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Multi objective prediction and optimization of control parameters of Friction stir welding on Casted AlSi10Mg plates with Taguchi – Gray Relational Analysis

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Abstract

In this study, a 3 mm thickness of AlSi10Mg Casted alloy plates was used in the friction stir welding process. The experimentations were conducted Using design of experiment to shorten the number of experiments and to get optimal friction stir welding parameters by utilizing Gray relational analysis based on the ultimate tensile and hardness test results. Orthogonal array of L9 (3^3) was used based on three main parameters and three stages for each parameter, where tool velocity of three stages are 800, 900 and 1000 Rpm, tool feed of 30,40,50 mm/min, plus axial load of 300,400 and 500 Kg. Using Minitab 17 software. Gray Relational analysis is used to explore the optimal set of process variables and their effects on the ultimate tensile strength and hardness of weld plates. The plates are effectively welded, tensile test and hardness is measured at room temperature. The end result shows that the tool velocity 1000 rpm, feed 50 mm / min, then axial load of 400 kg are dominant process parameters to join AlSi10Mg Casted alloy plates.

Keywords: Friction stir welding; AlSi10Mg casted alloy; Taguchi technique; Gray Relational Analysis; Ultimate Tensile strength, Hardness

1. Introduction

The need for high strength to weight ratio is continuously growing especially in automobiles and aviation sector in improving fuel efficiency and reducing harmful emissions [1]. AlSi10Mg alloy belongs to hypoeutectic aluminum alloys group. It is frequently used in automotive, aircraft and armed applications because of superior mechanical properties combined with low strength to weight ratio, corrosion resistance and quite decent castability [2]. The presence of Eutectic Al+Si phase in this alloy has greatly effects ductility and strength, and also effects machinability. One of the significant characteristics of AlSi10Mg alloy are low shrinkage and melting point, hence this alloy is highly suitable candidate for casting. FSW (friction stir welding) is solid state joining technique. Especially well-suited to aluminum alloys, even though much care is taken in welding, these are difficult to fusion weld without experiencing hot cracking, porosity, or distortion. The rotating tool's Frictional heat and plastic flow cause major microstructure changes, resulting in variations in the weld's quality on mechanical properties [3]. A nugget or a stir region, a thermo-mechanically affected zone (TMAZ), and a heat affected zone make up the FSW zone (HAZ). The stir zone's grain structure is exceptionally equiaxed and extremely fine, resulting in improved ductility and mechanical endurance [4]. In FSW, the plates are heated to a temperature of one third of its melting point of metal hence the mechanical properties of the welded region, such as ductility and strength, are much higher than in conventional techniques [5-7]. Here, welding process optimization is the primary concern in order to achieve an improved weld joint, as incorrect chosen parameter leads to tool failure and lower weld efficiency. Researchers use a number of optimization methods, such as Taguchi, Grey relation analysis, and ANN, to arrive at the best solution for industrial problems [8,9].

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2. Experimental Work

In this work, AlSi10Mg casted alloy manufactured through casting process is used for experimentation work. 100 mm long 50mm width and 3mm thick Plates are obtained by wire EDM and Spectrometric analysis of chemical composition (Table 1) was also included.

Table 1 AlSi10Mg alloy chemical composition after casting

Si	Mg	Cu	Mn	Fe	Ni	Zn	Pb	Sn	Ti	Al
9.0-11.0	0.2- 0.43	≤0.05	≤0.47	≤0.58	≤0.05	≤0.1	≤0.05	≤0.05	≤0.15	Balance

In this work, FSW is used to join AlSi10Mg alloy plates using R.V. Machine tools make with 3 ton capacity equipped with CNC control. The tool used to join AlSi10Mg plates fabricated by using H13 grade tool steel with 12 mm diameter shoulder and straight cylindrical pin with 4 mm diameter and 2.8mm length, shown in fig.1. Prior to welding, edges were thoroughly cleaned by mechanical method and applied ethanol solution, to make sure edges are free from any contamination. Then the plates are rigidly clamped on to the FSW machine table using clamps and T-bolts. Three FSW parameters were selected with three levels shown in table.2. Friction stir welding carried out using 9 different parameter combinations that were derived using Taguchi's DOE concept. Gray relational method is used to study the response of output parameters over input parameters [5].

Figure 1 Friction Stir welding Setup

Figure 2 FSW Tool

Table 2 Input process variables and their corresponding levels

Parameters	Symbol	stages		
		I	II	III
Tool velocity	St	800 rpm	900 rpm	1000 rpm
Welding speed	Fw	30 mm/min	40 mm/min	50mm/min
Axial Force	Af	300 kg	400 kg	500 kg

After welding, using wire EDM specimens for Tensile and microstructural analysis are cut perpendicular to the weld direction as per ASTM E8-4 from all nine samples. Tensile tests were conducted using Nano BISS 25KN fig.3 using 0.1mm/min as strain rate and Average Ultimate tensile strength and percentage of elongation was measured with three trails fig 4, using Digital micro hardness tester (HVS-100B model) was used to measure the micro hardness in the weld zone loading 200gm and a reside time of 15 sec used to measure micro hardness at HAZ. Tensile test results, micro hardness along with theirs corresponding levels of process variables are listed in table.3

Table 3 Experimental Trails using L9 orthogonal array and their response

Experiment Number	Tool Velocity (T_s)	Welding speed (F_w)	Axial load (A_l)	UTS	HAZ Micro Hardness
1	1	1	1	131.54	65.74
2	1	2	2	125	68.12
3	1	3	3	126.13	63.41
4	2	1	2	131.8	65.47
5	2	2	3	100	76.77
6	2	3	1	128	68.49
7	3	1	3	117.5	77.03
8	3	2	1	136.92	70.6
9	3	3	2	140.95	75.49

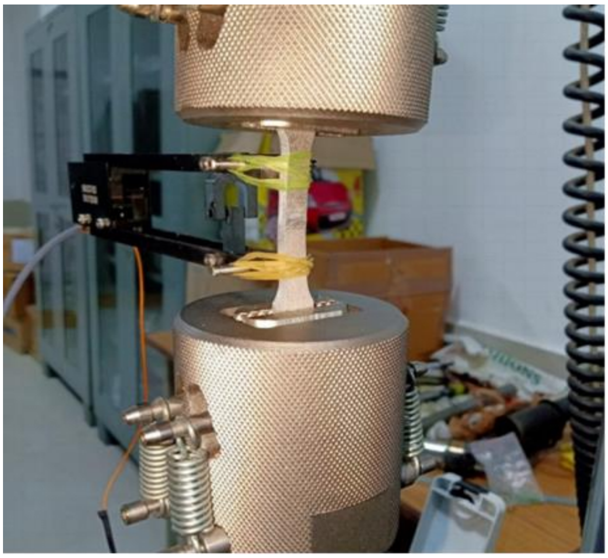

Figure 3 Tensile test setup

Figure 4 Tensile Test Samples

2.1. Gray Relational Analysis

Grey relational analysis technique has been used where n = number of trails, yij = detected response significance where i=1, 2, ...n; j=1, 2...k This is used to solve problems where the goal is to increase the quality of a desired characteristic. This is known as the larger-is-better scenario, **a**nd to be an important method for optimizing multiple responses. To find the optimum value in GRA, the sequence of steps are:

Step I S/N Ratios are determined by below equations

i) Higher is the better

S/N ratio($\boldsymbol{\eta}$) = $$-10\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{x^{2}_{ij}} \qquad (1)$$

(This is known as the Higher – is **-** better scenario, in which the aim is to maximization of response.)

where n= the number of replicas, x_{ij}=observed responses, where i=1, 2, ...n; j=1, 2...k This is useful for situations where the objective is to increase the quality parameter of interest. This is referred to as the "higher is better" situation.

ii) The lower the better.

$$\text{S/N ratio}(\boldsymbol{\eta}) = -10\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n} {x_{ij}}^2 \qquad (2)$$

(This is known as the smaller-is-better scenario, in which the aim is to minimization of response.)

Step II x_{ij} is normalize as Z_{ij} (0≤Zij≤1) using the formula to minimize uncertainty and elude the impact of using diverse units Before using the grey relation theory or some other methodology to analyze the original data, it is important to normalize it. To make the sum of this array approximate to 1, an equivalent value subtracted from the same list of values. We investigated the normalization process's sensitivity to the sequencing results, because the normalization process affects the rank. As a result, when using grey relation analysis to normalize data, we suggest using S/N ratio value.

$$Z_{ij} = \frac{x_{ij} - \min(x_{ij}, i = 1, 2, ...n)}{\max(x_{ij}, i = 1, 2, ...n) - \min(x_{ij}, i = 1, 2, ...n)} \qquad (4)$$

(applied for S/N ratio with higher is the better scenario)

$$Z_{ij} = \frac{\max(x_{ij}, i = 1, 2, ...n) - x_{ij}}{\max(x_{ij}, i = 1, 2, ...n) - \min(x_{ij}, i = 1, 2, ...n)} \qquad (5)$$

(applied for S/N ratio with Lower the better scenario)

Step III Using the S/N ratio values that have been normalized, evaluate the grey relational co- efficient

$$\gamma(x_0(k), x_i(k)) = \frac{\Delta\min + \xi\Delta\max}{\Delta_{0j}(k) + \xi\Delta\max} \qquad (6)$$

Where

- J=1,2,3…m, n are the number of experiments conducted and m is output response
- $x_0(k)$ is the reference sequence ($x_0(k)$ =1,k=1,2,3…m); $x_i(k)$ is a particular comparison sequence.
- $\Delta_{0j}(k) = \|x_0(k) - x_i(k))\|$ is The distinction between x_0(k) and x_i(k) in absolute terms.
- $\Delta\min = \min_{\forall j \in i} \min_{\forall k} \|x_0(k) - x_i(k))\|$ is the smallest possible value for x(k)
- $\Delta\max = \min_{\forall j \in i} \min_{\forall k} \|x_0(k) - x_i(k))\|$ is the largest value of x(k)
- ξ is the distinguishing coefficient, ξ , is within the given range $0 \le \xi \le 1$ (the coefficient may be modified depending on the system's practical needs).

Step IV obtain the Gray Relational Grade

$$\overline{\gamma_j} = \frac{1}{k}\sum_{i=1}^{n}\gamma_{ij} \qquad (7)$$

where $\overline{\gamma_j}$ is grey relational rating for jth trail, and number of output features are k.

Step V Determine the best factor to use and the best degree combination for it.

Good product quality needs The greater the grey relational grade(GRG), as a consequence, the factor effect can be assessed using the GRG., similarly for each controllable factor, the optimal degree should be calculated.

For instance, to assess the impact of a factor i, we determine the average grade value(AGV) for each level j, and indicated as AGV_j , the effect, E_i, can be defined as

$E_{i= Max(AGVij)}$-min($_{AGVij}$)

once we control factor i, Finest value of J* is obtained by

j*=max$_j$ ($_{AGVij}$)

2.2. Implementation of the GRA

Step I Using one of the Eqs (1), (2), compute S/N ratios of the initial conditions and the S/N ratios for a given response. Depending on what kind of quality characteristics you're looking for. Table 3 shows the computed S/N ratios related to each quality characteristic.

Step II S/N ratio values should be normalized by Eqs. (3), (4) and (5). Table 3 shows the results.

Step III The grey relational analysis should be carried out. using the information in Table 3, Using Eq, (6) compute the grey relational co-efficient using normalized S/N ratio values. ξ can be assumed as 0.5 in Eq. (6) for this run. Since all process parameters are equally weighted, [10]. Table 4 summarizes the results.

Step IV The GRG can then be calculated using Eq. (7). then, grades are taken into account when attempting to solve the multiple-response parameter problem. Table 5 summarizes the findings.

Step V Maximum of grade values is taken into consideration (Table 5),,we can obtain optimal parameter conditions Ts3 Fw3 A_l 2.

2.3. Grey relational analysis

Table 4 S/N Ratios and corresponding Normalized S/N ratios

Experiment number	S/N Ratios		Normalized S/N ratios	
	UTS	HAZ Hardness	UTS	HAZ Hardness
1	42.3812	-36.3566	0.7987	0.1855
2	41.9382	-36.6655	0.6501	0.3682
3	42.0164	-36.0432	0.6763	0.0000
4	42.3983	-36.3208	0.8045	0.1643
5	40.0000	-37.7038	0.0000	0.9826
6	42.1442	-36.7125	0.7192	0.3961
7	41.4008	-37.7332	0.4698	1.0000
8	42.7293	-36.9761	0.9155	0.5520
9	42.9813	-37.5578	1.0000	0.8962

Table 5 Grey relational co-efficient and associated grey grade values

Experiment number	Grey relational co-efficient		grey grade values	
	UTS	HAZ Hardness	Grade	Gray Order
1	0.7130	0.3804	0.3644	5
2	0.5883	0.4418	0.3434	8
3	0.6070	0.3333	0.3135	9
4	0.7189	0.3743	0.3644	7
5	0.3333	0.9664	0.4332	4
6	0.6404	0.4529	0.3644	6
7	0.4854	1.0000	0.4951	2
8	0.8554	0.5274	0.4609	3
9	1.0000	0.8281	0.6094	1

Table 5 was used to compute the GRG means to each degree of controllable parameters, which were then summarized in Table 6. Highlighted values in Table 6 indicates larger GRG, the superior the compound performance characteristics. So, the controllable parameters' and their optimal values are: Tool velocity of 1000 rpm (stage 3), feed rate of 50 mm/min (stage 3), axil load of 400 kg (stage 2).

Table 6 Response table for GRG (grey relational grade)

Parameters	stage 1	stage 2	stage 3	Rank	
Tool velocity	0.340	0.387	0.522	0.181	1
Welding speed	0.408	0.413	0.429	0.021	3
Axial Load	0.397	0.439	0.414	0.042	2

Total mean value of the GRG = 0.417

Table 6 shows the responses for Gray relational grade, Rotational speed has given rank 1, hence it has more influence on the tensile strength and hardness among three input parameters, as it causes more frictional heat input during welding. Large heat input causes grain refinement and leads to better Ultimate tensile strength and micro hardness. Next influential parameter among three is the Axial load raked 2, and the least influential parameter is the Feed Rate ranked 3.

3. Results and discussion

In this article, Using Taguchi's experimental design process, the parameters influencing the multiple performance characteristics of Friction stir welding of AlSi10Mg Casted alloy were investigated. For better multiple performance characteristics, the optimum Friction stir welding parameters were established. (Ultimate Tensile strength, Micro hardness) in the FSW process with the aid of grey relational analysis. Where three separate controllable parameters are used, this study suggests using an orthogonal array in conjunction with GRA to optimize multiple performances of the FSW process: Tool velocity, Feed rate, and Axial Load. Since tool velocity is a major factor in heat generation near the weld zone, tool velocity was considered a sensitive parameter in the FSW phase. At low tool velocity, heat generation is limited, resulting in poorer plastic deformations and weld region is sufferers with insufficient material flow, lowering hardness. However, with greater tool velocity, the heat produced increases, causing turbulence to form coarse grains. As a result, the hardness of the material is reduced. As welding speed increases, the hardness values decreases. [11].

4. Conclusion

- Looking at GRG values and table 6 reveals that higher GRG aims better multiple response. As a result, ideal levels in FSW of AlSi10Mg casted alloy for the combination of desired output characteristics Ts3 Fw3 A_l 2 parameters. With this combination it is possible to get more Ultimate tensile strength and reasonable Micro hardness in the heat effected zone of FSWed joint.
- 2 According to the GRG findings, tool velocity, axial load, and Axial load have a significant impact on different responses.
- This work can be considered as reference to establish the optimized process parameters for joining Additive Manufactured AlSi10Mg.

Compliance with ethical standards

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Disclosure of conflict of interest

All authors declare that they have no conflict of interest.

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