnel. There was limited steady flow during the weld stage hence confined formation of a fine surface finish.

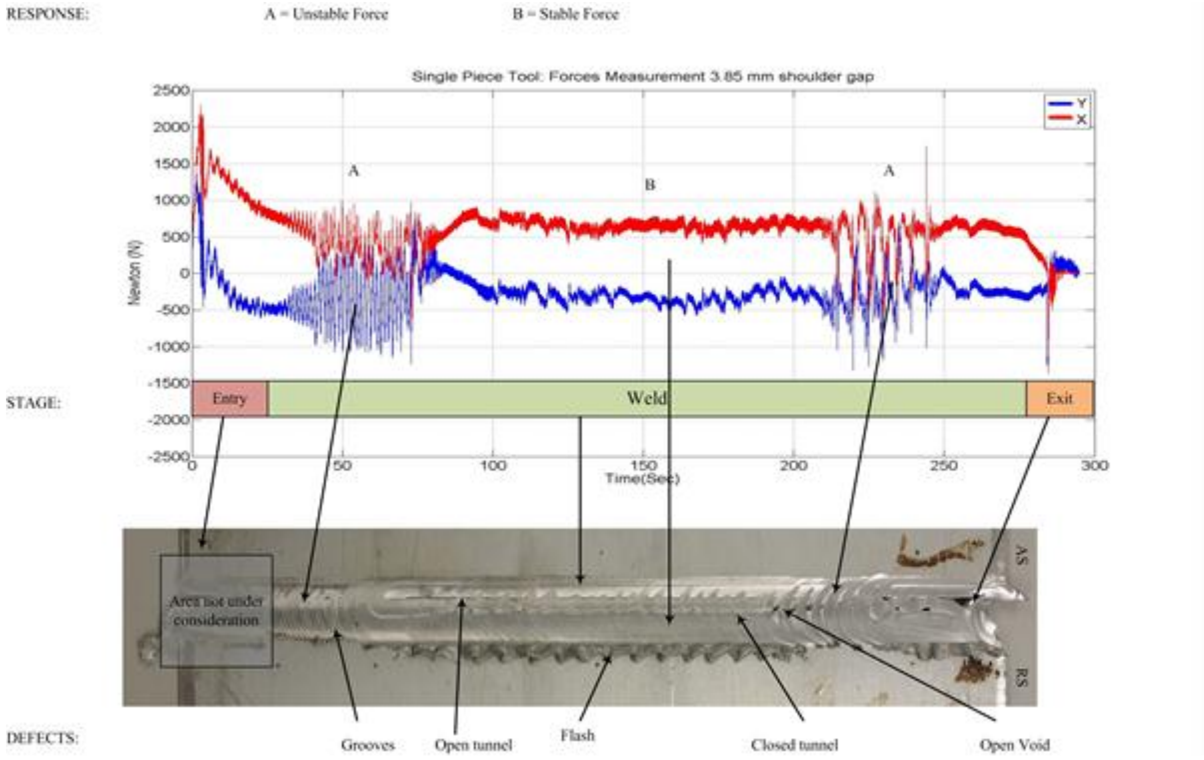


AS = advancing side; RS= retreating side

Figure 2: Case 1.1: 0% Interference. Photograph of upper surface.

(b) Case 1.2: 3.75 % Interference.

As displayed in Figure 3, a rind of flash was produced, and we identify this as a *wave* defect. The wave recorded for this interference was 10 mm pitch at 5 mm height. The peak of the wave pitch leans towards the weld direction. Moreover, based on the force responses, it can be seen that at the weld stage the stable force wavelength varied. The change is believed represent the establishment of the wave flash. Besides that, the rough surface finish was present early and near the end of the weld stage: this corresponds to the fluctuating forces evident at this time. A closed tunnel defect was persistent throughout the weld, and there were also some open voids and open tunnels in places, indicating a generally poor flow of material.

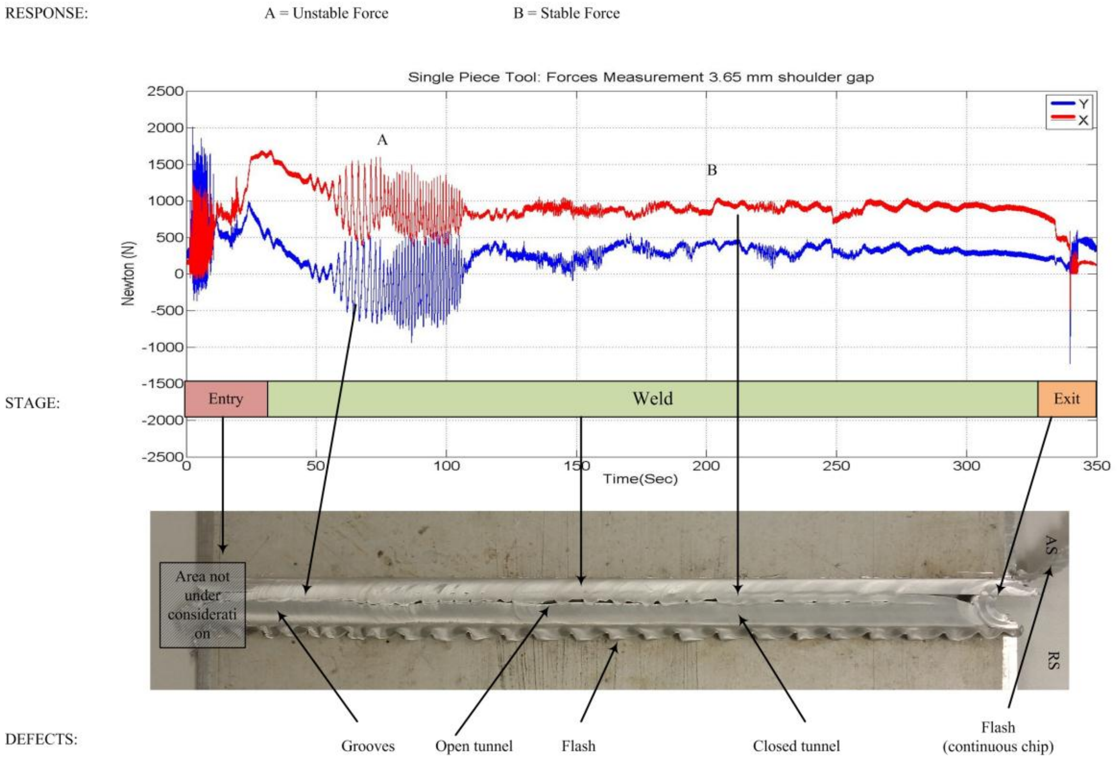


AS = advancing side; RS= retreating side

Figure 3: Case 1.2: 3.75% Interference. Photograph of upper surface.

(c) Case 1.3: 8.75% Interference.

Excessive wave flash was produced in this case of high interference, see Figure 4. The flash size of 15 mm pitch at 7 mm height was recorded and this exceeded Case 1.2. It was also found that the flash was upright. Another defect was the production of continuous *chips*. The effect of the excessive wave flash is also evident in the forces measured during the weld stage. The formations of the excessive flash and continuous chip production are exit transport mechanisms that remove material from the weld pool. This is consistent with the observed thinning of the weldments. In contrast to the other cases, rough surface finish (and associated fluctuating force) only occurred once after the tool entry. The open tunnel defect was more prevalent that in the other cases, and is also consistent with a loss of material explanation. There were few closed tunnels. Furthermore, it was found that high force was generated and the F_Y response was unexpectedly positive at high interference.



AS = advancing side; RS= retreating side

Figure 4: Case 1.3: 8.75% Interference

3.2 FRICTIONAL ENGAGEMENT & REACTION FORCES BETWEEN TOOL AND SUBSTRATE

It was found that F_x was higher in magnitude than F_y at the weld stage, for all three cases. This means that the rotating tool creates significant lateral thrust, directed at the substrate on the retreating side (RS). A comparison of the forces for the three cases is shown in Figure 5.

We propose the following explanation with reference to Figure 6: the departing side of the tool is engaged with hot plasticised substrate material > the forward side of the tool engages with more solid substrate material and therefore sustains a higher interface force > thus the frictional engagement is greater at the forward side of the tool than the rear > the rotation of the tool (clockwise from above in this case) therefore biases the tool to move in the direction of rotation at the forward edge > this results in a lateral displacement of the tool towards the substrate on the retreating side. This interpretation is consistent with the observation that the lateral force was greatest for greatest interference (Case 1.3).

Another interesting effect was the change in the longitudinal force F_y with interference. This force reduced with increasing interference, eventually reversing. In Cases 1.1 and 1.2 where interference was non-existent or low, the force F_y experienced by the substrate (and measured by the force platform) was directed in the direction of tool motion. (The sign convention is for this to be a negative value). This may be explained as the aluminium resisting the forward propagation of the tool, in a typical action-reaction effect. However at maximal interference (Case 1.3) the force is observed to reversed, i.e. the substrate experiences a force *opposite* to the direction of tool motion. This is counter-intuitive. Our suggested explanation is that the flanges, for the high-interference case, preferentially grip the substrate on the retreating side. In turn, that this is a consequence of the tool being deflected to the retreating side as per the explanation for lateral force F_x above. This leads us to suspect that the two force effects are coupled, that the lateral displacement also changes the longitudinal force.

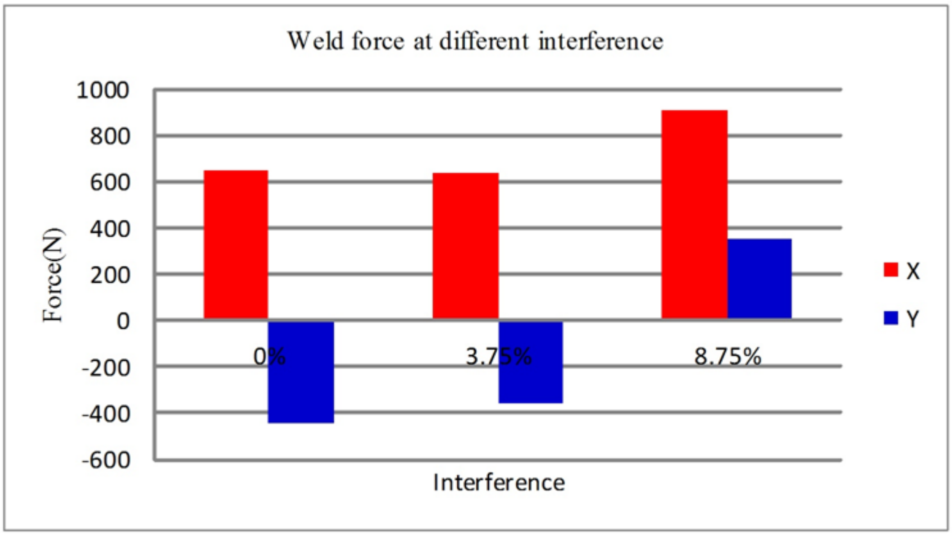


Figure 5: Stable force at weld stage (mean during steady progression)

3.3 MECHANICS OF SLIP-STICK

These lateral and longitudinal strains of the tool are dynamically generated, and transient behaviour is expected in such systems. The tool elastically strains as it engages with the viscoplastic substrate. We suggest this effect the slip-stick behaviour observed in bobbin welding, where the tool proceeds in lurches rather than continuously. Thus the proposed causal sequence is: the tool engages at the forward face and is deflected rearwards > the friction at the forward face deflects the tool laterally (explained above) > the tool snatches at the retreating side of the plate (especially with high interference, explained above) > the reaction force springs the tool forcible forward into the fresh substrate > the cycle continues. In other of our tests (not reported here) we have noticed that the slip-stick behaviour is worse when there is more compliance in the system, though we have not quantified the effect. The compliance can arise from clamping arrangements of the plates, strain of the tool (especially for slender tools and smaller pin diameters), or floating collets for the tool holder. The substrate also adds compliance: while its in-plane stiffness is high, thin materials can bend out of plane, i.e. move in the Z axis. In our case the load cells also add unwelcome compliance into the system. Slip-stick is a complex behaviour with serious consequences for weld quality, and has not been fully addressed in the research literature. The presentation interpretation of it being an elastic-viscoplastic interaction between tool and substrate goes some way to understanding, and thereby preventing, the phenomenon.

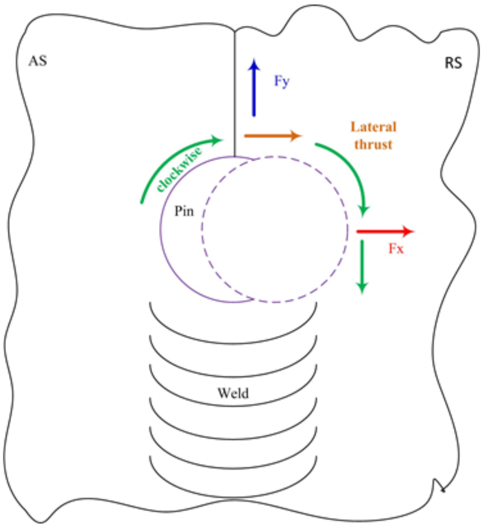


Figure 6: Butt joint plan view

Many of the fluctuating force episodes (shown above in Figures 2-4) can be interpreted as the system lapsing into the slip-stick regime. Note that F_y in these figures crosses the axis, i.e. the force oscillates from positive to negative. This is consistent with the slip-stick explanation given above. We suspect that the low frequency oscillations (e.g. Figure 4) are a consequence of the *shoulders* interacting with the substrate, and are associated with higher interference, whereas the higher frequency oscillations (e.g. Figure 2) are driven by *pin* interactions. This is speculative, but is consistent with the evidence presented here. Moreover, for weld material to be successfully contained, the *dynamic seal* mechanism needs to be preserved. This means that the plasticised material, which is transported around the tool, needs to be retained within the weld zone until it has re-solidified. The seal is dynamic, as there is nothing that physically retains the material other than the moving shoulders and the resistance of the substrate beyond the weld zone. The slip-stick behaviour disrupts this seal, because the sudden lateral and longitudinal lurches expose the plastic material. This explains why the rind flash (a) increased with interference, and (b) was located on the retreating side. The sudden movement of the tool towards the retreating side squeezes plastic material out of the weld zone, and the edge of the tool cuts into the substrate hence the rind with its periodic wave shape.

3.4 THERMAL EFFECTS

The lateral motion also means that there is more tool-substrate interaction occurring on the retreating side than the advancing. We see confirmatory evidence for this in the higher temperatures recorded on the retreating side, see Figure 7.

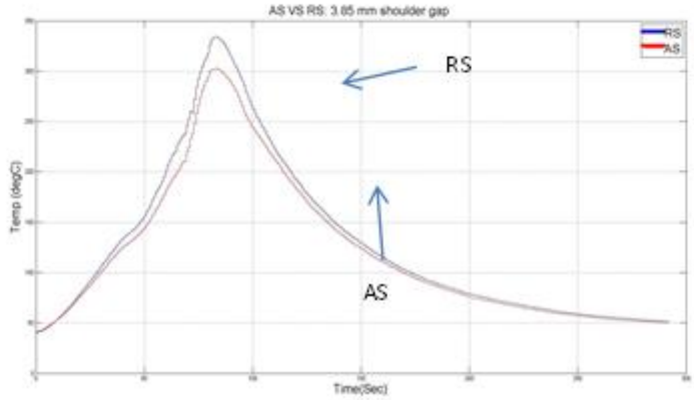


Figure 7: Temperature measurement at advancing side and retreating side as the tool passes.

It is also interesting to note the difference in temperature profiles in regions of steady tool progression as opposed to oscillating forces (and presumed slip-stick behaviour), see Figure 8. The stable regime is hotter than the oscillating. We suspect this is because the oscillating regime gets rid of heat by ejecting material (chips and rind) besides minimum shoulder contact, but this is tentative and needs further investigation.

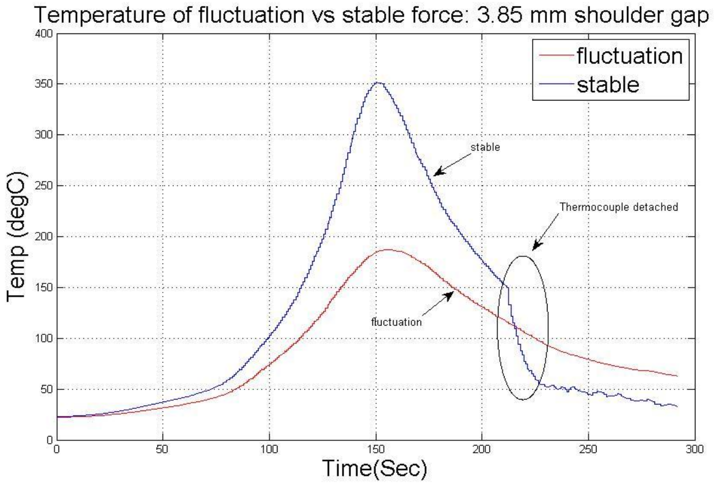


Figure 8: Temperature measurement at fluctuation and stable force.

The temperatures of the substrates increased linearly with interference, see Figure 9. With only a few data points not much can be reliably concluded from this, other than the general upward trend.

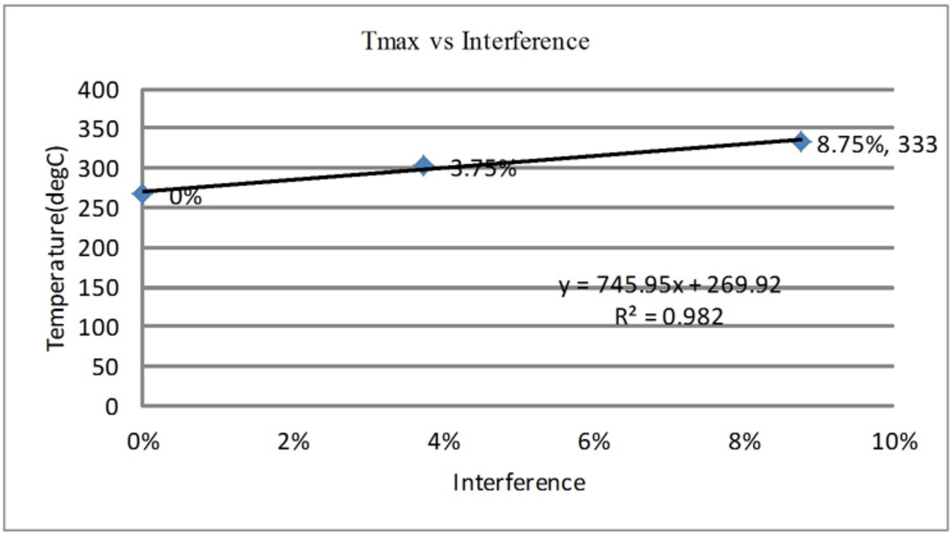


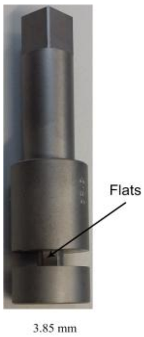
Figure 9: Maximum temperature measured at different interference

The results identify that interference gives significant impact on weld quality for bobbin tool. At low interference, the friction rotation and material stirring is done by the pin, with the shoulder having minimum effect. This leads to deflection and open void defects. In contrast, at high interference both pin and shoulder play their role in stirring the materials. The weld stage is more stable with less fluctuation force. However the process produces higher force hence higher temperature development is also recorded.

3.5 APPLICATION TO OTHER CASES

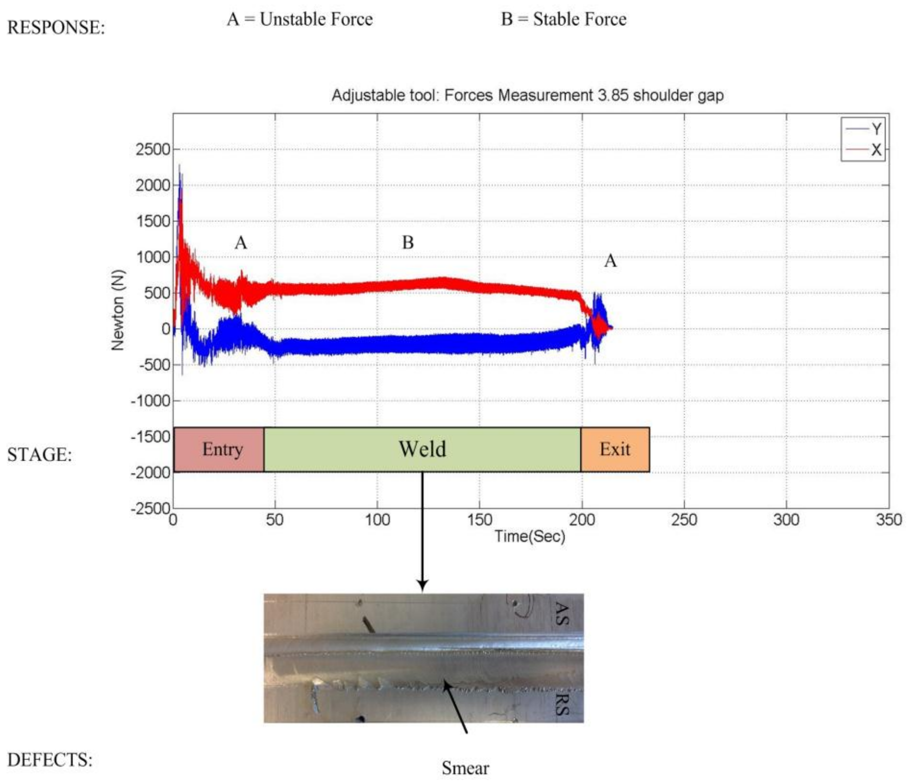
The studies were extended to different tool configuration and fabrication as seen in Table 2.

Table2

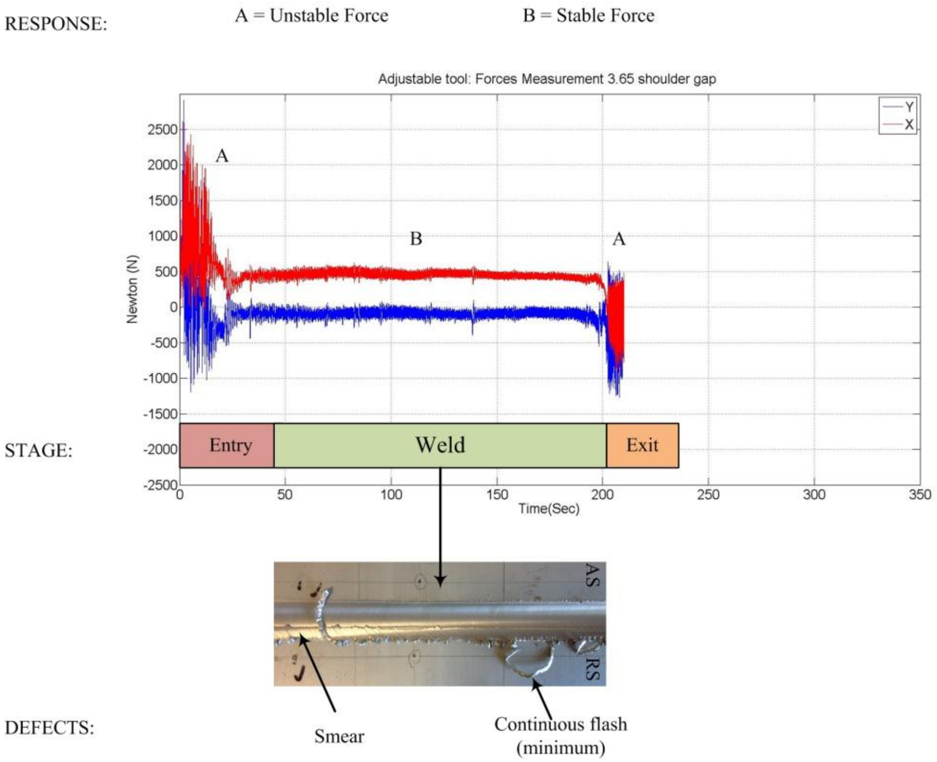
No.	Tools Type	Tool Features	Spindle Speed (rpm)	Travel Speed (mm/min)	Case
AD1	Adjustable tool  Similar tool used in [2].	Shoulder: Tapered and Scrolled. Pin: Threaded Cylindrical pin with 3 flats. Shoulder gap: Slip gauge used to setup the gap at 3.85mm and 3.65mm.	800	80	AD 1.1 Adjustable tool scroll, threaded, 3 flats set to 3.85 mm gap (3.75% interference)
					AD 1.2 Adjustable tool scroll, threaded, 3 flats set to 3.65 mm gap (8.75% interference)
SP2	Single piece tool 	Shoulder: Flat and concave (7°). Pin: Cylinder with 3 flats. Shoulder gap: 3.85mm (Shoulder edges had been modified to include 1.5mm of 15° chamfer)	650	60	SP 2.1 Single piece tool cylindrical , 3 flats built to 3.85 mm gap (3.75 % interference)

Adjustable Tool

For the AD1.1 and AD1.2 cases acceptable welds were produced. The success was attributed to the addition tool features. Based on the visual inspection, the amount of flash formation was increased at high interference, consistent with previous cases. Smear and continuous types of flashes were produced, see Figure 10. Wave flash that was seen in case 1.2 and 1.3 was absent. This suggests the flash depends on the tool features. The F_x magnitude for both cases was similar. One of the problems with adjustable tools is the potential for the welding forces to open the gap, especially if the interference is high. This is what happened in this case. In addition, the presence of assembly tolerance between the pin and the hole of the shoulder causes widening in angle [3].Because of in-situ shoulder gap alteration the forces measurement for the adjustable tools may not be the actual magnitude representing the interested interference effect. However, it can be seen that with the present of tool features, the stirring mechanism was improved hence reduced the effect of rigidity compliance. This was depicted by the reduction of F_y magnitude towards positive, with better weld formation.



(a) Case AD1.1:3.75% interference



(b) Case AD1.2:8.75% interference

Figure 10: Adjustable tool at difference interference. (a) Case AD1.1:3.75% interference (b) Case AD 1.2: 8.75% interference.

Single piece tool with 3 flats pin

High force fluctuation was seen for cylinder pin with three flats at 3.75% interference. A grooved surface finish was present along the weldment. Some smear flash was also present. The result shown an improvement of weld formation compared to 1.1, 1.2 and 1.3 cases. This is attributed to the stirring mechanism introduced by the flats enhancing the material flow. Pin features with flat faces are generally believed to have better material dynamic swept volume compared to a cylindrical pin [13]. But high force was required to transfer large amount of material. This force was fluctuating as the consequences of alternate friction between the cylindrical and flat regions of the rotating pin. These transient forces are shown in Figure 11.

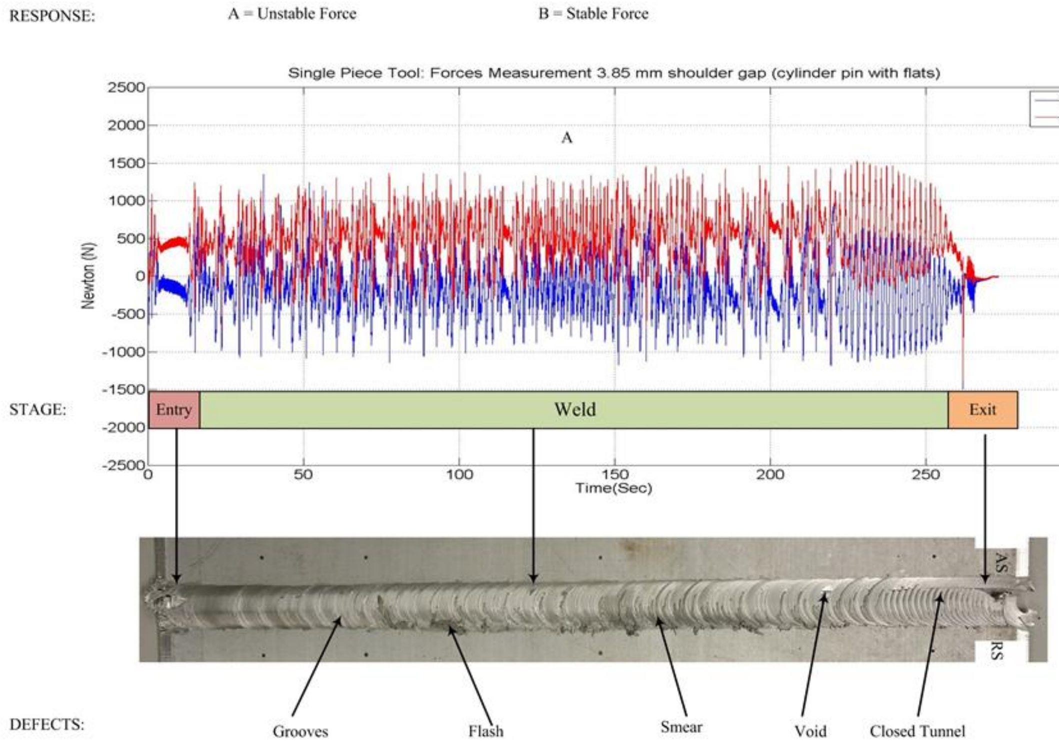


Figure 11: Case SP 2.1: 3.75% Interference.

4 DISCUSSION

Model of causality

The results obtained from the experiments were summarised in the conceptual theory shown in Figure 12. This is represented in IDEF0 [12]. The model proposes relationships of causality between the shoulder gap parameter, process responses and weld quality. This complements earlier work [2], by adding the shoulder interference effects. The model is intended to summarise what is currently known about the causal relationships in the area under examination. It may be used as a guide to practitioners who are seeking to optimise the quality of weld processes. It also serves as a framework to integrate research findings and identify where the gaps are in the body of knowledge.

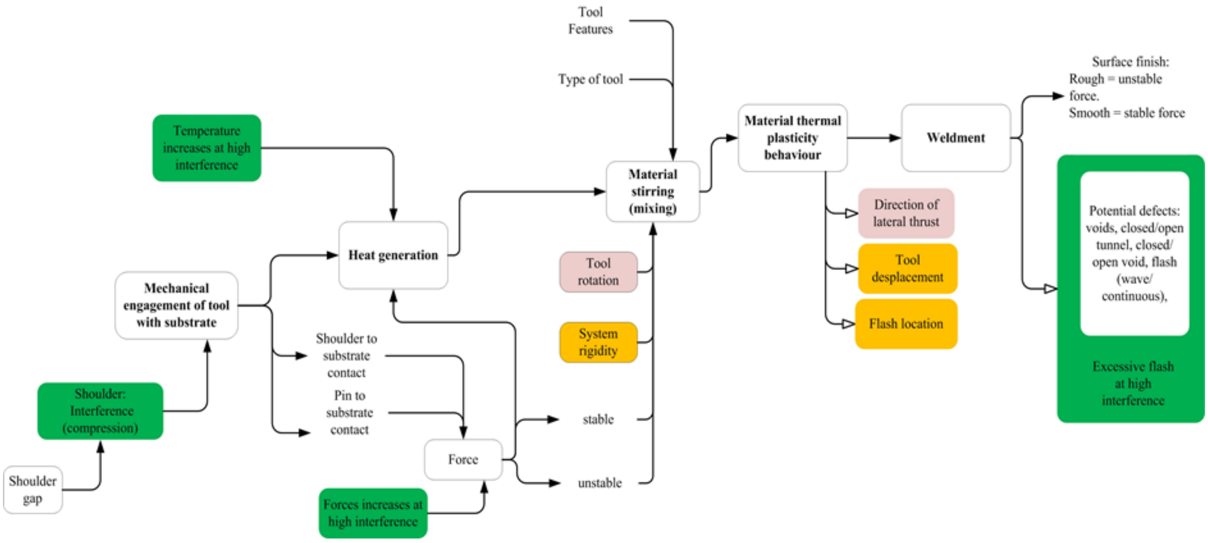


Figure 12: Causality model for bobbin friction stir welding compression ratio (interference).

EVALUATION

This work makes novel contributions in several areas. First, it develops a theory, based on empirical data, for the effects of shoulder interference in bobbin friction stir welding. It shows that shoulder gap relative to plate thickness (hence compression or interference) is an important process variable in its own right and needs consideration. Second, it proposes a mechanism for slip-stick, which is given in terms of a dynamic interaction between an elastic tool and a viscoplastic substrate. Third, it integrates the findings within a broader model that represents the casual relationships.

The limitations of this work are that it was conducted at specific spindle speed and travel speeds (i.e. these were independent variables), it used a manual milling machine as the FSW equipment, the tool features were limited in variety, the tests were limited to only one grade of aluminium and one thickness, and the sample size was small. However, the mechanics principles are expected to be generally valid.

Opportunities for further research are plentiful, including further empirical approaches, a better understanding of the effects of tool features, exploring the thermal effects, simulating the viscoplastic zone, and determining appropriate production settings.

5 CONCLUSION

The purpose of this work was to better understand the impact of shoulder gap on weld formation. Implications of shoulder interference are:

(a) Unstable force occurs because of minimum contact between shoulder and substrate hence material stirring is not efficient. Forces are more stable at high shoulder interference.

(b) Higher force and temperature are generated for higher interference, along with greater rind flash formation.

(c) Assembly tolerances and restraints used in BFSW need to be such that the parts are firmly held together, otherwise slip-stick behaviours result.

(d) Of the interferences examined here, the intermediate case (3.75% interference) is recommended, though the weld quality is improved by the provision of additional tool features such as flats.

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