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A REVIEW OF MECHANICAL AND THERMAL MODELLING OF FRICTION STIR WELDING

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ABSTRACT

Friction Stir Welding (FSW) is a type of solid-state joining process that involves joining of metals without fusion or filler materials. The frictional heat is produced by a rapid rotating non-consumable high strength tool pin that extends from a cylindrical shoulder. FSW has been widely applied to join aluminum alloy, titanium alloy and other materials which are difficult to weld by fusion welding. FSW is a solid-state joining process that creates high-quality, high-strength joints with low distortion and is capable of fabricating either butt or lap joints, in a wide range of material thicknesses and lengths .Thus accurate and better understanding of the materials flow and temperature distribution during the process. However numerical simulations are challenging due to numerous complexity involved in FSW. For this experimental and simulation analysis thermocouple was used for continuous temperature measurement along transverse direction of butt joint. The converted milling machine was used for frictions stir welding process. So that heat affected zone, fusion zone and thermally affected zone identified through microscopic technique.

Keywords: *FSW, pin shoulder, diameter, thermal modelling, rpm and microstructure.*

I. INTRODUCTION

Friction Stir Welding (FSW) is most widely used to join the aluminum alloy, titanium alloy and other materials which are difficult to weld by fusion welding. During friction stir welding the frictional heat is produced by a rapid rotating non-consumable high strength tool pin that used in the form of cylindrical shoulder. In this paper using a stationary rapid rotating non-consumable high strength cylindrical shoulder pin, but work pieces moves along a transverse direction. Thomas et al. [1] was purposed a friction stir welding is a types of solid states welding in 1991 at the welding institute, UK, Has revolution the joining of high strength hard enable Al alloys such as 7XXX and 2XXX series, because of low joint efficiency. A friction heat is produced by relative movement between stationary rotating high strength cylindrical shoulder pin and transverse movement of workpiece.

In traditional method more difficult to weld because aluminum is an active metal and it reacts with oxygen in the air to produce a thin hard film of aluminum oxide on the surface. The melting point of aluminum oxide is approximately 1926˚, which is almost three times the melting point of pure aluminum, 660˚. Welding defects occurs such as cracks, porosity, voids and inclusions during fusion welding. In this welding process affect the quality and mechanical properties of welds. Additional, distortions in final finished products is also reduced due to decreased in the residual stress to reduce the heat flux.

Applications of the friction stir welding process range from aerospace, automotive, marine, rails and various other structural components. In friction stir welding a non-consumable cylindrical shoulder rotating pin, the force applied vertically downward direction. The friction between the tool and work pieces increase with increased in temperature at this weld region and work pieces is gets practically deformed easily.

By camilleri et al.[2](2005,2006) give the concept of longitudinal contraction stress and transverse contraction angular to replace the thermal elastic and plastics stage of the work piece, Decreased the welding stress by using analytical model. In friction stir welding phase transformation are ignored in aluminum alloy materials. The thermal analysis occurs due to heat generated by friction between non- consumable cylindrical shoulder pin and work pieces.

II. PRINCIPLES OF FRICTION STIR WELDING

The solid states welding processes is carried out in room temperature as well as in elevated temperature without melting the work pieces. In the solid states welding process provides better quality of welding, and consist the strength and cohesion of metals. A defect-free crystal fails by a cleavage along a crystallographic plane where, the inter atomic force is the weakest. The two new surfaces produced, and surface energy is defined as the work done. The strength of crystal (σ_c) occurs in the following forms

$$\sigma_c = \left(\frac{E\,\gamma}{d}\right)^{\frac{1}{2}} \qquad (1)$$

Where E is the young modulus of elasticity of the material and d is the lattice spacing in cleavage plane. However, in brittle solid, the failure takes places by the extrusion of the cracks already present, and the bulk strength (σ_b) is occurs following

$$\sigma_b = \left(\frac{E\,\gamma}{L}\right)^{\frac{1}{2}} \qquad (2)$$

Where (L>>d) is the length of crack. The failure occurs in polycrystalline ductile, material is due to movement of dislocations and get, result in plastic instability and stress takes much lower than the equation (1).

The bulk strength of a material is much lower than the bonding forces of the constituent atoms. So, a good welding does not require to, achieves a strength equal to that between the adjacent lattice planes. Moreover, it should be remembered that at the room temperatures, that is with negligible creep, even a plane of lattice is not weaker then the bulk material.

III. DESIGN OF CYLINDRICAL SHOULDER PINS

A specially designed non-consumable cylindrical tool is rotated and stationary about an axis, to process the required location within a sheet or plates. Tool has small diameter pin with concentric large diameter cylindrical shoulder. Tool shoulder and length of entry control the penetration depth. When the shoulder contacts the metal surface, its rotation creates additional frictional heat and plasticizes a large cylindrical metal column around the inserted pin. The shoulder additionally provides a forging force that contains the upward metal flow caused by the tool pin.

Following types of non-consumable cylindrical shoulder pins used in friction stir welding shown in figure 1.

1. Straight cylindrical
2. Taper cylindrical
3. Threaded cylindrical
4. Square cylindrical
5. Triangular cylindrical

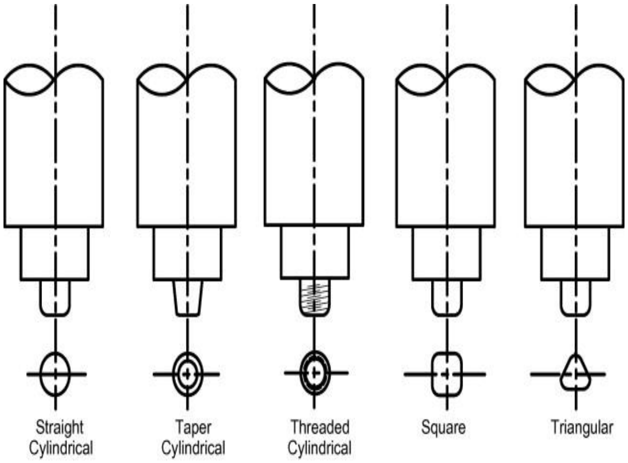

Figure 1 indicates types of cylindrical shoulder pins (S.Emamian et.al.)

IV. WELDING STRESS MODELING FOR FRICTION STIR WELDING

Welding stress induced during friction between cylindrical shoulder pin and work piece, and heat generated occurs near the welding zones. First of all temperature distribution occurs in welding process. Then induced welding stress in, friction stir welding are solved. Also welding stress occurs during cooling process of weld pool. Taking cylindrical co-ordinates to solve this equations. The Cylindrical shoulder pin rotates along axial direction, these axial direction occurs alone Z-direction. The Motions of work piece occurs along radial direction. During the FSW of plates as the weld pool contracts on cooling, this contraction is resisted by rest of the plates have not melted. As such, a tensile stress is generated in the weld, and this is balanced by the compressive stress in the parent metal. Typical distribution of these, stress in a plate weld. This residual stress may result in cracking of brittle material and is not important as far as a ductile material is concerned.

V. RESIDUAL STRESS

Residual stress are those stress which exist in the body if all external load removed. They are called internal stresses. Residual stress, exist in body due to the non-uniform temperature distribution. The development of residual stress can be explained by considering heating and cooling under constraint. Taking all three bar initially at room temperature. The middle bar heated up, but thermal expansion is restrained by side bar. Consequently compressive stress induced in the middle bar, they are increase with increasing temperature until the yield stress in compression is reached. The yield stress represents the upper limit of stresses in a material, at which plastic deformation occurs. When the heating stop and middle bar is allowed to cool off, its thermal contraction is restrained by side bar. The compressive stress changed into the tensile stress, and increased with decreasing temperature until the yield stress in tension reached. The residual stress in the side bar are compressive stress and equal to one-half of the tensile stress in the middle bar. The figure 2 shown thermal stress induced in composite bar.

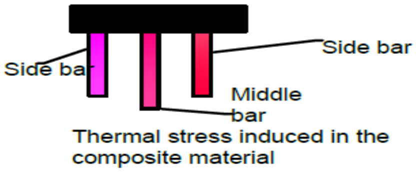

Figure 2 indicates thermal stress induced in composite bar (*Prof. SATISH C SHARMA*)

VI. METALLURGICAL CHANGES

In the friction stir welding process metallurgical change occurs during welding. These changes are due to the heating and cooling of the weld and heat affected zones of the parent materials. Such changes significantly affect the quality of the weld. The wide variety of changes that may takes places depend on various factors, for example

1. The nature of the material, that is single phase , two phase,
2. The nature of the heat treatment occurs if any
3. The nature of cold working.

Typical example of metallurgical changes.
Lets us example the fusion welding of two pieces of a single-phase material, which have been cold worked to yield a desired grain orientation. These cold worked working grains result in a high strength and low ductility. However, on fusion welding, a random grain growth again takes places within the welding zones ,the grains becomes coarse due to heat input (annealing), and a partial re-crystallization also occurs. The strength falls much below that of the parent material. With increasing distance from the melt boundary, the grains, becomes finer until the heat affected zones with elongated grains is reached.

Lets us now consider a two phase material which drives its strength within the melt boundary is again too low. But, in the immediately, adjacent heat affected zones, the thermal cycle results in heating and quenching followed by further aging. This aging process, recovery some of the strength. The material beyond, this zones is only due to heat of welding and become harder with loss of strength. During friction stir welding heating occurs during friction between non-consumable rotating cylinder shoulder pin and work pieces, and plastic deformation occurs in the work pieces. The heat is concentrates on the cylindrical shoulder pin due to combination of tool rotations and translating motion of work pieces. As a result joint is produced in the form of solid states, because of various geometrical features of the shoulder pins, the material movement around the cylindrical shoulder pin is to be study. During friction stir welding materials is undergoing a plastics deformation at a elevated temperature, resulting in fine and crystallized grains. In friction stir welding fine microstructure occurs, and gets good mechanical properties obtained, in the welding process occurs in three form (a) unaffected base metal (b) heat affected zones (HAZ) (c) thermo mechanically affected zones shown in figures 3. In this process material changes its behavior due to the rotating non-consumable tool. The work pieces changes its behavior affected by the friction stir welding cylindrical shoulder pin, dimensions of shoulder pin and parameter of welding process. Friction heat and plastically deformed work pieces during friction stir welding creates a fine grain and re-crystallized grains in the stir zones. And also elongated grains occurs in the thermo-mechanically affected zones. There is no difference in grain structure as compare to the base material. Figure 5 shown metallurgical change in the base metals. The softened HAZ region characterized by dissolution and strengthening occurs during friction stir welding. The heat affected zones occurs in the base material shown in figure 4 indicating thermal stress distribution in the weld metal, or a thermoplastics, which is not melted. In heat affected zones thermal diffusivity play great role. If the thermal diffusivity of the material is large, the material cooling rate is high and the heat affected zones is relatively small. If the thermal diffusivity is very low, material cooling rate is slow and the large heat affected zones occurs. The figure 5 indicating metallurgical phase change occurs during the solidification of weld work pieces.

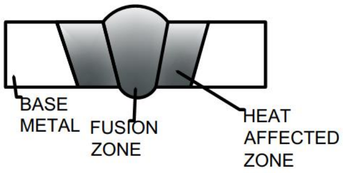

Figure 3 indicating heat affected zone (Mustafa Kemal Kulekct, mechanical properties of friction stir welding.)

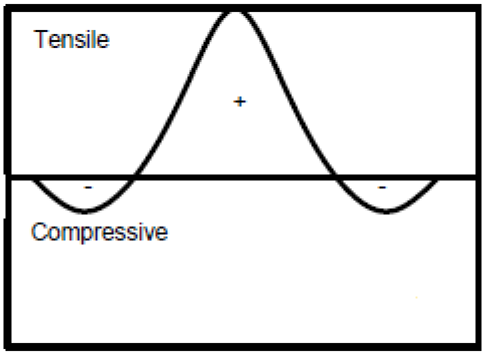

Figure 4 Thermal stress distribution in weld plates (Nurul Syahida Mohd Nasir et.al.).

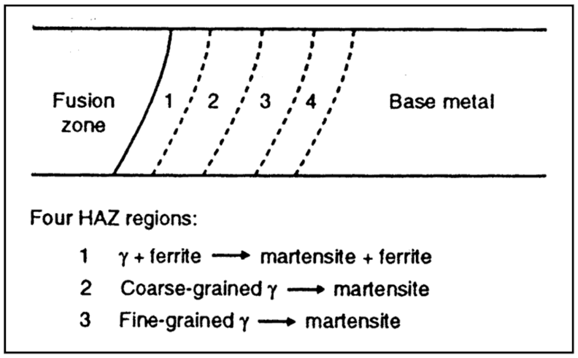

Figure 5 indicating metallurgical phase changes (T.V Rajan et.al.)

VII. TEMPERATURE DISTRIBUTION IN FRICTION STIR WELDING

According to Yaan (2010) Simiret al. (2006) consist of uniform temperature distribution in shoulder pin. Consider a cylindrical shoulder pin in which one dimensional radial heat conduction is taking places under steady heat conductions. The following equation taking from heat and mass transfer by Er. R.K. Rajput.

L = length of the shoulder pin

K = Thermal conductivity
q_g= Uniform heat generation per unit volume per unit time
h = Heat transfer coefficient
t_a = Ambient temperature

In order to obtain temperature distribution, consider an element of radius r and thickness.
Heat conduct in radius r

$$Q_r = -k.2\pi rL.\frac{dt}{dr}$$

Heat generated in the element

$$Q_g = q_g \times 2\pi r \cdot drL$$

Heat conducted out at radius, $r + dr$,

$$Q_{(r+dr)} = Q_r + \frac{d}{dr}(Q_r)dr$$

Under steady state conditions

$$Q_r + Q_g = Q_{(r+dr)} = Q_r + \frac{d}{dr}(Q_r)dr$$

$$Q_g = \frac{d}{dr}(Q_r)dr$$

$$Q_g \cdot 2\pi r \cdot dr \cdot L = \frac{d}{dr}[-k2\pi rL] \cdot dr$$

$$Or \quad \frac{d}{dr}\left[r \cdot \frac{dt}{dr}\right] = -\frac{q_g}{k \cdot r} \qquad (3)$$

Equation (3) is steady states one directional heat conduction in radial direction
Equation (3) on integrating we get

$$r \cdot \frac{dt}{dr} = -\frac{q_g}{k} \cdot \frac{r^2}{2} + c_1$$

$$\frac{dt}{dr} = -\frac{q_g}{k} \cdot \frac{r}{2} + \frac{c_1}{r} \qquad (4)$$

again integration we get

$$t = -\frac{q_g}{k} \cdot \frac{r^2}{4} + c_1 loge\, r + c_2 \qquad (5)$$

wherec_1 and c_2 = constant integration
The constant c_1 and $c_2$are evaluated from the boundary conditions as follows
At $r = R, \quad t = t_w$
Heat generated = Heat lost by conduction at cylindrical shoulder pins

$$Q_g(\pi R^2 2 \times L) = -k \times 2\pi RL \times \left[\frac{dt}{dr}\right] r = R$$

Also, at $r = 0, \ \left(\frac{dt}{dr}\right) = 0$

Since in case of a cylinder, center line is line of symmetry for temperature distribution and as such $\frac{dt}{dr}$ (temperature gradient) must be zero.

Temperature gradient $\left(\frac{dt}{dr}\right)$ at the surface (that is at r = R) is given by

$$\left[\frac{dt}{dr}\right]_{r=R} = -\frac{q_g}{k} \times \frac{R}{2} + \frac{c_1}{R}$$

Also from boundary condition , we have

$$\left[\frac{dt}{dr}\right]_{r=R} = -\frac{q_g}{k} \times \frac{R}{2}$$

$-\frac{q_g}{k} \times \frac{R}{2} + \frac{c_1}{R} = -\frac{q_g}{k} \times \frac{R}{2}$ or $c_1 = 0$

Applying boundary condition [r =R, t = t_w to equation (5) we obtain,

$$t_w = -\frac{q_g}{k}\times\frac{R}{4} + c_2$$

$$c_2 = t_w + \frac{q_g}{k}\times\frac{R}{4}$$

Substituting the values of c_1 *and* $c_2$in equation (5) we have the general solution for temperature distribution.

$$t = -\frac{q_g}{k}\times\frac{R}{4} + t_w + \frac{q_g}{k}\times\frac{R^2}{4}$$

t= $t_w + \frac{q_g}{4k}[R^2 - r^2]$ (6)

It is evident equation (6) that temperature distribution is parabolic and the maximum temperature occurs at center of the cylindrical shoulder pin (r = 0) and its value is given by

$$t_{max} = t_w + \frac{q_g}{4k}\times R^2 \qquad (7)$$

By combining equation (6) and equation (7), we arrive at the following dimensionless from of temperature distribution:

$$\frac{t - t_w}{t_{max} - t_w} = \frac{q_g\,[R^2 - r^2]}{4k\,\frac{q_g}{k}\times R^2} = R^2 - \frac{r^2}{R^2} = 1 - \left(\frac{r}{R}\right)^2$$

$$\frac{t - t_w}{t_{max} - t_w} = 1 - \left(\frac{r}{R}\right)^2 \qquad (8)$$

Also heat energy generated within the cylinder shoulder pin (per unit time) = heat energy dissipated (per unit time) by convection at the cylinder shoulder pin boundary that is

$$q_g \times (\pi R^2 \times L)) = h \times 2\pi RL(t_w - t_a)$$

$t_w = t_a + \frac{q_g}{2h}\times R$ (9)Inserting the values of $t_w$in equation (6) we obtain the temperature distribution (in) in terms of t$_a$ as

$$t = t_a + \frac{q_g}{2h}\times R + \frac{q_g}{4k}[R^2 - r^2] \qquad (10)$$

The value of t_{max}, at r = 0, is given by

$$t_{max} = t_a + \frac{q_g}{2h}\times R + \frac{q_g}{4k}R^2 \qquad (11)$$

This is required expression of temperature distribution in non-consumable rotating cylindrical shoulder pin.

VIII. DESIGN OF JOINTS

A welded joint is a permanent joint which is obtained by the fusion of the edges of the two parts to be joined together, with or without the applications of pressure and filler material. In the friction stir welding, friction heat produced between rotation of non-consumable cylindrical shoulder pins and work pieces. Mainly two types of welding joint used in friction stir welding process shown in figures 6.

Lap joint:- The lap joint or the fillet joint is obtained by overlapping the plates and the welding the edges of the plates. The cross-section of the fillet is approximately triangular. The fillet joint may be single transverse fillet, double transverse fillet and parallel fillet

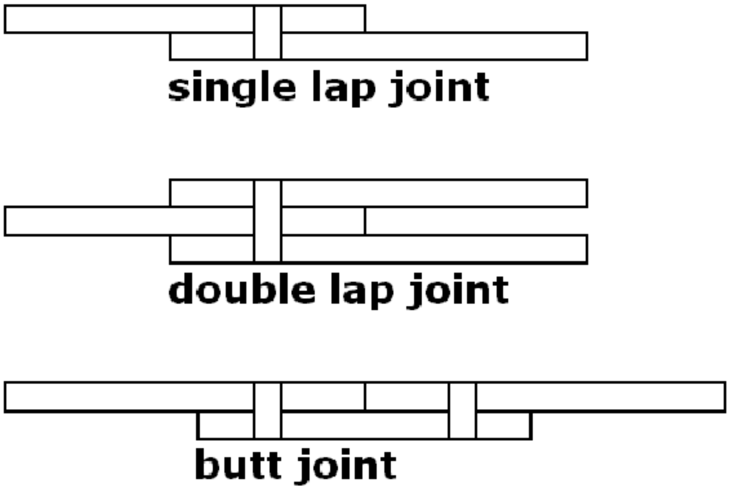

Figure 6 indicating types of joint (Galtieri Giovanna et.al)

Butt joint:- The butt joint is obtained by placing the plate’s edges shown in figure 7. In butt welds, the plate edges do not require beveling if the thickness of plate is less than 5 mm. On the other hand, if the plate thickness is 5 mm to 12.5 mm, the edges should be beveled to V or U groove on both sides. The main consideration involved in the selection of weld type are following.

(1) The shapes of the welded component required.
(2) The thickness of the plates to be welded and
(3) The direction of the forces applied.

Strength of butt joint:- The butt joint are designed for tension or compression. Consider a single V-butt joint. In case of butt joint, the length of leg or size of weld is equal to the throat thickness which is equal to thickness of plates. Tensile strength of the butt joint (single-V or square butt joint)

Figure 7 indicates butt joint (Syambabu Nutalpati et.al.)

$$P = t \times l \times \sigma_t$$

where l = length of weld. It is generally equal to the width of plate.
and tensile strength for double-V butt joint ig given by

$$P = (t_1 + t_2)\, l \times \sigma_t$$

Where t_1= throat thickness at the top, andt_2= throat thickness at the bottom.

It is consider that size of the weld should be greater than the thickness of the plate, but it may be less.

The stress in welded joint are difficult to determine because of the variable and predictable parameter like homogeneity of the weld metal, thermal stress in the welds, changes of physical properties due to high rate of cooling etc. The stress are obtained on following assumptions:

(1) The load is distributed uniformly along the entire length of the weld and,
(2) The stress is spread uniformly over its effective section.

IX. ANALYSIS OF RESIDUAL STRESS INDUCED IN BUTT JOINT

According to Masubuchi and Martin, the distribution of residual stress occurs in butt joint.
The distribution of the longitudinal residual stress σ_x can be approximated by equation.

$$\sigma_{x(y)} = \sigma_m \left(1-\left(\frac{y}{b}\right)^2\right) exp\left[-\frac{1}{2}\left(\frac{y}{b}\right)^2\right]$$

$Where\ \sigma_m$ is the maximum residual stress, which is usually as high as the yield strength of the weld metal. The parameter b is the width of the tension zone of σ_x.

X. TENSILE TEST

Tensile test occurs on the welding material to determine the mechanical properties shown in figure 8. The tensile test most widely used to determine the strength of materials. The parameters which explain the stress strain curve obtained during the tension test , ultimate tensile strength, yield strength , modulus of elasticity and toughness. Ultimate tensile strength increasing with rotational speed and decreasing with transverse feed. The strength mainly depends upon the heat generated during friction stir welding and heat produced by rotational speed, feed and plunge force.

XI. CONCLUSION

In the friction stir welding tensile strength depend upon rotational speed. The tensile strength increasing with increased rotational speed and decreasing with increasing transverse feed because frictional heat, depend upon the rotational speed of tool. For low transverse feed heat will not transfer rapidly along the weld line but low feed helps in better strength. For larger shoulder diameter generated frictional heat will not concentrate near the weld line.

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