Friction Stir Welding Laboratory

Casting Forming and Welding Lab (ME39007)

Experiment No. 4: Friction Stir Welding

Objectives:

- To perform friction stir welding (FSW) on two similar aluminum sheets of same gauge by varying the FSW tool rotational and worktable translational speeds.
- To analyse the influence of spindle tilt on surface defect (like amount of flash formation, weld root defects, etc.) by visual examination.
- To study the influence of FSW tool rotational and worktable translation speed (i.e. welding speed), on welding force (F_x), axial force (F_z) and power consumption.

Instruments required:

- Numerically controlled FSW machine having load cell attached to it (to measure force and torque during welding),
- Fixture for clamping the workpiece on the machine table,
- Al sheets of dimensions ($100 \times 50 \times 2.5$ mm^3),
- FSW tool (having flat shoulder surface and straight circular pin),
- Few others necessary equipments for tightening and loosing the desired nuts and bolts.

Hurdles in Welding Aluminum:

- Difference of hydrogen solubility in liquid and solid state of aluminium alloy, leads to hydrogen trapping inside the weld and formation of defects like blow holes, porosity etc.
- Formation of aluminium oxide on exposed surface, which is non-conductive, hard and has high melting point (approx 1900°C).
- High thermal conductivity as compared to steel, which causes rapid heat distribution due to conduction within the material
- High thermal expansion (almost twice of steel) and high shrinkage volume (approx 6% of volume) increases distortion and weld crater size.

Though various techniques like MIG, TIG, rotary friction welding is used for welding aluminum alloy but none of them could provide high weld strength required for aerospace or marine industries due to high Heat affect zone (HAZ), distortion etc. To achieve high weld strength friction stir welding was developed at The Welding Institute (TWI), UK in 1991 [1].

Theory of FSW

In friction stir welding a rotating non-consumable tool with specially designed shoulder and pin is plunged on the abutting edge of firmly clamped work piece than traversed along the weld line to form a weld and finally plunge out from the work-piece (as shown in Fig. 1). Tool serves two purposes, firstly softening of material by heat generation through friction and plastic deformation, and secondly mixing of material by pin stirring to form weld.
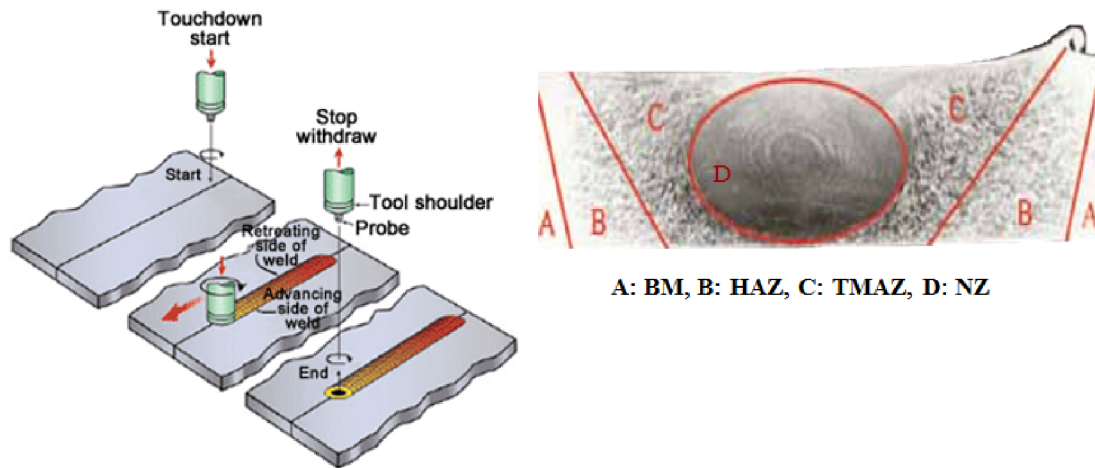
Fig. 1 Basic steps involved in a FSW (left side), and various micro-structural zones in a typical FSW cross-section (right side); [2]

The side of the workpiece where the tool rotation and tool translation vectors are same, is called advancing side (AS); and the side where the tool rotation and translation vectors remain opposite is called retreating side (RS). Furthermore, a typical friction stir welding cross-section consists of four micro-structural zones; namely stirred zone or nugget zone (NZ), thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and unaffected or base metal zone (BM). Threadgill [2] gave the nomenclature to different FSW zones. The stirred zone is the region where the work-piece material gets stirred due to influence of both rotary shoulder and pin. Obviously, materials at this zone remain subjected to high strain, high strain rate and higher temperature (due to heating by both friction and large plastic deformation). TMAZ is subjected to heat and some inertia of the materials from the NZ (which causes grain orientation) and material in HAZ is subjected to heat. Temperature in HAZ is less as compared to HAZ of fusion welding. After HAZ the region which remains unaffected is called base metal.

Mechanics of material flow:

Nature of material flow during FSW is extreme complex and very difficult to clearly understood. However, most of the researchers agreed that the material flows from the leading edge of the tool to the trailing edge through retreating side (RS); and at last, centrifugally forged into the advancing side (AS). They justify this concept by reporting that, whenever there occurs some significant material loss (either by excessive flash or by some other means) the total amount of material required to be forged in the AS finds lacking; and hence, defects like groove and tunnel formation always takes place only in the AS.

Mechanism of heat generation and stabilization during FSW:

The mechanical work-done by the FSW tool on the work-piece (both by the frictional rubbing and materials stirring) gets converted into heat; according to law of conservation of energy. This heat generation raises the work-piece temperature. With increase in work-piece temperature, the yield strength of the material decreases. Therefore, less work is required for further plasticizing of material and rate of heat generation decreases. This results in decrease in temperature; and hence, this mechanism stabilizes the temperature during FSW and avoids melting of the material.

Mechanics of defect formation:

Surface flash, root flaws and worm holes are the defects which occur most often in FSW; however, few other defects like surface galling, nugget collapse, kissing bond etc. are also occur time to time. Appendix-II provides detail on these defects. In general, as the FSW tool is plunged into the material; a key hole is formed, and work-piece material starts stirring around it. When, the tool starts to travel along the

welding line; the hot plasticized stirring material is forged into the key hole generated due to pin travel. Thus, improper choice of FSW parameters and/or lack of axial pressure (beneath of the FSW tool shoulder) leads to defect formation. Zhang et al. [3] proposed a mathematical model and formulated a relation among axial pressure, tool rotational speed and work-table translational speed, in order to get a defect free weld. The relation is given below, (for complete derivation of the relation, please see the appendix-II).

$$P * r_{rate} \geq \frac{V}{k\left(r_{shoulder} - r_{pin}\right)}$$

Where, P is the axial pressure, r_{rate} is the inverse of welding rate, V is the volume of the key hole, k is a constant depends on the material properties and weld temperature, $r_{shoulder}$ and r_{pin} represent radius of tool shoulder and pin, respectively. According to this relation for a particular FSW tool, the weld speed must be less than a specific value, when the axial pressure and tool rotational speed are kept constant; and/or if welding speed is kept constant, then the axial pressure and tool rotational speed must be larger than a specific value, in order to achieve a defect free weld.

Experimental procedure:

1. Switch on the MCB switch (electric input to the machine), On/Off switch on the machine body at the left side and start the computer monitor attached with the machine.
2. Then, double click on the 'stir welding' icon on the desktop in order to start the software. Once the software gets started; it will ask for pressing hydraulic knob for switching it on, and then for spindle home.
3. Fix the FSW tool into the spindle through proper dimension of collet, and then tight the adapter nut using semicircle spanner.
4. Place the work-piece on the anvil of machine work-table. Make sure the sheets are being placed in such a manner that the joining line is parallel to the machine X-axis, and then clamp the work-piece using bolts.
5. Once it will be done, choose the 'manual mode' option from the available options. Insert suitable values for work-table movement, and move the work-table against fixed FSW tool for obtaining the X_{start}, X_{end} and $Z_{end\ position}$ values. Here, X_{start}, X_{end} denotes start and end point of welding on the work-piece clamped, and $Z_{end\ position}$ denotes the point up to which the FSW tool will reach during plunging.
6. Come out from the 'manual mode' and then go to the 'parameter' for specifying the parameters for weld to be conducted. If required change the spindle tilt angle.
7. After specifying the parameters go to the 'auto mode' and click on icon 'continue', to start the weld. But, before pressing 'cycle on' switch, make sure that the coolant pump for spindle is switched on.

8. After finishing of the weld, switch off the coolant pump, and hydraulic knob.

Fig. 2 Work-piece with process parameter details
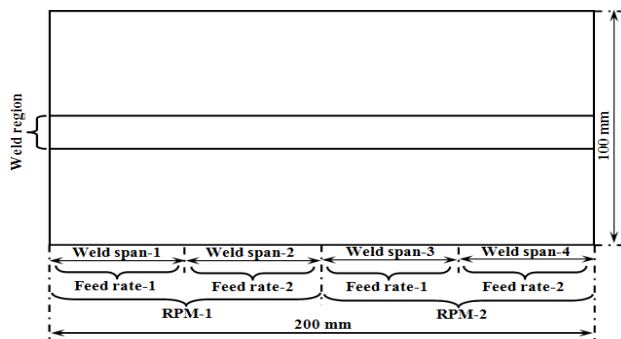
Work-piece dimension (length × width, mm²)	
Tool shoulder diameter (mm)	
Tool pin profile	
Tool pin diameter (mm)	
Tool pin height (mm)	
Work-piece sheet thickness (mm)	
Plunge depth (mm)	

Table1 Work-piece and tool dimensions

OBSERVATION TABLE

Sr. No.	Tool rotational speed (rpm)	Welding speed (mm/min)	Average axial force F_z (N)	Average spindle torque (N-m)	Welding force F_x (N)
1.	Rpm1	Feed rate 1			
2		Feed rate 2			
3	Rpm 2	Feed rate 1			
4		Feed rate 2			

Table 2 Welding runs with corresponding parameters for the respective weld span

Results and Discussion:

Data of the experiment will be mailed to the student and they have to do the following

- Calculate average value of axial force, welding force and power (= spindle torque* tool rotational speed).
- Fill the observation table with respective values as calculated in above step
- Plot F_z, F_x and power with respect to rpm and feed rate. While plotting graph keep 1 parameter constant (say rpm) and vary other (say feed rate), so that effect of process parameters can be studied on forces and power. Total 3 graphs will be plotted. Sample graph is shown below. Interpret the result
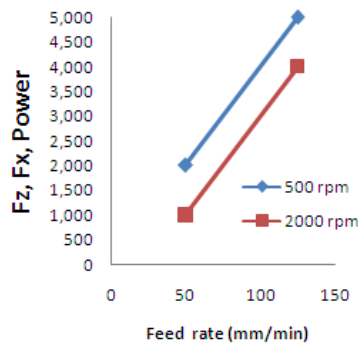
Fig. 3 Sample plot for output parameter versus process parameters

Conclusion:

Here, students have to write (very briefly) about the overall effect of spindle tilt and other varied parameters on weld defects (mainly surface flash and root flaws, by visual inspection), and on forces and power consumed during welding. Spindle tilt by 1° - 2° (depending upon the work-piece sheet thickness) may reduce the flash formation when compared to 0° spindle tilt case.

Precautions:

1. Before clamping the work-piece on the anvil the edges of the faying surfaces should be straight, so that there should not be any gap between faying surfaces; in order to achieve good weld.
2. The joining line should be parallel to the machine X-axis, and the anvil should be placed in such a position so that the FSW tool pin centre should not be off-set from the expected joining line.

3. When coming out from the manual mode, move the spindle up in the Z-axis; otherwise while selecting auto mode the spindle will directly move to the last Z-value the spindle had in the manual mode.
4. Before pressing the 'cycle on' knob in the monitor panel the work-piece should be rigidly clamped on the anvil, and the allen bolts (placed at the right bottom side of the anvil) must be tightened in order to prevent the vibration of anvil along Y-axis

Benefits of using FSW:

There are a number of benefits of using FSW [4]; however, only few important benefits are addressed here.

1. No distortion of the work-piece takes place; since the process occurs at the solid state. Also, better dimensional accuracy, better surface finish, and less softening at the HAZ are achieved; which results in better weld strength.
2. Due to continuous dynamic recrystallization, fine equiaxed grains are developed in the stirred region, which further improves the mechanical and metallurgical properties of the weld.
3. Since no consumable is used, so the weld composition remain same as the base metal; hence, problems associated with the compositional change remain completely absent here.
4. Since no fumes and no harmful rays are generated, and also no shielding gas is required; so the process is environment as well as operator friendly.
5. The process is energy efficient, because relatively less energy is required in FSW when compared to other welding processes (like laser, plasma and electron beam welding).
6. It reduces the fuel consumption, because the process is widely being used in aerospace, automotive, shipbuilding and marine industries to fabricate less weight component, which reduce the fuel consumption.
7. Very good scope for repeatability, as the process is easy to automate.

Limitations of FSW:

1. At the end of welding a pin hole remains present in the region where the tool is plunge out. This leads to some amount of material loss.
2. Significant thinning takes place at the weld region due to formation of ribbon flash.
3. The process requires adequate reaction force from the bottom side for producing sound weld; so, use of backing plate is must.
4. Sufficient clamping force is also required in order to oppose the abutting force. Because of that completely elimination of residual stress is still difficult.

Applications of FSW:

There are a number of fields where friction stir welding is being utilized for fabrication of various parts [5]. However, few main areas are listed below.

Aerospace industry

1. Wings, fuselages
2. Cryogenic fuel tanks for space vehicles
3. Aviation fuel tanks
4. Repair of faulty MIG welds

Railway industry

1. Rolling stock of railways, underground carriages, trams

2. Railway tankers and goods wagons

Automotive industries
1. Engine and chassis cradles, Body-in-white structure, Tailor welded blanks
2. Wheel rims
3. Truck bodies, Tail lifts for lorries, Armour plate vehicles
4. Fuel tankers

Shipbuilding and marine Industries
1. Panels for decks, sides, bulkheads and floors
2. Boat sections
3. Helicopter landing platforms
4. Marine structures

Construction industries
1. Aluminium bridge
2. Window frames
3. Aluminium pipelines
4. Heat exchangers and air conditioners, using Friction Stir Channelling

Electrical industries:

1. Electric motor housings
2. Bush bars
3. Electrical connectors

Electronics industries:

1. Apple next generation iMac [6]

Questions:

Q1. What is the significance of plunge force or axial force in FSW?
Q2. How does the temperature stabilization occur in FSW?
Q3. What is the role of welding speed on defect formation in FSW?
Q4. Why does the weld power increases with increase in tool rotational speed?
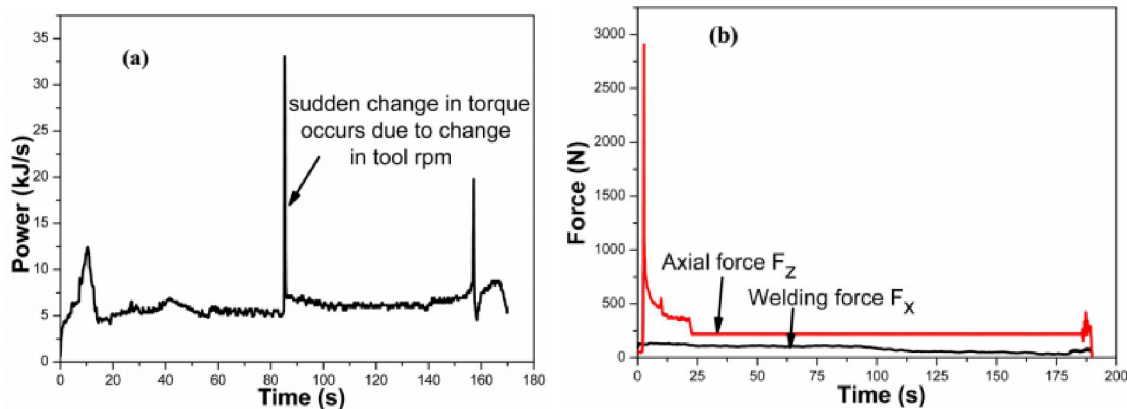
Samples of plot obtained from FSW

Fig. 3 (a) Variation of power versus time   (b) Variation of forces versus time

References:

[1]   W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, S. P. Temple, and C. J. Dawes, "Friction stir butt welding," PCT/GB92/022031991.

[2]   H. Jin, C. Ko, S. Saimoto, and P. L. Threadgill, "Microstructure of Friction Stir Welded Joints in AA5182," Mater. Sci. Forum, vol. 331–337, pp. 1725–1730, 2000.

[3]   H. Zhang, S. B. Lin, L. Wu, J. C. Feng, and S. L. Ma, "Defects formation procedure and mathematic model for defect free friction stir welding of magnesium alloy," Mater. Des., vol. 27, no. 9, pp. 805–809, 2006.

[4]   R. S. Mishra and Z. Y. Ma, "Friction stir welding and processing," Mater. Sci. Eng. R Reports, vol. 50, no. 1–2, pp. 1–78, 2005.

[5]   R. Nandan, T. Debroy, and H. Bhadeshia, "Recent advances in friction-stir welding – Process, weldment structure and properties," Prog. Mater. Sci., vol. 53, no. 6, pp. 980–1023, Aug. 2008.

[6]   Apple, "Website addresses," 2013. [Online]. Available: https://www.apple.com/in/imac/design/.

Appendix-I
Parameters affecting Friction Stir Weld

Simply knowing physics of the process and mechanics of weld formation are not enough; but, the proper understanding of effects of various parameters affecting FSW process, and various defects occurs in a FSW, their causes and remedies are also essential in order to produce good quality welds. Here (in appendix-I) a little explore is being given on those various influencing parameters. Causes and remedies of various FSW defects will be explored in the next appendix.

There are a number of parameters which affect the FSW process. Broadly they can be classified as design parameters, process parameters and material parameters. These are tabulated in Table-A1.

Table A1 Various parameters affecting FSW

Process parameters	Design parameters	Material parameters
Tool rotational speed	Tool shoulder shape and size	Workpiece material
Worktable translational speed	Tool pin shape and size	Anvil material
Tool tilt angle (towards the trailing edge)	Joint geometry	Tool material
Plunge depth		

Effect of process parameters:

Each parameters do not find direct relationship with all the output characteristic, rather have influence on only few characteristic; like tool rotational speed has direct influence on tool torque, but has indirect influence on the welding force and axial force. Similarly, welding speed has direct influence on the welding force, but has indirect influence on the axial force; whereas, plunge depth finds direct influence on the axial force and indirect influence on the welding force. Further, if the tool is tilted towards the trailing edge; then some part at the leading edge of the tool does not keep contact with the work-piece. As a result, reduction in flash formation takes place. This also influence the heat generation, and prevent excessive softening at the HAZ.

Effect of design parameters:

Tool shoulder diameter, its shape (either flat with scrolled, or concave), and tool pin profile also influence the weld quality up to great extent. Tool shoulder diameter has direct relationship with the axial force, and tool pin profile has direct relationship with the welding force. Also, increase in the shoulder diameter reduces the flash formation (up to some extent) without tilting the spindle. A constant ratio (2.5 – 3) of tool shoulder diameter to the pin diameter produces good weld.

Effect of material parameters:

        Tool material, anvil material and few other environmental conditions decide the rate of heat dissipation. Use of a good heat conductive material for anvil, makes the welding of some alloys (titanium and its alloys) easier; whereas for welding of aluminum and copper alloys, use of low heat conductive materials for anvil reduces the unnecessary heat loss during welding, and improves the weld quality.

Appendix-II
Friction Stir Welding Defects

As it has been seen, that the whole FSW process is carried out by the machine itself with least human intervention; so defect free weld is quite obvious. However, it has already been mentioned in the previous section that distinct property of work-piece material and wrongly chosen parameters can lead to defect formation. Hence, deciding suitable parameters (e.g. designing of FSW tool shoulder and pin, selection of tool rpm, worktable feed and plunge force etc.) for a particular work-piece material is a rigorous task. Proper understanding of various FSW defects (their causes and remedies) can make this rigorous task a little simpler. That`s why, here an attempt has been made to classify various FSW defects, and then, on their causes and remedies.

There could be different perspective to classify various FSW defects. One perspective could be based on the geometrical shape of the defect, like point, line or volume defect. Another perspective could be based on the location of the defects; like surface defects, and internal defects. Similarly one more perspective could be based on few certain conditions in which few specific kinds of defects are formed; like defects from, either too cold weld condition or too hot weld condition, and defects due to fault in designing of tool and/or fixture etc. Here, the defects are being classified (Table-A2) considering the latter perspective.

Table A2 Classification of various FSW defects

Defects due to too cold condition	Defects due to too hot condition	Defects due to fault in design
Lack of fill	Ribbon flash	Lack of penetration
Lack of fusion (kissing bond)	Nugget collapse	Excessive indentation
Wormhole	Surface galling	Oxide entrapment
	Root flaws	

Lack of fill:

This defect is observed just like a wide crack at the advancing side (shown in Fig. A1a). It is caused due to insufficient forging action. It can be avoided by either increasing the plunge force or by tilting the spindle towards the trailing edge of the tool.
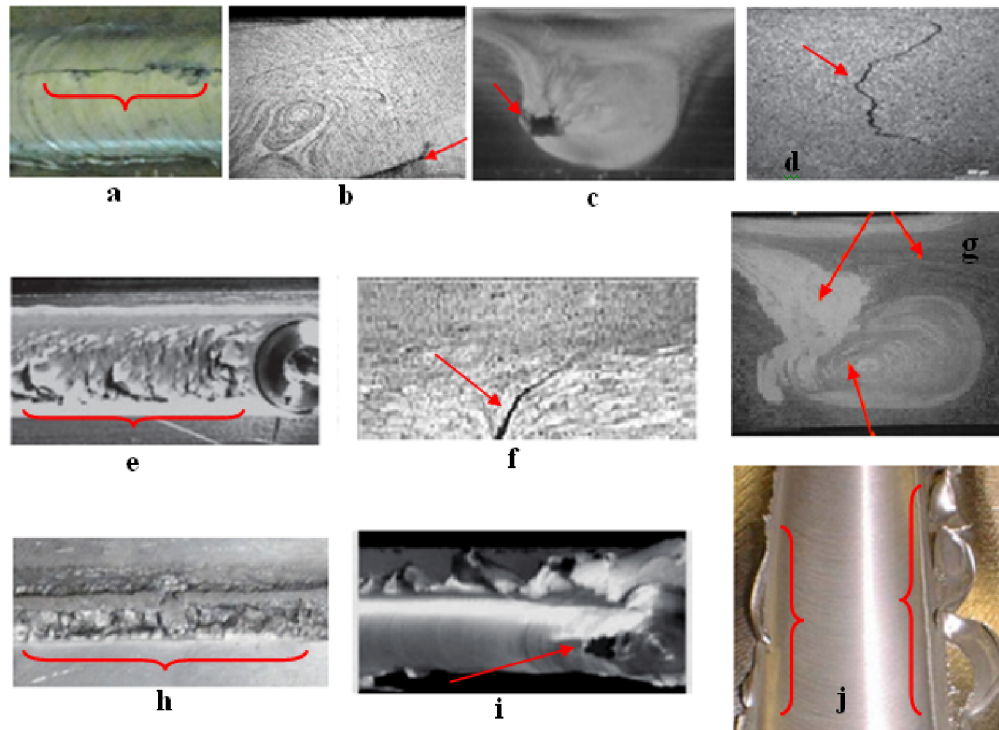
Lack of fusion:

It occurs due to insufficient weld temperature. It is also called 'kissing bond' (shown in Fig. A1b). It can be avoided by either increasing the tool rpm or by doing some modification in the pin profile.

Wormhole:

It occurs due to either insufficient material to be filled into the cavity at the AS, or due to too high welding speed (shown in Fig. A1c). It can be avoided by either applying sufficient plunge force on the tool shoulder or by decreasing the welding speed.

Ribbon flash:

It occurs either due to relatively large plunge force and/or due to mismatch in the work-piece sheet thickness (shown in Fig. A1j). Sometimes if the sheet thicknesses are same; yet, slight flash formation takes place only at the RS. If it is so, then it can be avoided by tilting the spindle towards the trailing edge of the tool.

(Note: All the figures are only for representation of defects, and are not to scale)

Fig. A1 Various FSW defects; (a) Lack of fill, (b) Lack of fusion, (c) Wormhole, (d) Oxide entrapment, (e) Surface galling, (f) Lack of penetration, (g) Nugget collapse, (h) Root flaws, (i) Excessive indentation, (j) Ribbon flash.

Nugget collapse:

It occurs due to too high tool rotational speed (shown in Fig. A1g). It can be avoided by reducing the tool rotational speed.

Surface galling:

It occurs due to sticking of the work-piece material with the tool shoulder and pin surfaces (Shown in Fig. A1e). Generally, few work-piece materials (like aluminum and few others) easily attain the temperature where sticking starts to occur. It can be avoided by regulating parameters which affect the rate of heat generation and dissipation.

Root flaws:

It occurs due to sticking of the workpiece material on the backing plate or anvil (shown in Fig A1h). This condition happens, when the pin height remains slightly larger than the desired limit. It can be avoided by reducing the tool pin height to the desired limit.

Lack of penetration:

It can be seen from Fig. A1f. It occurs due to slightly smaller pin length. It can be avoided by increasing the tool pin length to the desired limit.

Excessive indentation:

It is shown in Fig. A1i. Sometimes operator gives relatively larger plunge force in order to avoid the defect occurs from lack of penetration, without increasing the pin length. It results in excessive flash formation (also called excessive indentation). It can be avoided by reducing the plunge force.

Oxide entrapment:

This occurs due to presence of oxides on faying surfaces. Hence, when the sheets are welded without removing the oxides; it got entrapped into the weld zone, and appears as a zigzag line (shown in Fig. A1d), when micro-structural analysis is done. In order to prevent this defect to occur, the oxides layers should be removed from the faying surfaces before welding.

A mathematical model for defect free welds:
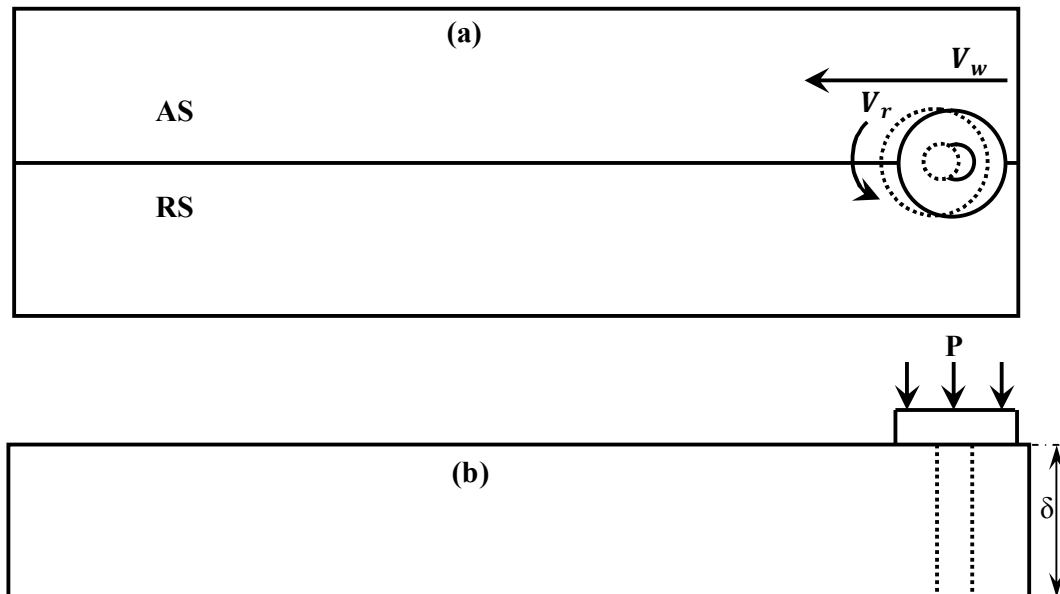
Fig. A2 (a) Creation of cavity due to pin travel (top view), (b) FSW tool subjected to plunge force (side view)

As already mentioned that; when FSW tool is inserted into the workpiece, a pin hole is formed, and when the tool starts to translate along the joining line the material stirring around the pin hole (i.e. around the tool pin) is centrifugally forged into the cavity created due to pin translation. So, the FSW process can be considered as the micro-hole formation and filling process (as shown in the Fig. A2) [3].

Let us consider that;

v_w = Welding speed

v_r = Tool rotational speed

P = Welding pressure

l = Welding tool linear movement per revolution

δ = Workpiece sheet thickness

$r_{shoulder}$ = Radius of tool shoulder

r_{pin} = Radius of tool pin

v_{rate} = Welding rate

r_{rate} = Inverse of the welding rate

V = Volume of the micro hole created due to pin travel per revolution

S = Volume of the materials centrifugally forged into the hole per second

t = Time that the shoulder play effect on the microhole

Now, for a constant welding pressure P and constant tool rotation speed V_r; the time for which the shoulder play effect on the micro-hole would be,

$$t = \frac{r_{shoulder}}{v_w} \qquad (1)$$

If the micro-hole gets completely filled, then the fill metal must be equal to the volume of the micro-hole. If the time of filling of metal into the micro-hole is t_1, then

$$V = St_1$$

$$\Rightarrow t_1 = \frac{V}{S} \qquad (2)$$

Obviously, the time for which the shoulder play effect on the micro-hole should be greater than the time for filling the hole, in order to avoid any void or hole to remain present. Hence,

$$t \geq t_1 \tag{3}$$

Now, combining Eqs. (1) and (2), gives the following equation.

$$\frac{r_{shoulder}}{v_w} \geq \frac{V}{S} \tag{4}$$

The volume of the material centrifugally forged into the micro-hole per second depends upon the tool rotational speed, if the other parameters are kept constant. So,

$$S \propto v_r$$

Similarly, the frictional force under the shoulder will increase with the increase in the welding pressure (i.e. vertical force on the FSW tool). According to the momentum theory $m(v - v_0) = Ft$; so the forging speed (i.e. speed with which the material is being centrifugally forged into the micro-hole) will also increase with the FSW tool axial force. Hence;

$$S \propto P$$

The above relationship between S and the welding pressure P, and the rotational speed v_r can be combinly written as;

$$S = kPv_r \tag{5}$$

In the above equation, k is the proportionality constant, and it depends upon the material properties and the welding temperature.

$$\frac{Pv_r}{v_w} \geq \frac{V}{kr_{shoulder}}$$

$$\Rightarrow P \cdot r_{rate} \geq \frac{V}{kr_{shoulder}} \tag{6}$$

Now, if the tool pin size is also considered, then the Eq. (6) can be modified as;

$$P \cdot r_{rate} \geq \frac{V}{k(r_{shoulder} - r_{pin})} \tag{7}$$

For a particular FSW tool and work-piece material Eq. (7) can further be simplified as;

$$P \cdot r_{rate} \geq \alpha \tag{8}$$

Where, α would be constant for a particular FSW tool and work-piece material combination. Thus, if the welding pressure and the tool rotational speed are kept constant, then the welding speed must be less than a specific value, and/or if the welding speed is kept constant, then the welding pressure and tool rotational speed must be larger than a specific value; in order to avoid any voids. Hence, these three welding parameters are dependent on each other, if rest other parameters are kept fixed.