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Analysis of Heat Generation, Hardness Distribution and Tensile Strength of Friction Plug Welding

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***Abstract*—**The Friction plug welding (FPW), is a kind of process to join the two dissimilar/similar materials and no external heat is applied or no molten state involved. As no melting occurs, friction welding is not a kind of fusion welding process, but more than a counterfeit welding technique. The joint efficiency may be increased by interpolating heat source or pre-heating at the workpiece surface. The generation of heat flux at the mean surface is calculated by friction during the materials to consider the friction co-efficient. By changing the diameter of the plug, the land width can be changed to get an impact on the temperature profile. Mathematical and Analytical modeling has computed the impact of pre-heating. The temperature distribution values during the workpiece were computed for various plug diameters with various pre-heating temperature values from 250ºC-550ºC.

***Keywords*—** Friction plug welding, Heat, Friction, Temperature.

I. Introduction

Friction welding is one of such machining processes where heat generation due to friction between the two parts which are being welded. This process is now being used throughout the world as a reliable and automated welding [1] process in industries.

Friction welding is a kind of joining process that generates adjustment of materials under compressive force contact of workpieces, which is rotating relative to each other to generate heat and plastically displace material from rubbing down surfaces do not melt. [2] Filter metal and flux are not needed with this procedure.

Friction Stir Welding, a solid-state procedure is being applied to weld aluminum alloys of a different kind that were arduous to weld. Because of re-solidification and non-melting of metal, distortion is less and welding is porousness free. A non-damperable, rotating tool is kept into the surface with the plates to be welded.[3] Tool movement in direction of welding surface [9], heat is generated and less than the solidus temperature; the welding joints are built up. When shoulder comes into contact with the surface of plates, the temperature increases due to the heat produced and the pin of the shoulder stirs in the joining surface allowing the flowing of the material backside of the pin. As the tool passes the metal cools and a processed zone is produced. A tool made of a harder material than the plates to be joined is used. Presently use of FSW process is used to join materials with high temperatures, as the harder tools are being developed.

The process of Friction plug welding (FWP), is a kind of welding in which initially faulty weld stuff is changed by the plug, that is friction welding into its original place. The basic principle is illustrated in figure 1.

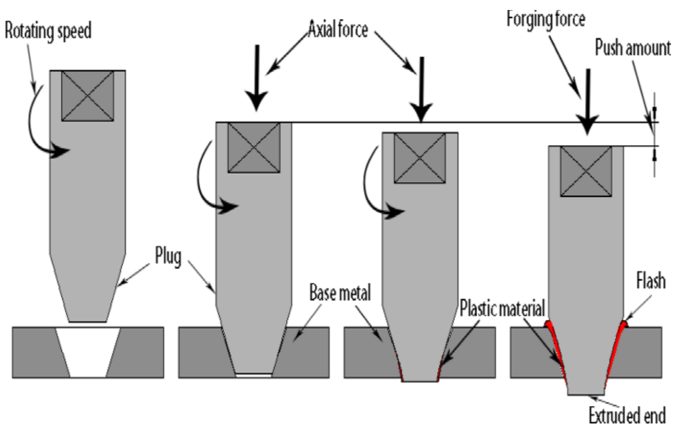

Figure 1: Schematic diagram of the FPW process

The FPW key process is as follows: first of all, a hole is produced into desired geometry parameters at the stand whence interested. Second, an expeditiously rotating plug is exerted into the hole underneath the action of axial force and interface between the hole and plug quick frictional heating and defacement, that is probably called the welding phase. Forthcoming, the plug rotation is suddenly stopped and a molding force is applied on weld surface when the hole is stuffy, hence create FPW weld. In the end, extract the plug and quern surface plain.

The FPW is used for repairing weld defects under the background of friction stir welding (FSW). As compared to other welding technologies, the FPW exhibits better performance to weld aluminum alloys. The defect can be repaired with better joint strength, low stress and smaller distortion. Friction plug welding (FPW) is a solid-state welding procedure by which a rounded plug is spinning, with a force applied, to fill the hole.

The use of a friction plug welding process is one of the proposed methods used to repair the defects that might occur during the friction stir welding process. Figure 2 shows a schematic view of the friction plug weld process.

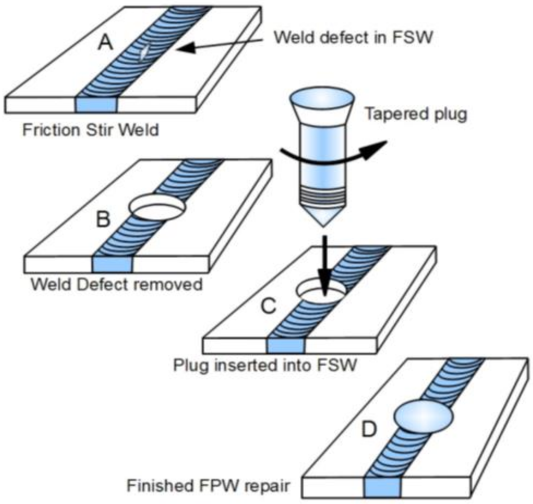

Figure 2: Friction plug weld process

The joining process begins when the moving part produces frictional heat at the bottom portion of the hole to permit plasticization. The 3-D finite element analysis was executed to perusal heat transfer and thermal phenomena of FSW of aluminum. Two welds, with very short pin and with long pin were checked out. The boundary condition for FSW is fixed and heat flux is calculated.[17]

Here in this work friction plug welding of aluminum alloy is pondered for mathematical modeling. on the basis of frictional heat, the generation of heat flux is calculated. The material pre-heating is changed in various ranges for getting the impact on temperature profile in the workpiece. Temperature distribution with various plug diameter is calculated using one-dimensional heat conduction.[18]

II. Literature Review

Friction stir welding (FSW) is a newly introduced process which provides better quality joints and also low cost. For any type of research work in this area, the most important phase is to get knowledge of already available literature.

Yong-Jai Kwon et al. [4] presented the friction stir welding among 5052 aluminum plates, having a thickness of 2 mm. The rotation speed of tool ranging from 500 to 3000 rpm with a constant stride speed of 100 mm/min. The tool rotation speed for Welded joints was 1000 to 3000 rpm. Onion ring structure was observed in the friction-stir-welded zone (SZ) At [500,1000,2000] rpm. On onion rings, the effect of tool rotation speed(TRS) was noticed. The grain size in the SZ is smaller than in base metal and is reduced with a decrease of the TRS. Observation showed that tensile strength, the strength of the joint is more than the parent metal. Observation also proved that the joint is not more ductile than the base alloy.

A study directed by G. CAO and S.KOU [5] was purposed at observing whether the boundary temperature in the workpiece can trigger liquation during friction stir welding (FSW) of Al alloys and limit lower bound of the melting temperature range which was seen in some computer simulations. AA 2219, an Aluminium-copper alloy was the workpiece material because of its certain lower bound of the melting temperature array whose eutectic temperature is 548°C. Besides friction stir welding (FSW), gas metal arc welding (GMAW) of Alloy 2219 was also introduced to give a stratum for checking liquation in FSW of Alloy 2219. Study under both scanning electron microscopy and optical shown and found that in GMAW of Alloy 2219, q (Al2Cu) particles featured as in-situ microsensors, which shows liquation due to reaction between Al and Cu forms eutectic particles when reaches eutectic temperature. No evidence of q-induced liquation was found in FSW suggesting that the eutectic temperature was not achieved.

J. Adamowski et al. [6] examined microstructural variations and mechanical properties in FSW in the AA 6082-T6 with changing process parameters. The tensile test of the welds was completed and the relationships among the process parameters were checked. Optical microscope observed the microstructure of the weld interface. Microhardness of resulting joint was also measured. Hardness reduction was observed in weld nugget and heat-affected zone (HAZ), test welds show resistance on the increment of welding speed in observation. Reason for this phenomenon was thermal asymmetry and kinetic of the friction stir welding process. At TMAZ and interface of weld nugget, the initial stage of the longitudinal, volumetric defect was found. Hardness was less to that of fusion welding (FW). In the nugget zone, wormhole (tunnel) defects were found.

H.J.LIU et al. [7] observed the friction welding characteristics of AA 2017-T351 sheet in which they have studied the microstructure of the weld joints and found that the relation between the parameters. The graphs were plotted between revolutionary strength and pitch, Vickers Hardness and distance from weld center, fracture location at the joints and revolutionary pitch. From tension tests and the hardness tests, it was deducted that FSW also decreases the tensile strength of the material and makes the material soft. The microscopic analysis indorses generations of fractures in joint at the interface between the thermodynamically affected zone and weld nugget.

M.Vural et al. [8] researched the FSW competency of EN AW 2024-0 and EN AW 5754-H22 Aluminium alloys. These Aluminium alloys are widely used in the industry. The experiment showed that the hardness value of EN AW 2024-0 at the weld area is increased about 10to40 Hv. This can be the outcome of compact grain structure formation and recrystallization. But the hardness of EN AW 5754-H22 decreased due to loose grain structure formation and recrystallization. Welding performance of EN AW 5754-H22 is 57% and for EN AW 2024-0 is 96.6. Welding performance of different Al alloys EN AW 2024-0 and EN AW 5754-H22 is reached to 66.39%. Scanning electron microscope showed no change in the microstructure in the welding zone in the analysis of the welding zone. At the weld zones, hardness distribution didn't show any relevant change in hardness.

III. Mathematical Modeling

FPW modeling can be done in many steps. The friction pressure and heat generation across the interface are considered uniform. [12]-[15] Some assumptions are incorporated in the model:

- The coefficient of friction is constant and heat is generated only by friction.
- The behavior of workpieces material has assumed perfect elastic-plastic.
- The heat loss due to radiation has been ignored, as plasticity was assumed.

A. *Temperature distribution*

Generation of Heat

The thermal modeling equation for friction welding procedure is mentioned as eq. (1)

$$K\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right]+G=\rho c\frac{\partial T}{\partial t} \quad (1)$$

ρ, c, K is temperature-dependent, Friction welding process contains the heat generation by friction between two workpieces qf, and heating from irreversible plastic deformation of both workpieces qp.

Heat generation rate G is given as,

$$G = q_f + q_p \quad (2)$$

In this study, it has been assumed that Friction law of Coulomb is followed for friction between workpieces; Generation of heat due to plastic deformation (qp) and due to friction (qf) and can be determined by equations 3 & 4,

$$q_f = 2\pi R N \mu F_n \quad (3)$$

$$\eta\sigma\varepsilon \quad (4)$$

For heat flux generation, the correlation between torque and heat energy is to be made. Heat production and the change of heat may be calculated by dimensions of parts and operating characteristics. By using machine torque, heat generation of friction can be calculated as below,

$$\tau$$

$$qf = \left(\frac{2\pi N\zeta}{60A}\right) * \eta \quad (5)$$

Heat generation can also be determined using equation no 6,

$$q = U*A*\Delta T = U*A*(Tin-Tamp) \quad (6)$$

Distance from the contact surface (T_L) is calculated by

$$\frac{TL-T\alpha}{Tb-T\alpha} = 1/\cosh(mL) \quad (7)$$

Where At the nominal distance the temperature is T_L, T is denoted as ambient temperature and Tb is the temperature of the base plate. Tb can be determined by,

$$T_b = T_p + T_f \quad (8)$$

Where Tp is defined as the Pre-heat temperature and Tf is temperature due to friction, produced by the generation of heat

$$m = \sqrt{\frac{hp}{KA}} \quad (9)$$

The temperature at a distant place from the contact surface is determined,

$$\frac{T-T_a}{T_b-T_a} = e^{-mx} \quad (10)$$

Where,
T is denoted as temperature distribution,
$T\alpha$ = ambient temperature,
T_b = baseplate temperature,
x = distance of contact surface.

On the basis of heat conduction (HC) equations, as explained above, heat flux can be determined. The variation of temperature distribution can be studied by varying the temperature, preheating, and distance of workpiece and contact area. The plug diameter depends upon land width.

B. *Hardness distribution*

With the Hardness tests, the measurement of resistance of the material to indentation is done. Strength of the material is indicated by its hardness. In the test, indenter made of a harder material than test material is pressed with force on the surface of the tested material. After that, the indentation is determined. The hardness of the material is inversely proportional to the indentation area. There are different-different types of hardness tests in which Rockwell, Brinell, and Vickers are the common tests. Vickers tests were used to study the hardness of both the welds and base material in the course of this work. A diamond pyramid indenter is used by Vickers hardness test, which produces a pyramidal indentation.

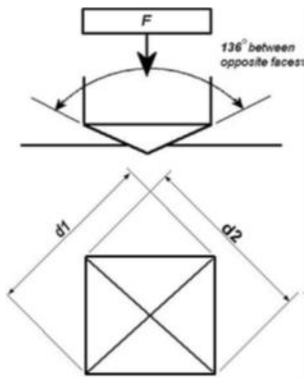

Figure 3: Vickers Hardness Test

The hardness is determined after the measurement of indentation:

$$VHN = 1.72 * \frac{F}{d1 * d2} \quad (11)$$

Where 'VHN' is denoted as Vickers Hardness Number, 'F' is the force of indentation and d1, d2 is the distances of opposite corners of the indentation.

In Vickers hardness test method indenter is of the diamond which indents the test material, in the form of a right pyramid with the angle of 136 degrees between two opposite face subordinated a load of 1- 100 kg and a square base. For 10-15 seconds, full load is normally applied. The two diagonals of the indentation remained in the surface of the material on the removal of the load are measured using a microscope and they're average determined. The sloping surface area of the indentation is calculated. Vickers hardness is the quotient found after the division of the kgf load by the square mm area of indentation. From the calculation of force-area ratio using the area of diamond indents in the base material, the hardness number is determined. Three surfaces were tested for every material; the longitudinal surface, the transversal surface, and the top surface. Clamping area of conventional bus bar ends is thinner and flattened than extruded part of the bus bar. So, both the flattened and the extruded parts had their hardness investigated. A number of tests can be made for every sample and the indentations made so that they form a square as given in figure 3.

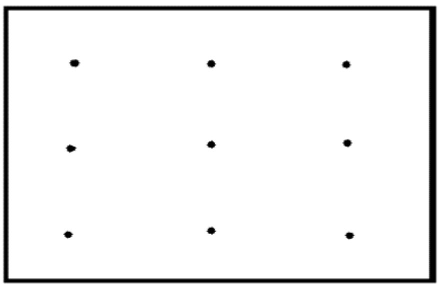

Figure 4: Hardness indentations for base materials

The hardness profile of FPW joint can be measured in three layers i.e. lower layer, the upper layer, and middle layer. The shape of the hardness profile would be in W-shape and the hardness of FPW joint depends upon microstructure and phases in different zones.

The hardness distribution on aluminum joints (AA5A06) is varied slightly for all the welding parameters. The maximum hardness appeared near the NZ and TMAZ. The reason for this AA5A06 joints is a non-heat treatable alloy, and therefore the temperature variation does not significantly affect the hardness. Near the NZ and TMAZ, the hardness was partially improved due to the refinement of the grains as a result of stirring action.

C. Tensile properties

The ability of a material to bear the loads tend to elongate is known as Tensile strength. Tensile strength(TS) resists tension(being pulled apart), while compressive strength resists compression(being pushed together). The ultimate tensile strength(UTS) is measured by the maximum stress that a material can undergo while being stretched or pulled before breaking. Some materials break very quickly, without the plastic deformation, which is defined as a brittle failure. Other materials, which are very ductile, including most of the metals, show some plastic deformation and possibly necking before the fracture.UTS is generally found by performing a tensile test and recording the engineering stress versus strain(S-S). UTS is the maximum point of the stress-strain(S-S)curve. This property is called intensive property; therefore the value of UTS does not depend on the size of the test specimen. It depends on other factors, such as preparation of the specimen the temperature of the test environment and material and the presence or otherwise of surface defects. Tensile strengths(TS) are generally not used in the design of ductile member but have importance in brittle members. It is known as stress, which is defined as force per unit area. Many materials shows linear elastic behavior, defined by a linear stress-strain relationship as in figure 4.Elastic nature of materials generally extends into non-linear region, represented up to which deformations are perfectly recoverable on removing the load; means, in tension a specimen loaded elastically will elongate, but it will return to its original shape and size when it is unloaded. Above this elastic region, for ductile materials, such as steel, deformations are totally plastic. While a plastically deformed specimen does not perfectly regain its original size and shape when it is unloaded.

Ductile metals pass a period of strain hardening after yield, in which value of stress increases again with an increase of the strain, and begin to neck, as the cross-sectional area of the specimen decreases due to plastic flow. In the sufficiently ductile material, if necking gets substantial, causes a reversal of the engineering stress-strain(S-S) curve (figure 5); this is due to the engineering stress is determined to take the original cross-sectional area before necking. Reversal point is the maximum stress on the engineering S-S curve, and the engineering stress coordinate of this point is the ultimate tensile strength(UTS), shown by point 1.

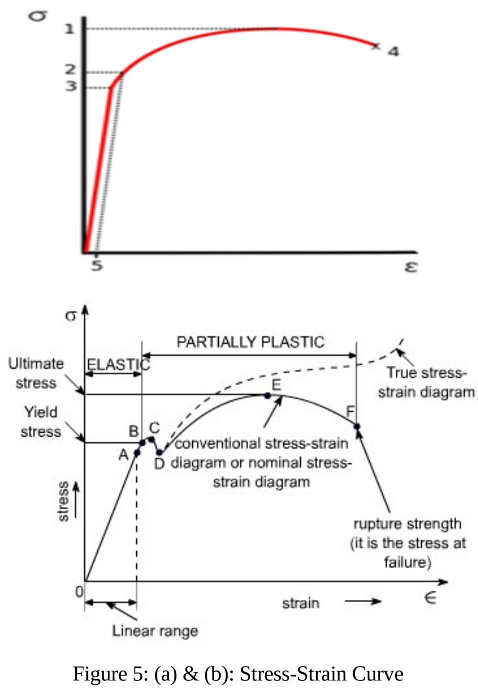

Figure 5: (a) & (b): Stress-Strain Curve

The points details of the curve are given below,

1 → Indicate the Ultimate Tensile Strength (UTS)
2 →Yield Strength
3 →Proportional Limit Stress
4 →Fracture
5 →Offset Strain

Yield strength(σy) is the point where plastic deformation gets a start. It is hard to specify correctly. But conventionally it is denoted as the intersection of the curve with a parallel straight line to elastic part of the curve offset 0.2% on x-axis. The yield strength is also defined as the stress needed to deform material by 0.2% permanently Slope of elastic part of the curve is known as modulus of elasticity, E. Tensile strength(TS) or Ultimate tensile strength(UTS), is the maximum stress achieved during a test. When the material starts to reach that point, the fractured cross-sectional area experiences reduction. This is the reason why the original area of the sample can't be used to model the true stress(σT) given below

$$\sigma T = \frac{P}{A\ actual} \quad (11)$$

For most of the metals approximation of the true stress is possible - true strain (ϵT) curve between yield stress(YS) and ultimate tensile stress(UTS) by the equations shown below,

$$\sigma T = K * \in_T^n \quad (12)$$

Where n and K are constant whose value change for every material.

From the tensile test, ending value acquired is the toughness of the material. Toughness represents ductility and combination of strength and is the ability of a material to bear mechanical energy up to failure point. Its value is equal to the area contained under the stress-strain curve and numerically given as,

$$U_T = \int_0^{\in f} \sigma * d \in \quad (13)$$

Where ϵf strain upon failure and U_T is toughness.

Tensile testing is used to calculate the maximum load (tensile strength), the material can withstand without failure. The load value or elongation value is the basis of the tensile test.

The stress-strain graph and fracture position of FPW sample welded at different conditions can be determined. The maximum ultimate tensile strength (UTS) [15] is contained by FPW joint and elongation of its value equivalent to that of base metal. There are many regions to find the minimum hardness and maximum hardness. The loss for welded joint ultimate tensile strength and elongation is considered as the disintegration of precipitates and distribution of ingredient particles.

Developing Mathematical Model

The response function tensile strength (TS) of the joints is a function of tool profile (P), rotational speed (N), welding speed (S) and axial force (F), and it can be expressed as,

$$TS = \oint(P, N, S, F) \quad (14)$$

The second-order polynomial (regression) equation used to represent the response surface 'Y' is given by,

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j \quad (15)$$

and for four factors, the selected polynomial could be expressed as

$$TS = b_0 + b_1(P) + b_2(N) + b_3(S) + b_4(F) + b_{11}(P^2) + b_{22}(N^2) + b_{33}(S^2) + b_{44}(F^2) + b_{12}(PN) + b_{13}(PS) + b_{14}(PF) + b_{23}(NS) + b_{24}(NF) + b_{34}(SF) \quad (16)$$

Where b_0 is the average of all responses and $b_1, b_2, \ldots b_{23}$ are coefficients which depend on interaction effects and respective main of the parameters. Values of the coefficients have been determined using the given below expressions (rf13)

$$b_0 = 0.142857 * \left(\sum Y\right) - 0.035714 * \sum\sum X_{ii} Y$$

$$b_i = 0.041667 * \left(\sum X_i Y\right)$$

$$b_{ii} = 0.03125 * \left(\sum X_{ii} Y\right) + 0{:}00372 * \sum\sum X_{ii} Y - 0.035714 * \left(\sum Y\right)$$

$$b_{ij} = 0.0625 * \left(\sum X_{ij} Y\right)$$

Every coefficient was tested at 95% confidence level (CL) [16] for their significance by applying students t-test with the use of statistical software package (SPSS). After calculating the significant coefficients, the relations were formed only using these coefficients. To predict the tensile strength of FPW joints the last mathematical relationship is formed between the FPW variables, developed by statistical design of experiments procedure are given below:

$$TS = \{240.86 + 6.71(P) + 4.38(N) + 9.29(S) + 5.96(F) - 14.66(P^2) - 8.17(N^2) - 10.54(S^2) - 13.79(F^2) - 1.68(PS) - 1.44(PF) - 2.19(SF)\} \ MPa$$

Advantages:-

- Strength is high
- Having good mechanical properties
- Heat input is low
- Quick process time
- Low cast

IV. SIMULATION RESULTS

The work is based on the study, analysis, and simulation. I will purchase the MATLAB software to install in my system. After studying many research articles about friction plug welding, I will implement the complete system in MATLAB software. I will develop a MATLAB model for heat generation analysis, Hardness distribution, and Tensile strength. The different types of simulation results will be analyzed to test the FPW.

A. *Temperature distribution*

For analysis of temperature distribution, parameters like contact area, preheating temperature, and distance from workpiece are changed.

By changing the plug diameter, the land width is changed. The various graphs are displayed for temperature and workpiece distance. It can be seen that temperature is linearly decreasing, on decreasing land width.

As shown in figure 6, 7, 8 and 9, various pre-heating temperature values like 300ºC, 400ºC, 500ºC, and 600ºC are displayed.

In figure 10 and 11, Temperature distribution vs displacement from contact surface with 16.0 mm and 4.0 mm land width is shown. It has been observed that temperature distribution is gradually decreasing with respect to the workpiece through its center point.

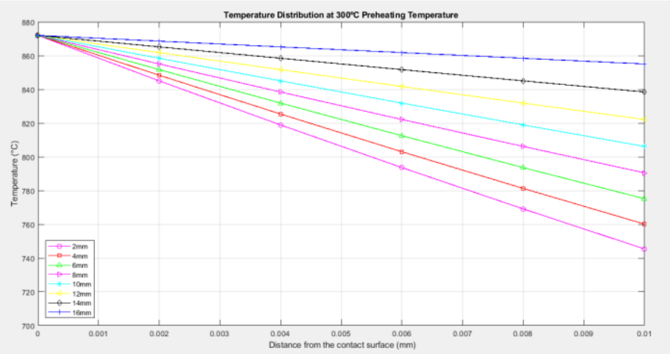

Figure 6: Temperature distribution at 300˚C preheating temperature

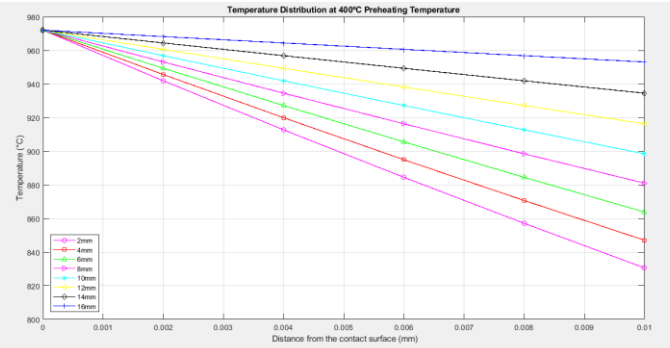

Figure 7: Temperature distribution at 400˚C preheating temperature

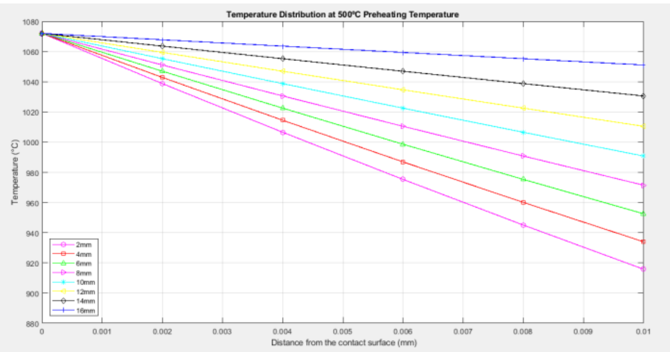

Figure 8: Temperature distribution at 500˚C preheating temperature

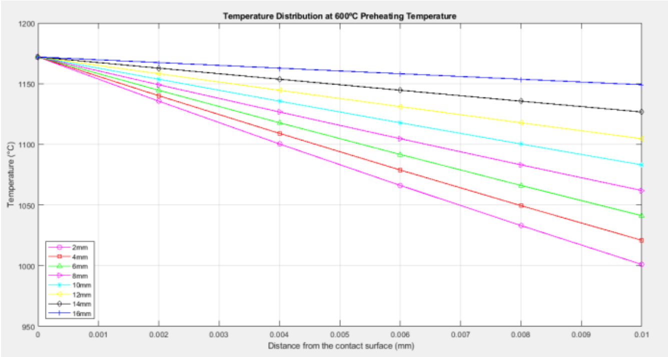

Figure 9: Temperature distribution at 600˚C preheating temperature

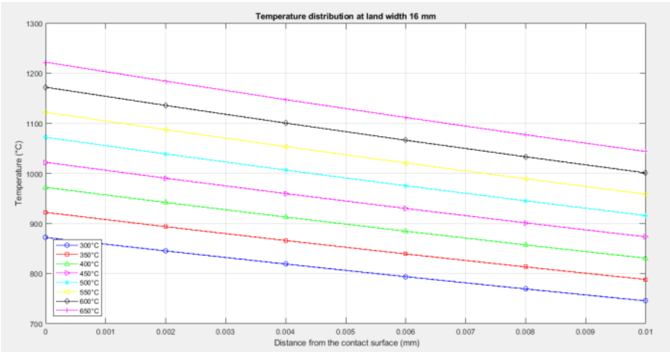

Figure 10: Temperature distribution at land width 16.0 mm

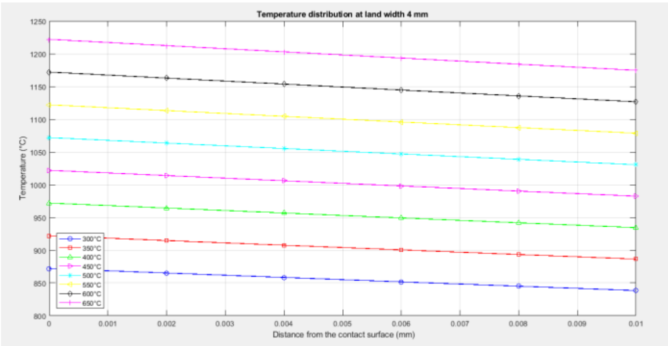

Figure 11: Temperature distribution at land width 4.0 mm

B. Hardness Distribution analysis

As shown in figure 6, the Vicker's hardness profile of the welding process is presented. The hardness of the TMAZ, HAZ, and HZ parent material region was computed. The hardness of the central zone was gradually less than the peripheral zone, and the hardness of the parent material was the lowest. The maximum value of hardness is at the central zone, shown in the TMAZ.

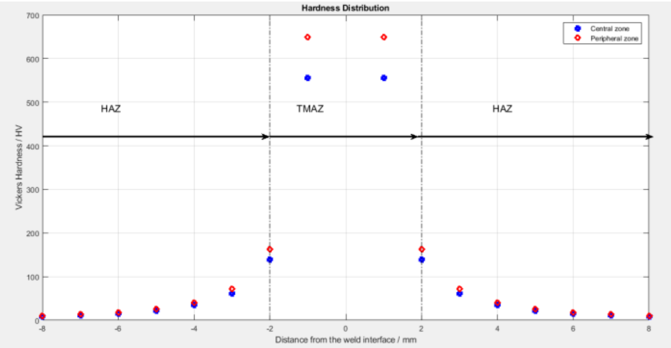

Figure 12: Hardness Distribution

C. Ultimate Tensile Strength (UTS) of Friction Plug Welding

As shown in figure 13, 14 and 15 graphs, used to understand the impact of FPW parameters on tensile strength like tool rotational speed, axial force, and welding speed.

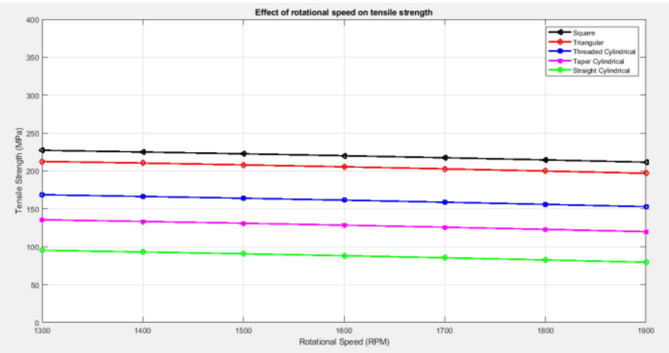

Figure 13: Effect of rotational speed on tensile strength

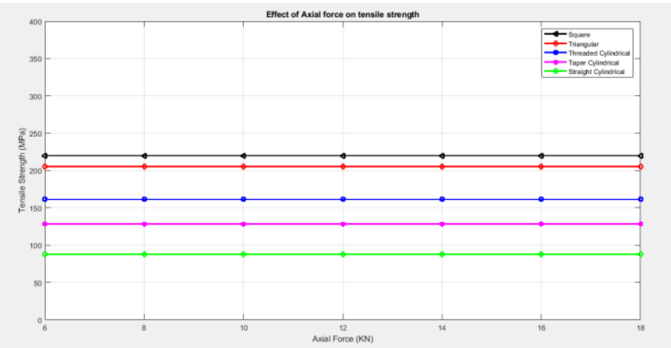

Figure 14: Effect of Axial force on tensile strength

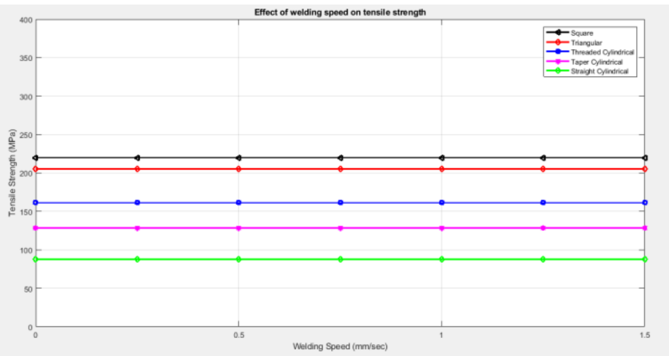

Figure 15: Effect of Welding Speed on tensile strength

CONCLUSION

A mathematical relation is formulated to get the tensile strength of friction stir welding joints by being inclusive welding parameters as well as tool profiles with the use of statistic tools like regression and experiments design. The heat flux is calculated because of friction during the materials for considering the coefficient of friction. Analytical model computed the impact of pre-heating. The temperature distribution in workpiece was computed for various plug diameters with various values of pre-heating temperature ranging 250ºC-550ºC.

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