MAXIMIZE TENSILE STRENGTH IN ALUMINIUM ALLOY JOINTS USING PARAMETRIC OPTIMISATION OF LINEAR FRICTION WELDING

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Abstract : *Joining of sheets, plates, rods and other elements of different shapes and structure is a basic requirement to build huge and large machinery, equipment and other structures. 'There are three major categories of material joining processes - mechanical fastening, adhesive bonding and welding. Welding differs from other joining processes in that the joint created by it, is very strong and permanent. Welding is a fast and economic technique to join metals together permanently. Joining of similar metals by welding is a common practice, yielding a structure with good mechanical properties and minimal defects. Joining of dissimilar metals is generally more challenging than that of similar metals, because of the differences in physical, mechanical and metallurgical properties of the parent metals to be joined. Friction welding is a strong state joining measure. The contact welding segments are compelled to rub against one another, in this manner producing heat at the interface. This relax the material on one or the other side of the scouring interface. The use of loss function which is then transformed into a S/N ratio to measure the performance characteristic deviating from the desired value and then S/N ratio for each level of process parameters is evaluated based on average S/N ratio response analysis and greater S/N ratio is corresponding to better quality characteristic irrespective of category and quality is evaluated based on average S/N ratio response analysis and greater S/N ratio is corresponding to better performance characteristic regardless of category and quality. The objective is to optimizing the process parameters of sand casting process including optimum levels.*

Keywords: *Al Alloy, LFW, Optimization, S/N ratio.,*

1.1 INTRODUCTION

Friction welding is used in many fields and is gaining importance in industrial applications as a mass production process for joining similar as well as dissimilar materials because the procedure is relatively simple. However, there are still unresolved issues in this method such as the difficulty in setting the appropriate welding conditions for some materials and obtaining of optimum welding conditions in friction welding machines.

Dissimilar joining involves the combination of base materials having different thermo-physical, mechanical, and chemical properties. Occurrence of joint failure is more in case of fusion welding of Aluminium alloys due to the thermal stresses developed. Solid-state joining provides an alternative to fusion joining. In this case the bonding occurs wholly in the solid state at temperatures lower than the solidus temperature of the base material

1.2 Linear Friction Welding (LFW)

The straight rubbing welding measure was first licensed in the late 1920s8, anyway there was next to no detail recorded on its utilization. A conversation of the idea was then recorded in the U.S.S.R. during the 1960s [58], yet the interaction was depicted as being "suspicious" for an assembling procedure [8,58]. This was because of the trouble in producing responding straight movement. Indeed, even today there is no authority meaning of the cycle and there is no general patent; in spite of the fact that there are numerous interesting explicit application patents[8,59]. The initial genuine organized investigation into the cycle occurred at TWI, Cambridge in the 1980sWhen compared to other friction welding processes, where there are numerous published works, there is relatively little information available about LFW until recently[1,3,10].

1.2.1 Process Phases

As described in section 1.2, linear friction welding is a solid-state joining process that works by linearly oscillating one work piece relative to another whilst under a large compressive force. Although one continuous process, LFW is said to occur over four[3,22,60] phases:

Phase I: Initial Phase

Contact exists between the asperities on the two surfaces to be joined and heat is generated due to friction, see Figure 2.1(a). The asperities soften and deform, increasing the true area of contact between the work pieces. As shown in Figure [2.7], the shear force can remain fairly constant throughout this phase due to the increasing contact area being offset by the decrease in yield strength of the asperities. Negligible axial shortening (burn-off) perpendicular to the direction of oscillation is observed. 14

Phase II: Transition Phase

The material plasticises and becomes highly viscous causing the true area of contact to increase to 100 percent of the cross-sectional area, see Figure 2.1(b), the shear force increases to overcome the material yield stress of the plasticised layer3. The heat conducts back from the interface plasticising more material and the burn-off begins to occur due to the expulsion of the viscous material.

Phase III: Equilibrium Phase

The interface force, thermal profile and burn-off rate reach a quasi-steady-state condition and significant burn-off occurs through the rapid expulsion of the viscous material from the interface..

Phase IV: Deceleration and Forging Phase

Once the desired burn off is reached, the relative motion is ceased and the workpieces are aligned. In some applications an additional forging force may be applied to aid consolidation.

1.2.2 Process Inputs

There are eight process inputs used during linear friction welding [1–3,6–8,13,17,39,46,61–68], these are:

- **Linear oscillation frequency**: The number of completed oscillatory cycles per second. Typical values used are between 20 Hz and 75 Hz.

- **Linear oscillation amplitude**: The maximum displacement of the oscillating workpiece from its datum point. Typical values used are between 1 mm and 5 mm.

- **Applied / Normal force**: The normal force applied to the workpieces during the oscillatory motion. The applied force is usually defined after the workpiece dimensions are known. This is so that a pressure may be defined. Forces are often defined to give pressures between 40 MPa and 120 MPa.

- **Ramp-up time**: The time taken to ramp-up the oscillation amplitude to the desired value. This typically takes less than a second.

- **Burn-off**: This can be measured in two ways:

- **Burn-off to distance**: The distance the workpieces shorten before the oscillatory motion is decayed to a stop.

- **Burn-off to time**: The time taken before the oscillatory motion is decayed to a stop. The burn-off achieved is then dependent on the combination of the other process inputs used. The burn-off distances recorded in the literature are typically between 1 mm and 6 mm.

- **Linear oscillation decay time**: Time taken to decay the amplitude and frequency from the processing value to zero. The process typically takes between 0.1 seconds and 2 seconds, with the former being more common.

- **Forging force**: The force used to help consolidate the workpieces once the oscillatory motion is ceased. As with the applied force, the value is usually defined after the workpiece dimensions are known. Typical values used generate a pressure between 40 MPa and 240 MPa.

- **Forging time**: The time the forging force is applied. Typical values used are between 1 seconds and 10 seconds.

Many authors appear to consider the frequency, amplitude, applied force and burn-off to be the process inputs of primary importance2,3,6,24,50,69,70. Furthermore, there are several important factors worthy of note that are dependent on the process inputs1,8,50:

- **Total upset**: This is the combination of the burn off distance plus any extra shortening achieved during the forging phase.

- **Shear / friction / interface force**: The force at the interface of the workpieces parallel to the oscillatory motion.

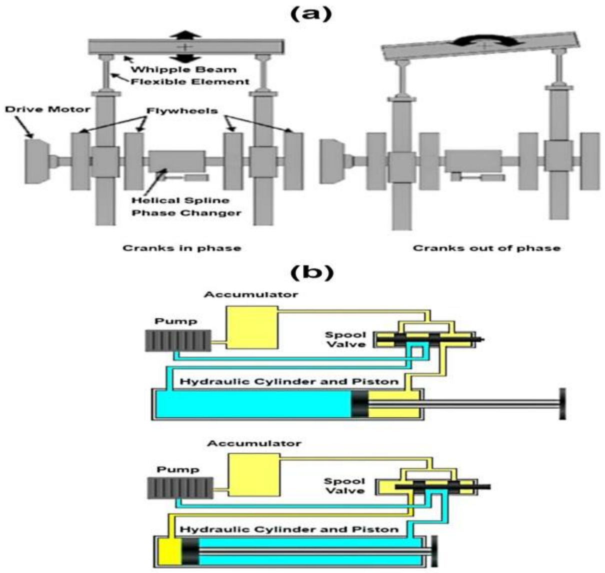
- **Burn-off rate**: The rate that the burn-off occurs during phase 3.

- **Welding time**: The time taken to complete the process.

1.2.3 Machines

On a basic level LFW machines work by oscillating one workpiece relative to another whilst under a large compressive force. According to Bhamji [90] , the force application is always generated by a hydraulic ram, whilst the oscillatory motion can be generated mechanically or hydraulically.

Mechanically worked frameworks frequently utilize an engine to pivot a driving rod. Joined to the driving rod are two wrenches that can be stage moved. A whipple shaft is joined to the wrenches. At the point when the wrenches are 180° out of stage the bar pivots around its middle direct causing the middle toward stay fixed, which successfully gives a wavering abundancy of nothing. To accomplish swaying amplitudes among nothing and the greatest, the stage move is adjusted somewhere in the range of 0° and 180° 2,90. The recurrence is subject to the cycles each moment of the motor2. Water powered working frameworks work by siphoning high pressing factor liquid into a heap of gatherers. A servo valve at that point permits the high compel liquid from the gatherers to be switched back and forth between each finish of a chamber. This sways a cylinder at an ideal plentifulness and recurrence. The tooling that holds the workpiece to be welded is joined to the furthest limit of the cylinder. This is delineated in Figure 1(b)



.Figure 1: Schematic of (a) mechanically operated motion91 **and (b) hydraulically operated motion**90**.**

2. METHODOLOGY OF JOINING OF SIMILAR AA 2024 PLATES

The plan of investigation for optimization of process parameters of similar joining of **AA 2024** is illustrated in the following stages:

Stage 1- Material selection based on need and applications

Stage 2 – Joint configuration

Stage 3 – Identifying the predominant process parameters in LFW

Stage 4 – Experimental setup

Stage 5 – Assumptions in FEM analysis of joining of **AA 2024**

Stage 6 – Fixing the range of the process parameters to obtain good joint

Stage 7 – Analysis of good joint

Stage 8 – Results and Discussion

2.1 Design of experiment

The process parameters for joining AA2024 AL plates by using LFW process is presented in Table 4. In this investigation Friction load, which is the predominant process parameter of LFW process and responsible factor for bonding is alone varied. All other parameters are maintained constant as their combined influence was not much significant factor for bonding. However, the parameters like frequency, forging time, friction time and forging load have their individual effect on the performance of the joints fabricated by LFW. LFW involves joining of materials through the relative motion of two components undergoing an axial force. The friction between the rubbing surfaces coupled with the strong applied pressure heats up the materials and creates the necessary conditions in the contact zone to soften the individual components and to form metallic bonds. When welding is obtained by forcing a stationary part against a part that is reciprocating in a linear manner. A real time LFW was carried out to fabricate similar joints of AL2024 by using indigenously built LFW machine for all the five trails for which FEM analysis was done. The observations of all five trails are presented in Table 5.3. It is evident that Trail 3 is proven to impart a good bonding of AL2024 plates.

Table 1: Range of the process parameters selected.

Parameters	Unit	Trial 1	Trial 2	Trial 3	Trial 4
Friction load	N	300	400	500	600
Friction time	Sec	30	30	30	30
Forging load	N	200	200	200	200
Forging time	Sec	3	3	3	3
Frequency	Hz	30	30	30	30

2.2. Joint configuration

Two plates of **AA 2024** of length: 55mm, width: 30mm and thickness: 6mm is used for fabricating the similar joints of the same. Square Butt joint configuration as illustrated in Fig.3

2.3 Validation of experiment

LFW offers many advantages over traditional fusion welding methods, including excellent mechanical properties avoidance of melting, allowing for a range of dissimilar materials to be joined. The two plates of AA2024 are initially positioned adjacent, in contact at the intended weld interface. During the process, one plate oscillates against other and no buckling is observed during the real time experimentation. A static forging load is applied on the stationary plate and frictional force is exerted by the oscillation of other plate over the stationary plate. It is evident that all the other parameters in this investigation are maintained constant expect friction load. In this investigation good bonding is obtained in Trail 2 where the frictional force is 500 N which is neither too high nor too low. If the frictional force is too low no bonding is established and if the friction force is too high flash formation along with incomplete fusion occurs. Thus, a balance nominal friction force along with other established parameters aid in good bonding due to minimum deformation and is evident in Trial 2.

Hence, it is proved that LFW process can also be used for fabricating the dissimilar butt joint of DSS and MS. However, the structural integrity of the bonding have to be investigated mechanically and metallurgical to apply LFW for fabrication of Dissimilar joints comprising of DSS and MS.

A predicted maximum tensile strength of the friction-welded specimen which is 482 MPa could be attained under the welding conditions of friction force of 15 kN, upset force of 27 kN and friction time of 90 s. The experimentally determined tensile strength was found to be 480 MPa and could be attained under the welding conditions of friction force of 15 kN, upset force of 27 kN and friction time of 30 s which show the consistency of the model. Three further validation experiments were performed and the response of both models was found in agreement with the experimental results. To test the accuracy of a developed model in practical applications, conformity test runs were conducted by assigning different values for the process parameter within their working ranges but are different from that of the design matrix. These tests were conducted using the same experimental setup to demonstrate the reliability of the predicted values.

Fig2: similar welded joints

Fig3: Test specimens

Table2: Breaking loads of Different trails

Specimen	I	II	III	IV
Breaking Load	9.46KN	9.62KN	8.50KN	8.82KN

2.4 TAGUCHI METHODOLOGY

Taguchi method recommends the use of loss function which is then transformed into a S/N ratio to measure the performance characteristic deviating from the desired value and then S/N ratio for each level of process parameters is evaluated based on average S/N ratio response analysis and greater S/N ratio is corresponding to better quality characteristic irrespective of category and quality is evaluated based on average S/N ratio response analysis and greater S/N ratio is corresponding to better performance characteristic regardless of category and quality.The objective is to optimizing the process parameters of sand casting process including optimum levels and the case study is done in a job foundry in central India. The Taguchi method can be applied by using eight experimental steps that can be grouped into three major categories as follows:

(1) Identify the main function of casting process.

(2) Identify the quality characteristic to be observed and the objective function to be optimized.

(3) Identify the control factors and their alternate levels.

(4) Identify noise factors and the testing conditions of the process.

(5) Design the matrix experiment and define the data analysis procedure.

• Performing the experiment:

(6) Conduct the matrix experiment.

• Analyzing and verifying the experimental results:

(7) Analyzing the data, determining the Optimum levels for the control factors, and predicting performance under these levels:

(8) Conducting the verification (also called confirmation) experiment and planning future actions.

2.5 SELECTION OF ORTHOGONAL ARRAY

Selection of an orthogonal array depends upon the number of control factors and interaction of interest. It also depends upon number of levels for the control factors of interest. L16 orthogonal array is selected with 16 experimental runs and six columns. Taguchi has provided in the assignment of factors and interaction to arrays.

Table 3: L16 Orthogonal array

Test Run	A	B	C	D	E
1	1	1	1	1	1
2	1	1	1	2	2
3	1	1	2	1	2
4	1	1	2	2	1
5	1	2	1	1	2
6	1	2	1	2	1
7	1	2	2	1	1
8	1	2	2	2	2
9	2	1	1	1	2
10	2	1	1	2	1
11	2	1	2	1	1
12	2	1	2	2	2
13	2	2	1	1	1
14	2	2	1	2	2
15	2	2	2	1	2
16	2	2	2	2	1

3. RESULT AND DISCUSSION

3.1 Experimental Results and S/N Ratios

The responses of experiments are recorded for the optimization. The optimization of research parameters is done in the Minitab 16 software through Taguchi Design of Experiments Technique. In this research, the focus is on a single defect which is cold shut so while inspection there is the only single defect is considered in the results. Because the major problem is because of cold shut defect. The Signal to Noise Ratio and mean is shown for the each experiment . Signal represents the desired value which is Percentage of approved casting in this case and noise represents undesirable value.

The SN ratios for different factors and different levels are shown . The rank is also given with the parameters. Rank shows that which factor has a high impact on the response. The average SNR for each signal level and for each factor is shown in Table which is calculating by using following:

Smaller the better

N = -10 Log10 [mean of sum of squares of measured data]

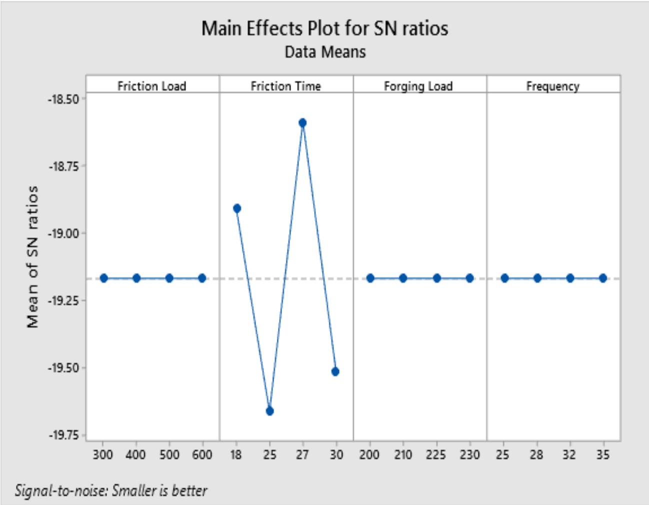
This is usually the chosen S/N ratio for all undesirable characterstics like “defects” etc. for which the ideal value is zero. Also, when an ideal value is finite and is maximum or minimum value is defined, then the difference between measured data and ideal value is expected to be as small as possible The generic form of S/N ratio then become

N = - 10 Log 10 [mean of sum of squares of {measured – ideal}]

Table 4: L16 Test run

Test Run	Friction Load	Friction Time	Forging Load	Frequency	Breaking Load
1	300	30	200	25	9.46
2	300	25	210	28	9.62
3	300	27	225	32	8.50
4	300	18	230	35	8.82
5	400	30	210	35	9.46
6	400	25	200	32	9.62
7	400	27	230	28	8.50
8	400	18	225	25	8.82
9	500	30	225	28	9.46

10	500	25	230	25	9.62
11	500	27	200	35	8.50
12	500	18	210	32	8.82
13	600	30	230	32	9.46
14	600	25	225	35	9.62
15	600	27	210	25	8.50
16	600	18	200	28	8.82



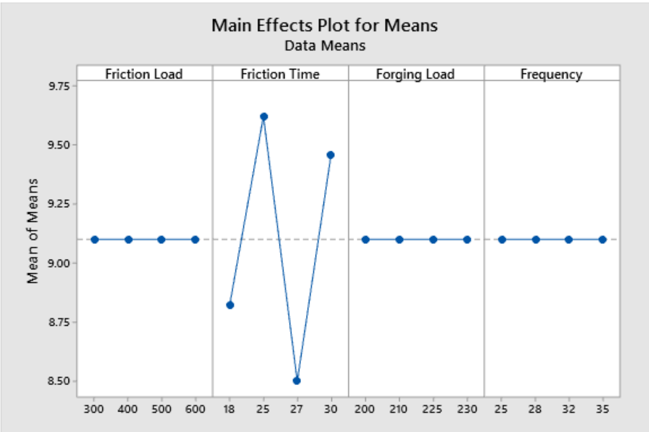


Table 5: Optimum Values

S.NO	FACTORS	Optimum setting	Level
1	Friction Load	300	1
2	Time	18	4
3	Forging Load	200	2
4	Frequency	25	1

4. CONCLUSIONS

The direct effect of the process parameters on the UTS responses has been found from the developed mathematical model. The variation of the responses with respect to each of the three process parameters, friction force, friction time and upset force, were plotted by keeping two parameters constant at their central level and varying the third within the upper and lower bounds. The same phenomenon has been reported during friction welding of mild steel. As the friction welding pressure increases, within limits, the tensile strength of the weld increases, approaching parent metal. Upset force has a negative effect on tensile strength. As upset force increases, the tensile strength decreases. This effect is probably due to the easy deformation of soft material at high forging pressure.

According to the ASM due to the high heat produced under increased friction force, friction weld may behave like hot worked material. The weld metal area has been reduced when the hot forged conditions are increased. It could enhance the more austenite phase in the weld zone. Therefore, the tensile strength found to be decreasing as upset force steps up, reaches a minimum and then increases. Friction force and friction time have a positive effect on tensile strength. As friction force and friction time increase. The same phenomenon has been reported during friction welding of dissimilar materials. The interaction effects of the process parameters on UTS have been found from a developed mathematical model force increases. It can be observed that there is a sudden increase in tensile strength as friction time changes from 60 to 90 s. The interaction between the upset force and friction force on tensile strength. It is clear that the curves show the same trend as the upset force increases. Tensile strength slowly decreases as Friction Force Decreases.

Some recommended areas for further work are:

- **Microstructure modelling**. Models could be used to investigate the impact of the processing conditions on the microstructure and alpha/beta phase evolution. This would allow for the effects of the processing conditions on the allotropic phase, average grain size, grain microstructure and grain spatial distribution to be characterised.

- **Extension to other materials**. The general methodology detailed in this thesis could be used to investigate the effects of the LFW process on the joining of aluminium and aluminium-lithium alloys, nickel-based superalloys and steels – all materials that are finding increasing industrial interest. Dissimilar material combinations could also be considered to understand how the different material properties affect the process and to identify conditions that mitigate intermetallic formation.

Process input characterisation and "triple point" removal. In comparison to research by other authors, the process input range in this study was fairly narrow. For example, the amplitudes investigated ranged between 1 mm to 2.7 mm, whereas the literature7,34 reports values as high as 5 mm. Future work could consider values outside of this range to see if the trends reported in this thesis are still valid. Future work could also consider investigating the effects of the process inputs on the keystone weld thermal profiles. Ideally, conditions that encapsulate the "triple point" region into the rapidly flowing material would be identified. This would allow for it to be expelled at the same rate as the rest of the interface material, reducing the burn-off required to remove the interface contaminants.

Geometry characterisation. With the exception of the work on the keystone geometry, this thesis investigated the joining of workpieces with symmetrical dimensions. Future work could consider the joining of non-symmetrical workpieces, such as coupons to plate

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