# A Review on Friction Plug Welding

**Vishan Singh**, M.Tech Scholar, Department of Mechanical Engineering, Goel Institute of Technology & Management, Lucknow, India.
**Shiv Kumar**, Assistant Professor, Department of Mechanical Engineering, Goel Institute of Technology & Management, Lucknow, India.

***Abstract*—** When two dissimilar or similar materials are joined using friction plug welding (FPW), there is no need for external heat or for the materials to be in their molten condition. Friction welding is more of a forgery than a genuine fusion welding procedure because no melting occurs during the operation. It is possible to increase the efficiency of joints by interpolating heat sources or preheating the work piece surface. When determining the generation of heat flux at the mean surface, the friction coefficient must be taken into consideration as well. The breadth of the land can be changed by varying the diameter of the plug and observing how this affects the temperature distribution. It is possible to calculate the influence of pre-heating by applying mathematical and analytical models. The temperature distribution values were calculated for a variety of plug sizes and pre-heating temperatures ranging from 2500C to 5500C. The values were determined even while the work piece was in operation.
It was decided to employ the response surface analysis approach in this study in order to find out how different parameters affect the tensile strength of 6082 aluminium alloy friction plug welding (FPW) joints.
The temperature field and force analysis were used to determine why the root of the joint seems to be a weak zone. The explanation for this appearance was explained. According to the findings, the rotational speed was more important than the upsetting speed and the welding time in determining the tensile strength of FPW joints.

***Keywords*—** Friction stir welding, Friction plug welding, Heat, Friction, Temperature, Hardness, Tensile etc.

## I. INTRODUCTION

Fractional welding is one of these types of fabrication techniques, and it involves the generation of heat as a result of friction between the two elements that are being welded. This technique is now being used in organisations all over the world as a trustworthy and automated welding procedure, and it is becoming increasingly popular.
Fractional welding is a solid-state joining process in which the material coalescence occurs under compressive force contact of spinning work pieces, resulting in the production of heat and the plastic displacement of material from rubbing surfaces without the use of melting. In this technique, there is no requirement to employ filter metal or flux [1].
Friction Solid-state stir welding is being used to weld difficult-to-weld aluminium alloys of various series, which is a solid-state technique. Because of the lack of melting and resolidification of the metal, the weld is free of porosity and exhibits minimal distortion. A non-consumable spinning tool is used to bring the plates that are to be linked into contact with one another. When the tool is moved in the direction of the joining surface, heat is generated, and the joints are formed below the solidus temperature of the material being joined. Due to heat generated when the shoulder comes into contact with the surface of the plates, the temperature of the joining surface increases. The shoulder's pin stirs the joining surface, allowing the material on the underside of the pin to flow into the joining surface. As the tool travels through the metal, the metal cools, resulting in the formation of a treated zone. When connecting plates, it is vital to use a tool that is made of a more durable material than the plates that are being linked. As more durable tools are developed, the FSW process is increasingly being used to mix materials that can withstand high temperatures [2].
Friction plug welding (FPW) is a method of joining two dissimilar or similar materials that does not require the use of external heat or a molten state. Friction welding is more of a forgery than a genuine fusion welding procedure because no melting occurs during the operation. It is possible to increase the efficiency of joints by interpolating heat sources or preheating the work piece surface. In order to calculate the generation of heat flux at the mean surface, the coefficient of friction between two materials must be calculated [3-4]. The breadth of the land can be changed by varying the diameter of the plug and observing how this affects the temperature distribution. Calculating the effect of pre-heating is accomplished through the use of analytical modelling. It was possible to compute the temperature distribution in the work piece for a variety of plug sizes and pre-heating temperatures ranging from 250oC to 550oC.
It is a type of welding in which an incorrectly welded weld material is replaced with a plug, which is then friction welded into the original position. The fundamental rule is depicted in Figure 1 of this document.

 

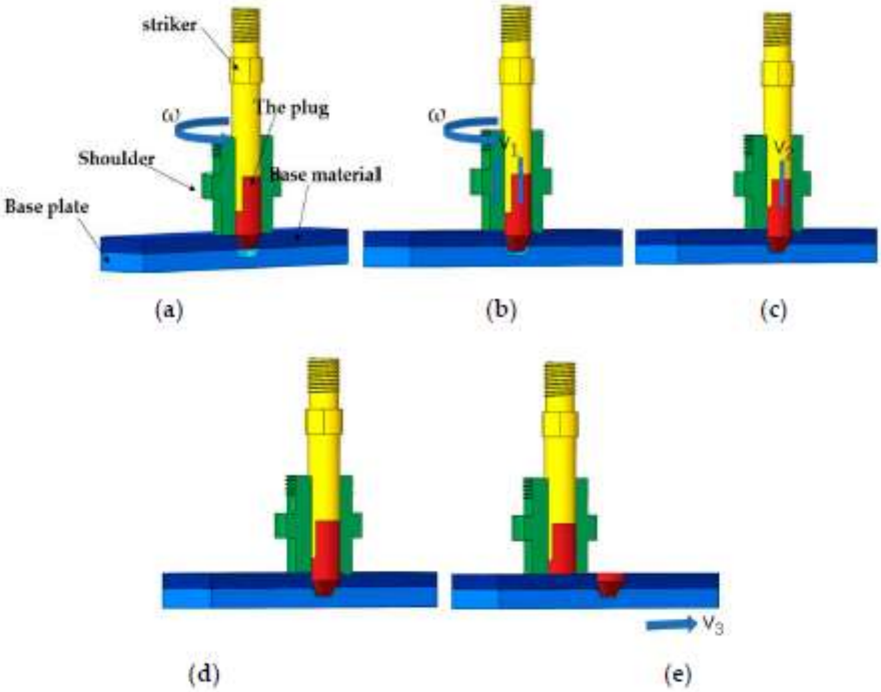


**Figure 1:** Schematic diagram of FPW process preheat phase, (b) friction feed phase, (c) upsetting phase, (d) pressure-holding phase, (e) disengagement phase

**Warm-up stage:** The pre-assembly, as shown in Figure 2a, ensures that the shoulder and upper surface of the base material, as well as the plug and hole, remain in close contact with one another. The shoulder and plug rotate at the same speed in order to achieve the preheating effect.

**Friction feed stage:** In Figure 2b, the shoulder and plug begin to push down at the same rate after a period of warming up. This brings the friction surface contact closer together and results in the generation of considerable amounts of heat. After a given amount of displacement, both the plug and the shoulder cease to spin and move.

**Upsetting stage:** After the shoulder and plug have stopped rotating, the striker immediately pulls the plug down at a predefined speed while the electric cylinder is in operation, as shown in Figure 2c. This causes the cylinder to upset.

**Pressure-holding stage:** The striker does not instantly retract after being quickly forced down, as shown in Figure 2d, but instead persists for a length of time to guarantee a tight bonding surface interaction.

**Departure stage:** The worktable and plug produce a horizontal relative displacement to chop off the extra part of the plug, as shown in Figure 2e. The shoulder then accelerates the removal of the extra stopper material from the workpiece.

With the help of the Design-Expert 8.0 programme, a mathematical model was constructed utilising the Box–Benhnken Design (BBD) approach, with the tensile strength of the FPW joint serving as the response value. The three parameters of the response surface experiment method (rotation speed, welding duration, and upsetting speed) were chosen in the manner shown in Table 3 with three levels for each of the three elements. We determined the optimal welding circumstances, selected two elements that had the largest impact on joint performance, and evaluated the impact of these elements on the formation of the joint.

**Table 1:** Coded and actual values of FPW parameters

| **Parameters** | **Unit** | **Levels** | | |
|---|---|---|---|---|
| | | -1 | 0 | +1 |
| **Rotational Speed (w)** | rpm | 1810 | 2215 | 2620 |
| **Welding Time (t)** | Sec | 25 | 30 | 35 |
| **Upsetting Speed (v)** | mm/sec | 1.2 | 1.6 | 2.2 |

As previously said, the key technique for FPW is as follows: first, a hole is cut out at the point of interest with the requisite geometrical specifications. Second, under the influence of axial force, a quickly spinning plug is placed into the hole, resulting in rapid frictional heating and defacement at the interface between the hole and the plug, which is most commonly referred to as the welding stage. In order to produce an FPW weld, the plug rotation is abruptly stopped and a moulding force is given to the weld surface after the hole has been completely filled. Finally, remove the stopper and quern the surface on a flat surface to cool.

The friction stir welding process (FPW) is used to correct weld faults in the context of friction stir welding (FSW). If you're looking to weld aluminium alloys, the FPW beats all other welding methods. Improved joint strength, less stress, and less deformation can all aid in the correction of the problem.

FPW is a solid phase welding procedure that includes rapidly spinning a circular plug while applying force to fill a hole in a piece of metal or plastic.

Using a friction plug welding technique to correct defects that may have appeared during the friction stir welding process is one of the recommended approaches for mending flaws that may have appeared during the friction stir welding process. Figure 2 illustrates a schematic representation of the friction plug weld procedure.

When the moving part generates frictional heat at the bottom of the hole, the joining process begins, allowing plasticization to take place at the bottom of the hole. Through the use of a three-dimensional finite element analysis, the heat transmission and thermal phenomena of aluminium FSW were explored. Two welds, one with a lengthy pin and the other with a very short pin, were subjected to close inspection. The heat flow has been estimated, and the boundary condition for FSW has been set in stone.

In this work, friction plug welding of aluminium alloy is taken into consideration for mathematical modelling purposes. When calculating heat flux generation, the frictional heat is taken into consideration. Modifying the pre-heating of materials within a specific range has the effect of altering their temperature profiles on the work piece. In order to compute the temperature distribution for different plug diameters, one-dimensional heat conduction is used.

## II. Literature Review

Friction stir welding (FSW) is a novel welding technique that produces low-cost, high-quality aluminium alloy joints. The first and most crucial step in conducting research in any field is to evaluate the available literature on the chosen topic.

Yong-Jai Kwon et al. [1] investigated friction stir welding between 5052 aluminium alloy plates with a thickness of 2 mm in order to determine its feasibility. While maintaining a constant traverse speed of 100 millimetres per minute, the tool rotation speeds ranged from 500 to 3000 revolutions per minute. Welded connections were achieved by rotating the tool at rates of 1000, 2000, and 3000 rpm, respectively. At 500, 1000, and 2000 rpm, the onion ring structure in the friction-stir-welded zone was clearly visible, as was the ring structure in the surrounding zone (SZ). It was discovered that the rotation speed of the tool had an effect on onion rings. It should be noted that the gain size in SZ is less than that in base metal, and that it diminishes as the tool rotation speed drops. According to the findings of the study, the tensile strength of the junction is greater than that of the parent metal. According to the results of the analysis, the joint is likewise less ductile than the parent alloy.

G. was involved in a research study. When CAO and S.KOU [2] set out to investigate whether excessive temperature in the work piece could cause liquation during friction stir welding (FSW) of aluminium alloys, they hoped to find out whether excessive temperature in the work piece could extend the bottom bound of the melting temperature range and cause liquation during computer simulations. The workpiece material was AA 2219, an Al-Cu alloy, chosen because it has a clear lower bound of the melting temperature array, which is the eutectic temperature of 548°C, and because it has a clear lower bound of the melting temperature array. Furthermore, gas metal arc welding (GMAW) of Alloy 2219 was utilised to establish a baseline for verifying the consistency of liquid in FSW of Alloy 2219 in addition to flux-cored welding (FSW). q ($Al_2Cu$) particles acted as in-situ micro sensors in the GMAW of Alloy 2219, indicating liquation due to the reaction between CU and Al, resulting in the formation of eutectic particles upon reabsorption, according to the findings of the study. Although there was no evidence of q-induced liquation in FSW, this does not rule out the possibility that the eutectic temperature was not reached.

J. Adamowski et al. [3] studied the mechanical properties and microstructural changes in Friction Stir Welds in the AA 6082-T6 using a variety of process parameters. After the welds were tensile tested, it was possible to determine the link between the process parameters. Using an optical microscope, researchers looked at the microstructure of the weld interface and found it to be satisfactory. A measurement was also made of the micro hardness of the final joint. Hardness loss was seen in the weld nugget and heat affected zone of the test welds, which were determined to be robust to increasing welding speed (HAZ). During the FSW process, there was a kinetic and thermal imbalance, which resulted in this phenomena. A longitudinal, volumetric flaw was observed at the interface of the weld nugget and the TMAZ, which was in the early stages of development. Hardness of the material was lower than the hardness of the material used in fusion welding. It was determined that there were tunnel (worm hole) defects in the nugget zone.

 

In their study of the friction welding properties of AA 2017-T351 sheet, H.J.LIU et al. [4] identified a correlation between the parameters. The microstructure of the weld joints was also examined by the researchers. Figures following depict the association between revolutionary pitch and strength, distance from the weld centre and Vickers Hardness, revolutionary pitch and fracture site at the joints, and the relationship between revolutionary pitch and Vickers Hardness. According to the results of the hardness and tension tests, FSW softens the material and reduces its tensile strength significantly. Microscopical examination of the cracks in the joint at the interface between the weld nugget and the thermodynamically damaged zone confirms their occurrence.

M.Vural and colleagues [5] evaluated the friction stir welding performance of the EN AW 2024-0 and EN AW 5754-H22 aluminium alloys. These two aluminium alloys are commonly utilised in the manufacturing industry. As a result of the experiment, the hardness value of EN AW 2024-0 at the weld area increased by around 10-40 Hv on average. This could be the result of recrystallization and the formation of a tightly packed grain structure in the material. The hardness of EN AW 5754-H22, on the other hand, has been reduced as a result of recrystallization and the formation of a loose grain structure. A 96.6 percent welding performance rating is assigned to EN AW 2024-0, but the welding performance rating assigned to EN AW 5754-H22 is 57 percent. The weldability of the dissimilar aluminium alloys EN AW 2024-0 and EN AW 5754-H22 was tested at 66.39 percent for the former and 66.39 percent for the latter. The microstructure of the welding zone was examined using a scanning electron microscope, and no modifications were discovered. At the weld zones, there was no significant change in the hardness distribution of the material.

Several current trends in the FSW process, weldment structure, and material characteristics at weld joints were examined by R. Nandan and colleagues [6]. It was the goal of this research to gain a fundamental understanding of the process and its molecular repercussions, which it accomplished. Further research is being done on the following topics: welding heat generation, heat transmission and plastic flow; welding tool design components; defect development analysis; and the structure and properties of welded materials. They emphasised the critical factors that must be addressed in order to reduce fracture and improve weld property uniformity, allowing FSW to be used to new technical domains and lower costs. Temperature transfer principles, material flow, tool–work–piece contact conditions, and the characteristics of several process parameters have all been developed, culminating in the development of efficient tools. It is also possible to count uncertain FSW parameters such as the friction coefficient, the extent of slide between the tool and the work–piece, heat transfer coefficients for different work–piece surfaces, and heat splitting between the work–piece and the tool at the tool–work–piece boundary, and processes to optimise these parameters are investigated.

## III. FRICTION WELDING PROCESS

Metal welding was the first successful application of this technique, which was initially reported in 1956 by the Russian Federation. Previously, this approach was used to mix thermoplastic polymers, and it was successful. One of the portions to be welded is rotated while the other is made to rub against the first under axial load. This increases friction between the two sections, which aids in the production of heat and the joining of the two pieces when the components are resting under greater axial load. The junction formed by this friction welding method is comparable in appearance to the joint formed by electrical resistance butt welding method. Neither filler metal, shielding gas, nor flux are required when using this friction welding method [8]. In addition to welding cylindrical elements such as tube or rod, this process can also be used to weld symmetrical components that can be rotated fast, such as gears.

- **Type of Friction Welding Process**

Friction welding processes are classified into following [9]

a. Energy Based classification
b. Relative motion classification

**a) Energy based classification**

- **Direct drive or continuous**

Continuous drive process is a variant where power or energy is provided by an infinite duration source and maintained for a preset period [9].

- **Stored energy**

The process variant where the energy for welding is supplied by the kinetic energy stored in a rotating system or fluid storage system [3].

- **Hybrid system**

It is the combination of some of the features of both the above method [9].

**b) Relative motion based classification**

- **Rotational**

It is a method in which one component is rotated relative to and in contact with the mating face of another component.

- **Linear oscillation**

In this method, one component is moved in a linear oscillating motion relative to and in contact with the mating face of another component.

 

- **Angular oscillation**

In this method, one component is moved in angular oscillating motion about a common component axis relative to and in contact with the mating face of another component.

- **Orbital**

In this method, one component is moved in a small circular motion relative to and in contact with the mating face of another component either with components rotating about its own central axis or with components rotating in the same direction about their own axes and at the same speeds but with their axes displaced [10,24].

➢ **Advantages of friction welding process**

- Friction welding is environmentally friendly process as it does not generate fumes, gases or smoke [11,23].
- Friction welding is suitable for quantities ranging from prototype to high production.
- As friction welding is a solid state process, possibility of porosity and slag inclusions are eliminated.
- Welding of unequal cross sections can be done by friction welding process.
- It allows choosing of either manual loading or optional automated loading.
- Dissimilar materials which are normally not compatible for welding can be friction welded.
- Friction welding is consistent and repetitive process.
- It consumes low energy and low welding stress.
- It reduces raw material cost with bi-metal applications.
- It reduces maintenance cost.
- It reduces machining labor, which in turn increases capacity and reduces perishable tooling cost.
- It reduces cost for complex forgings or castings.
- Self-cleaning action of friction welding reduces or eliminates surface preparation cost or time for some material combinations.
- In case of friction welding, joint strength is equal to or greater than parent material.
- It creates a narrow heat affected zone.
- It has accurate control over post welds tolerances.
- It is highly precision and repeatable process.
- No flux or filler metals or gases are required in case of friction welding.
- Create cast or forge like blanks, without the expensive costs of tooling and the minimum quantity requirements.
- Friction welded joint can withstand high temperature variation.

➢ **Applications of friction welding process**

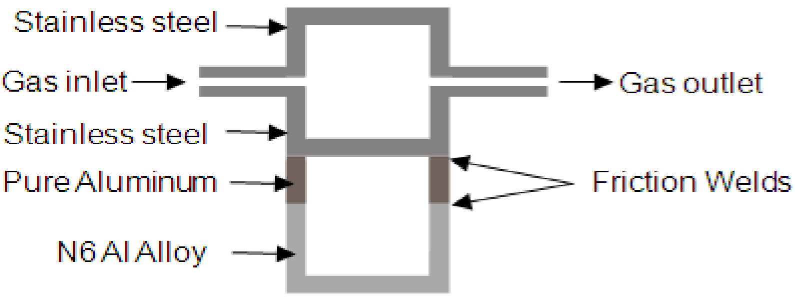


**Figure 3:** Nuclear Power Plant

**Figure 4:** Bi-Metallic Joint (Aluminum to SS304)

## IV. Defects in Friction Welding

Defects which can encounter during the friction welding process are as follows [12-15]:

a) Lack of bonding,
b) Cracks,
c) Non-metallic inclusions, and
d) Intermetallic phase accumulation

**a) Lack of bonding**

In this type of defect there is insufficient bonding between the faying surfaces, shown in Figure 5.

This is caused by low rotational speed or due to improper preparation of interface surfaces or due to insufficient heating time (friction time). This defect can be prevented by improved surface preparation and by optimizing the welding variables.

**b) Cracks**

Cracks are encountered in some specific zones, given as follows:

- Within the heat affected zone or its marginal area.
- At the sharp edged transitional area to weld flash
- Inside weld flash, in axial direction
- Internally on the faying interface

The cracks in the heat affected zone or in its marginal area are caused by the formation of coarse carbides in these zones. Remedial action involves affecting the quality of carbides by preheating the work piece to reduce the cooling rates after welding.

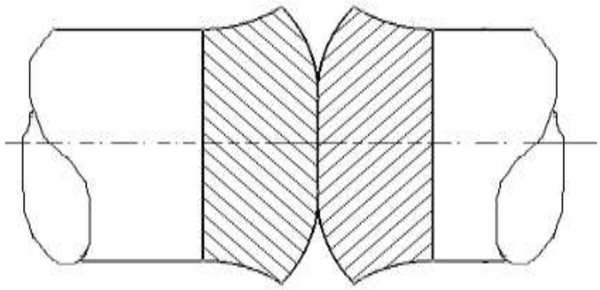

**Figure 5:** Lack of bonding in a friction welded joint

Cracks at the sharp edge transitional area to weld flash as shown in Figure 6 are caused by the use of high forge pressure. Thus, this can be prevented by reducing the forge pressure and adjusting the weld variables is another step for prevention of these types of defects 13].

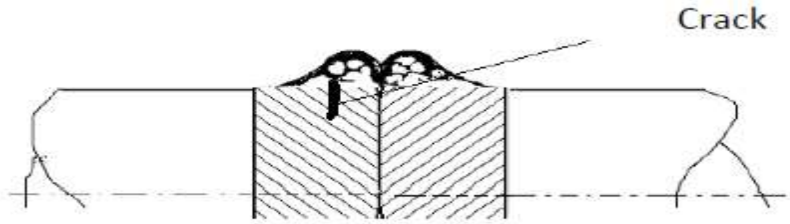


**Figure 6:** Crack at the sharp edge transitional area to weld flash

Cracks inside the weld flash, in axial direction as shown in Figure 7 are also caused by high forge pressure and because of generation of insufficient high heat during the process. By increasing the rotational speed and by controlling the weld cycle time to generate sufficient heat before applying the final forge pressure.

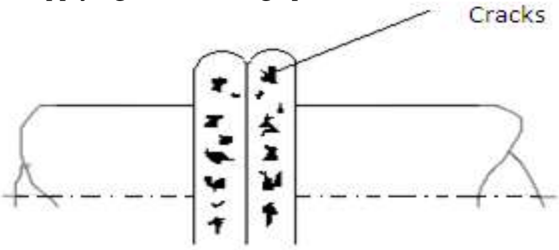


**Figure 7:** Crack inside the weld flash

Internal crack occurred during the welding of dissimilar component materials shown in Figure 8, can be removed by controlling the behavior of inter-metallic compounds at the faying surfaces.

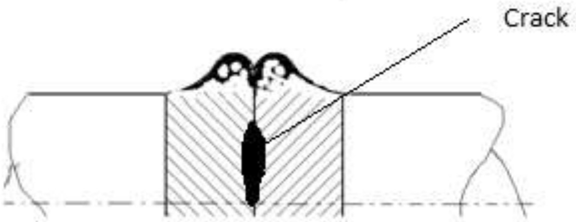


**Figure 8:** Internal cracks on the faying interface

**c) Non-metallic inclusion**

Solid inclusions of non-metallic forging matter in contact area lead to defect in friction welding [16,22], known as non-metallic inclusion, as shown in Figure 9.

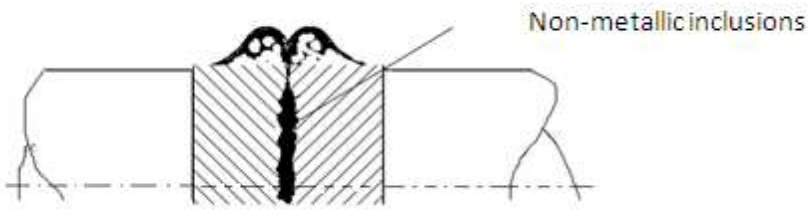


**Figure 9:** Non-metallic inclusions entrapped between the faying surfaces

During the forging stage the inclusions are entrapped. These inclusions may include scale, rust, cutting solution, drawing grease, etc. on the faying surfaces. These defects may also be caused by soiled center bore in the work piece. Cleaning of forging surfaces and the central bore is the solution for prevention of this defect [21].

**d) Inter-metallic phase accumulation**

Inter-metallic phase accumulation formation and depletion with contact area is shown in Figure 10. Incorrect welding variable and dissimilar component material are main reasons for its occurrence. The preventive measures include optimization of welding variables like rotational speed, cycle time and forge pressure and proper selection of component materials.

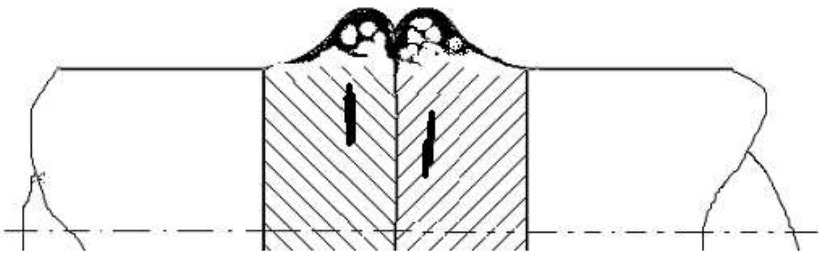

**Figure 10:** Inter-metallic phases inside contact

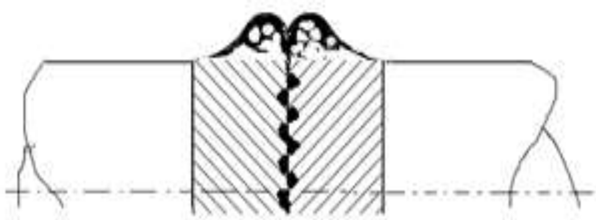

**Figure 11:** Inter-metallic phases along contact area

Carbides, oxides and nitrides may also accumulate in the bonding zone along the contact area as shown in Figure 11. This is cause by improper material preparation. Prevention of such occurrence includes greater homogeneity of component material being welded; proper selection and adjustments of welding variables to achieve the desire weld joint.

Sudarshan and Murty [17] have studied intermetallic layer formation at the weld interface of aluminum alloys and stainless steel. Won-Bae Lee, Luek-saeng, seing [18-20] studied, effects of intermetallic compound on the electrical and mechanical properties of friction welded copper-Aluminum bimetallic joints during annealing. H. Ochi, K Ogawa, Y. Yamomoto, G Kawai and T Sawai [21] studied the formation of intermetallic compounds in aluminum alloy to copper friction welded joints and their effect on joint efficiency.

## V. Conclusion

The response surface analysis approach was used to evaluate the impact of welding features on the mechanical properties of the FPW joint, and the optimal welding parameters were determined. In order to better understand the development and fault of 6082 aluminium alloy plug welded joints, the researchers used the change in axial force. The following are the most important conclusions reached:

1. The response surface optimization approach was used in this investigation, and it was discovered that the degree of influence of welding parameters on the tensile strength of the joint was w > v > t. The best welding parameters were 2277 rpm rotating speed, 35 s welding time, and 3 mm/s upsetting speed. The FPW joint's maximum tensile strength was 265 MPa.
2. A good coordination of rotating and upsetting speeds during the welding process can improve the plastic metal fluidity at the joint and improve its mechanical properties.
3. The weak connection at the root of the FPW joint is due to a weak contact force between the plastic metals on the bonding surface, and increasing the axial force can improve the interaction force between surfaces, resulting in a more reliable connection.

## References

**[1]** Yong-Jai Kwon, Seong-Beom Shim, Dong-Hwan Park, Friction stir welding of 5052 aluminum alloy plates, Trans. Nonferrous Met. Soc. China 19(2009) s23−s27.

**[2]** G.Cao, S.Kou, friction stir welding of 2219 aluminum: behavior of theta (Al2Cu) particles, The Welding Journal, January 2005.

**[3]** P. C. Lin, S. H. Lin, J. Pan, T. Pan, J. M. Nicholson and M. A. Garman, Microstructures and failure mechanisms of spot friction welds in lap-shear specimens of aluminum 6111-T4 sheets, Proc. of SAE World Congress, Detroit, USA (2004).

**[4]** H. J. LIU, H. FUJII, K. NOGI, Friction stir welding characteristics of 2017-T351 aluminum alloy sheet, JOURNAL OF MATERIALS SCIENCE 40 (2005) 3297 – 3299.

**[5]** M. Vural, A. Ogur, G. Cam, C. Ozarpa, On the friction stir welding of Aluminium alloys EN AW 2024-0 and EN AW 5754-H22, Archives of Materials Science and Engineering, Volume 28,Issue 1,January 2007.

**[6]** R. Nandan,T. DebRoy,H.K.D.H.Bhadeshia;Recent Advances in Friction Stir Welding – Process, Weldment Structure and Properties, Progress in Materials Science 53 (2008) 980-1023.

**[7]** P. Thornton, A. Krause and R. Davies, Aluminum spot weld, Weld. J., 75 (1996) 101-108.

**[8]** Li, K.; Liu, X.-M.; Zhao, Y. Research Status and Prospect of Friction Stir Processing Technology. Coatings 2019, 9, 129.

**[9]** Magalhães, V.M.; Leitão, C.; Rodrigues, D. Friction stir welding industrialisation and research status. Sci. Technol. Weld. Join. 2017, 23, 400–409.

**[10]** A. Gean, S. A. Westgate, J. C. Kucza and J. C. Ehrstrom, Static and Fatigue Behavior of Spot-Welded 5182-0 Aluminum Alloy Sheet, Weld. J., 78 (1999) 80-86.

**[11]** Li,W.; Jiang, D.; Yang, L.; Pan, J.; Qu, R.; Sun, T. Numerical simulation of temperature field and prediction of microstructure in friction hydro pillar processing. J. Mater. Process. Technol. 2018, 252, 370–380.

**[12]** Sun, Y.; Fujii, H.; Sato, Y.; Morisada, Y. Friction stir spot welding of SPCC low carbon steel plates at extremely low welding temperature. J. Mater. Sci. Technol. 2019, 35, 733–741.

**[13]** Hartley Paula, J. Friction plug weld repair of space shuttle external tank. Weld. Metal. Fabric. 2000, 68, 6–8.

**[14]** Metz, D.; Barkey, M.E. Fatigue behavior of friction plug welds in 2195 Al–Li alloy. Int. J. Fatigue 2012, 43, 178–187.

**[15]** Du, B.; Cui, L.; Yang, X.; Wang, D.; Sun, Z. Weakening mechanism and tensile fracture behavior of AA 2219-T87 friction plug welds. Mater. Sci. Eng. A 2017, 693, 129–135.

**[16]** Hynes, N.R.J.; Velu, P.S.; Nithin, A.M. Friction push plug welding in airframe structures using Ti-6Al-4V plug. J. Braz. Soc. Mech. Sci. Eng. 2018, 40, 158.

**[17]** Cui, L.; Yang, X.; Wang, D.; Hou, X.; Cao, J.; Xu, W. Friction taper plug welding for S355 steel in underwater wet conditions: Welding performance, microstructures and mechanical properties. Mater. Sci. Eng. A 2014, 611, 15–28.

**[18]** Du, B.; Yang, X.; Liu, K.; Sun, Z.; Wang, D. Effects of supporting plate hole and welding force on weld formation and mechanical property of friction plug joints for AA2219-T87 friction stir welds. Weld. World 2019, 63, 989–1000.

**[19]** Metz, D.F.;Weishaupt, E.R.; Barkey, M.E.; Fairbee, B.S. A Microstructure and Microhardness Characterization of a Friction PlugWeld in Friction StirWelded 2195 Al-Li. J. Eng. Mater. Technol. 2012, 134, 021005. Metals 2020, 10, 1454 14 of 14.

**[20]** Landell, R.; Kanan, L.F.; Buzzatti, D.; Vicharapu, B.; De, A.; Clarke, T. Material flow during friction hydro-pillar processing. Sci. Technol. Weld. Join. 2019, 25, 228–234.

**[21]** Cui, L.; Yang, X.;Wang, D.; Cao, J.; Xu,W. Experimental study of friction taper plug welding for low alloy structure steel: Welding process, defects, microstructures and mechanical properties. Mater. Des. 2014, 62, 271–281.

**[22]** T. Iwashita, Method and apparatus for joining, US Patent 6,601,751, published 5 August (2003).

**[23]** T. Iwashita, Method and apparatus for joining, EP Patent 1,149,656, published 19 October (2005).

**[24]** H. Badarinarayan, F. Hunt and K. Okamoto, Friction stir welding and processing, in Friction Stir Welding and processing (ed. R.S. Mishra et al.), ASM International (2007) 235-272.