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Weightage Allocation to influential parameters in FSW for Yield Strength Evaluation

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ABSTRACT
Friction Stir Welding is the process used for joining relatively softer material like aluminum and its alloys, using a non-consumable tool. The flow of material governs the yield strength of the joint in FSW and there are various parameters which affect this flow. The analytical study conducted in this paper presents rotational speed, welding speed, axial force and tool pin radius as the most influential of these parameters. This work is an attempt to study their effects on yield strength separately by considering maximum temperature generated in the weld zone as governing constraint and then finding and empirical relationship considering the weightage of each parameter in yield strength calculation. This results in the evaluation of optimal range of these parameters and optimal value of yield strength.
Keywords – Friction Stir Welding, Parameter Optimization, Weightage Allocation, Yield Strength

I. INTRODUCTION

The most common Aluminum alloy that finds numerous applications is Al-6061 which has 95-98% of Aluminum and can be joined with the help of soldering and brazing[1]. However, due to melting in these processes, it loses its alloying material and properties and also exhibits cracking which makes the use of these processes inefficient with softer material[2]. Hence the need for a new method was felt which led to the invention of Friction Stir Welding Process. The invention of FSW was carried out at TWI (The Welding Institute) – UK in December 1991[3].

In this process, a very softer region is created between two joining surfaces by generating tremendous heat between them and then huge mechanical pressure is applied which leads to intermixing of mating surfaces resulting in good quality of weld[4]. The translation of tool along the welding direction creates high plastic deformation and flow of plasticized metal.

The process, although seems beneficial for softer materials, show many defects in the weld material[5]. These defects vary with the material or tool positioning and process parameters[3]. Many researchers have studied the variation in defects along with welding speed, tool rotational speed, material position, tool profile etc. and analyzed the behavior of different zones (HAZ - Heat Affected Zone, TMAZ - Thermo-mechanically Affected Zone and NZ - Nugget Zone) of the weld[4,6].

Apart from the behavior of different heat zones, previous studies also include the effect of process parameters, tool geometry and different setups on yield strength and hardness of the weld joint produced. This effect can be analyzed with the help of Taguchi Process[7] and Response Surface Methodology[8]. The contribution of each of these process parameters for valuation of yield strength and hardness of weld material had been represented as separate empirical relationships in previous research works[9-11].

These empirical relations form the basis of research in this paper. The contribution of each parameter can be allotted a weightage and an optimum range of parameters can be found so as to achieve optimal yield strength with the help of a single relationship among all parameters and yield strength. The maximum temperature achieved in the welding zone is considered to be the governing constraint for deciding the range of process parameters which must be less than the solidus temperature of the material.

II. METHODOLOGY

2.1 Identification of all influential parameters for the process

The parameters which have been proved to be influential to the process are tool material, tool rotational speed, welding speed, tool pin radius, pin profile, shoulder diameter, probe design and length, probe retraction, axial force, existence of backup plate etc. The first step is to analyze the level of influence of these parameters on the quality of weld produced.

2.1.1 Tool Material

Tool material plays an important role in the formation of defect free welds. It can be selected on the basis of either the properties required from the tool or the type of material to be welded. The properties such as high strength, excellent ductility, hardness, stability, creep resistance are provided by Nickel and Cobalt based alloys. Similarly, for higher operational temperatures, Tungsten based alloys are a great option.

However, for different materials to be welded, tool materials are selected as given in the Table 1. The tool material determines the rate of friction heating, tool strength and working temperature, that ultimately determines which materials can be friction stir welded.

Table 1: Tool materials for commonly used base metals

Welding material	*Tool material*
Titanium alloys	Tungsten alloys
Magnesium alloys	Tool steel, WC Composite
Aluminium Alloys	Tool steels, Co-WC Composite
Copper alloys	Ni-alloys-alloys, PCBN, Tool steels

2.1.2 Rotational speed

The temperature increases with the increase in rotational speed; so a reasonable range is essential to be identified. The maximum heat generated in a Friction Stir Weld directly depends on Rotational Speed; this relation is given by:

$$q = \left(\frac{2\pi}{S}\right)\mu NFR\eta \qquad (1)$$

where;

q= maximum heat generated

N= Rotational Speed

F= Axial Force

R= Tool Pin Radius

μ=coefficient of friction between tool and weld material

η=Weld Efficiency

Also, tool rotation speed is directly proportional to yield strength of the aluminum alloys. Aluminum alloy with higher yield strength can be welded without defects at higher rotational speed and vice versa. More rotational speed will give more heat generation which makes intermixing better. The relationship is given by:

$$N = 31.60 \times (Y.S)^{0.66} \qquad (2)$$

where;

Y.S. = Yield Strength

2.1.3 Welding Speed

Also termed as traverse speed or traverse rate, this parameter affects inversely the temperature in welding zone, as given in (1). Alloys with higher yield strength can be fabricated without defects at lower welding speed and vice versa. Lower welding speed will provide more time for the material to get welded and thus makes intermixing better. The relation between welding speed and yield strength is given below:

$$S = 1116.8 \times (Y.S.)^{-0.458} \qquad (3)$$

2.1.4 Axial Force

Axial force is the prime factor responsible for the flow of material in welding zone. The higher the force, higher will be the flow of material and subsequently, higher will be the weld strength. It also affects directly the temperature generated in thermo-mechanically affected zone (TMAZ) of a weld joint, as shown in (1).

The axial force is directly proportional to the yield strength of base metal. Aluminum alloy with lower yield strength can be welded without defects at lower axial force and vice versa. Insufficient downward force causes no vertical flow of material and when axial force was increased beyond the limit large mass of flash and excessive thinning were observed due to higher heat input. The relation used between these two quantities is given as:

$$F = 0.627 \times (Y.S.)^{0.707} \qquad (4)$$

2.1.5 Tool Pin Radius

In comparison to other factors, pin radius is less influential for temperature generation although it affects directly the heat generation in welding zone. The pin radius is directly proportional to the yield strength of the base metal. Alloys with higher yields strength can be welded without defects at higher pin radius and vice versa. The relation between yield strength and pin radius has been established similar to the other relationships and can be expressed as:

$$R = (8.67 \times 10^{-6}) \times (Y.S.)^{1.108} \qquad (5)$$

2.1.6 Tool Profile

It has been observed that out of the most common tool profiles in FSW, i.e. Taper Cylindrical, Triangular, Square and Hexagonal, the profile which provides highest Yield Strength and Ultimate Tensile Strength to the weld produced is Hexagonal. It is shown in Fig. 1.

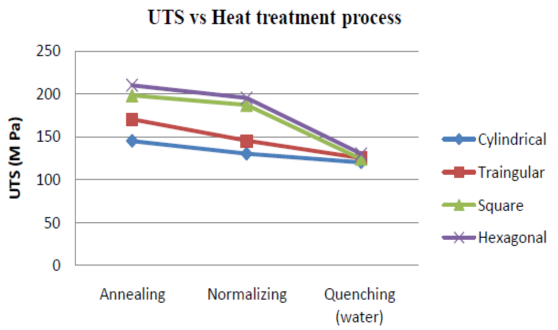

Fig. 1: Effect of Tool Profiles on Ultimate Tensile Strength for different Heat Treatment Processes

From all the influential parameters mentioned above, the parameters which mostly affect yield strength of the material are rotational speed, welding speed, axial force and pin radius. Hence further study is done on these four factors.

2.2 Find the optimal range of all parameters with respect to temperature

Three levels of each parameter, as given in Table 2, are decided and using these values, different combinations of all parameters are made.

Using (1), the maximum heat generated at different values of each parameter can be calculated, keeping the others as constant; one example is shown in Table 3.

The heat generated can then be used to calculate the maximum temperature by the following equation:

$$q = mC_v\Delta T \quad (6)$$

where;
m= Mass of the Weld Specimen
C_v= Specific Heat of Weld Material at constant volume
ΔT= Temperature increased during welding

Table 2: Levels of Parameters

S. No.	Parameter	Level 1	Level 2	Level 3
1	Rotational Speed	550	650	750
2	Welding Speed	90	100	110
3	Axial Force	20	25	30
4	Pin Radius	0.002	0.003	0.004

Table 3: Temperature Variation with Pin Radius keeping other parameters at first levels

N	F	S	R	D	Q	T
550	20	90	0.002	20	3.892	165.083
550	20	90	0.003	20	5.839	232.125
550	20	90	0.004	20	7.785	299.166

Similarly, all the other temperatures are evaluated and the variation of temperature along with pin radius at different levels of rotational speed, welding speed and axial force are analyzed.

The range of each parameter which gives the value of maximum temperature less than solidus temperature (582°C) and high enough to be considered as weldable temperature will be the optimal range for that parameter.

This step will be repeated for each parameter so that an optimal range of each of these parameters is found.

2.3 Evaluate an optimal set of parameters values

The equations (2-5) define the effect of each parameter on yield strength. The result of these equations is tabulated as:

Table 4: Yield strength at different values of parameters

N	YS	S	YS	F	YS	R	YS
550	75.8	90	244	20	134	0	74.1
650	97.7	100	194	25	184	0	111
750	121	110	158	30	238	0	148

However, our objective is to find out an optimal set of values for each parameter which will maximize the yield strength of weld joint. Hence the value of each parameter from its respective range which gives maximum value of yield strength is considered as the best or optimal value.

2.4 Sensitivity Evaluation for each parameter with Yield Strength

As it is clear from Table 4, that a slightest variation in tool pin radius (as low as 0.001m) shows drastic change in yield strength of weld joint numerically. Hence its weightage is assumed to be 50% as compared to the other parameters. This assumption can be favored by the fact that slopes of each graph from **Figure 2 - Figure 5** give the sensitivity of each parameter with respect to the yield strength.

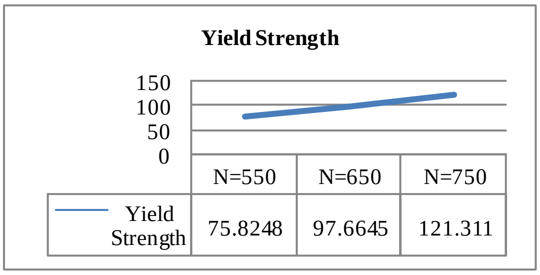

Figure 2: Rotational Speed v/s Yield Strength

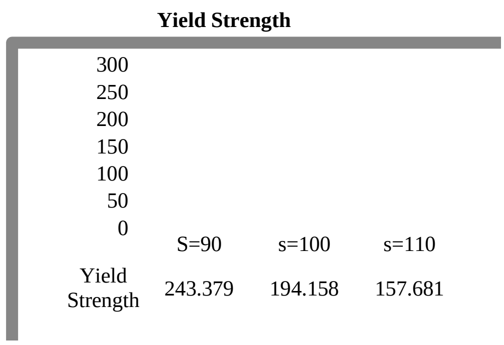

Figure 3: Welding speed v/s Yield Strength

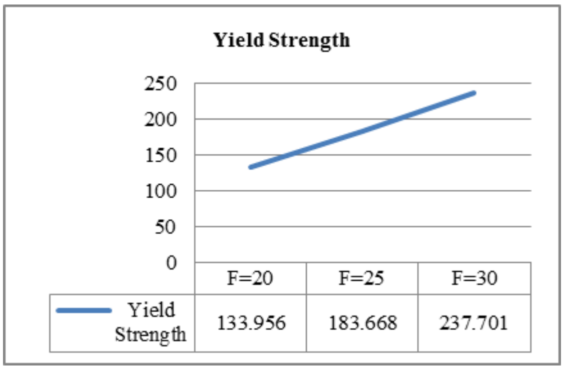

Figure 4: Axial force v/s Yield Strength

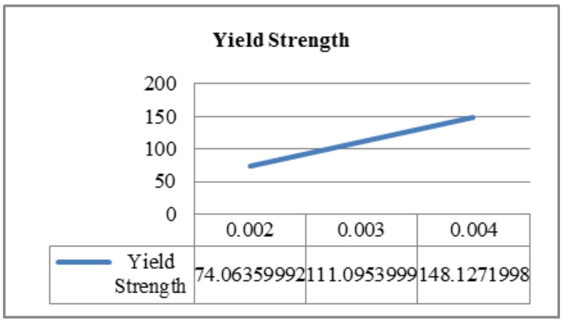

Figure 5: Pin radius v/s Yield Strength

The higher the sensitivity of the parameter, the higher will be the assigned weightage for that parameter in yield strength calculation. The sensitivities are calculated as follows:

$$S_1 = 1.218 \quad S_2 = -5.022$$
$$S_3 = 9.942 \quad S_4 = 37039.39$$

2.5 Analysis of the weightage of all parameters on yield strength

The weightage of each parameter is calculated as follows:

$$W_i = \frac{S_i}{\sum_{i=1}^{3} S_i} \times 0.5$$

0.5 is multiplied to the ratio of sensitivity and sum of sensitivities because of the fact that only 50% of weightage is left for parameters apart from the tool pin radius. Using the above equation, the weightage of rotational speed, welding speed and axial force are found to be:

$$W_1 = \frac{1.218}{16.182} \times 0.5 = 0.0375$$
$$W_2 = \frac{5.022}{16.182} \times 0.5 = 0.155$$
$$W_3 = \frac{9.942}{16.182} \times 0.5 = 0.307$$

2.6 Formation of a single relationship between parameters and yield strength

Hence, the relationship between all four parameters and yield strength is developed as follows:

$$Y.S. = 0.0375 \times Y.S_N + 0.155 \times Y.S_S + 0.307 \times Y.S_F + 0.5 \times Y.S_R$$

III. RESULT

All these parameters and their effects on yield strength are studied simultaneously and the weightage of each parameter on this yield strength is found. The weightage can be shown with the help of a graph as in Figure 6.

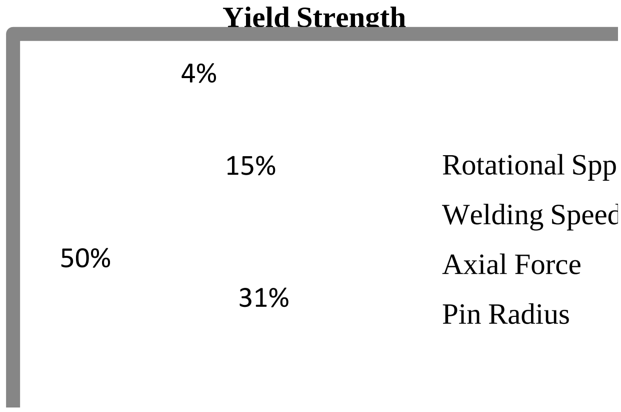

Figure 6: Influence of each parameter on Yield Strength

IV. CONCLUSION

The study shows that the parameter which has highest influence on Yield Strength is Pin Radius while the parameter with lowest influence is Rotational Speed. This result shows that experiments can be done with rotational speed and welding speed up to some extent but Pin Radius needs to be well specified and there are very less chances for its variation. Also, the future scope for this weightage allocation includes its verification and appropriate modifications by performing different experiments.

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