Multi Response Optimization of Friction Stir Welding Process Parameters on Dissimilar Magnesium Alloys AZ 31 and ZM 21 using Taguchi-Based Grey Relation Analysis

S.Prasath, S.Vijayan, D. Elil Raja

This article presents the optimization of process parameters in Friction Stir Welding of Dissimilar Magnesium Alloys AZ 31 and ZM 21 with multiple responses based on Taguchi orthogonal array with grey relational analysis. The responses considered are tensile strength of the joint and weight loss in the salt fog corrosion test. The process parameters considered for optimization are the Rotational speed of the tool, Tool pin profile and axial load. The aim of this study is to find the best process parameters to maximize tensile strength while minimizing the aspect weight loss in the salt fog corrosion test. Based on the grey relational grade and ANOVA, optimum parameters have been identified and validated by the confirmation run. It has been concluded that tool pin profile and rotational speed are the dominant parameters while the axial load considered did not have significant effect on the responses.

KEYWORDS: GREY RELATION ANALYSIS; L16 ORTHOGONAL ARRAY; MULTI RESPONSE OPTIMIZATION, MAGNESIUM ALLOYS AZ 31 AND ZM 21, FSW AND SALT FOG CORROSION

INTRODUCTION

The thirst of new high specific strength structural materials is highly needed to solve and improve the fuel efficiency problems that faced by the transportation industries (Automotive or air space). A material which withstands load as well as it should be less in weight is required in the current scenario. Magnesium alloys are emerging as important engineering materials, especially in aerospace and automobile sectors, because of their low density (1.73 to 1.85 g/cc), high strength-to-weight ratio, high damping capacity and recyclability. Though the Magnesium alloy captures its attention in automotive industries, it has its own inherent properties of poor corrosion and wear properties have limited their use in industries.

In traditional fusion welding (tungsten inert gas and metal inert gas) of magnesium alloys results loss in mechanical

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properties as compared to its base material significantly due to the coarsening of the grain especially in the heat affected zone (HAZ) [1,2].The limitations of coarsening of grains in HAZ region has been overcome by the electron beam welding and laser welding [3–7].The Friction Stir Welding is the best among all the welding process as its overcomes all the problem associated with fusion welding process like stress induction, pores, excessive spatter, undercutting, burn-though, weld-pool sag, porosity, oxide inclusions, loss of alloying elements, liquation and solidification cracking. Compared to fusion welding processes the solid state Friction Stir Welding (FSW) process offers many advantages such as no splash, no smoke, and no oxidation, and no shielding gas [8]. The significant process parameters are rotational speed, tool pin profile, welding speed and axial load [9].Thus FSW is a suitable process for welding dissimilar magnesium alloys AZ 31 and ZM 21.In this paper multi response optimization is carried out based on the Taguchi L9 Orthogonal array with Grey Relational analysis. The responses considered are the tensile strength of the FSW welded joints and the material weight loses in Salt Fog Corrosion test.

EXPERIMENTAL PROCEDURE

The experimental procedure, chemical composition, mechanical properties, fabricated different tool profile of the tool as well as its geometry and the levels of the process parameter are debilitate discussed in our earlier publication [10] and the same experimental procedure is followed for this paper.Taguchi based Grey relation analysis L9 experimental design is used in this investigation for multi response optimization. The ASTM E 8 standard is used for testing for tensile strength. Three samples of the specimens were tested to avoid the noise level of the responses. The mean values of tensile strength and the weight loss due to salt fog corrosion test is reported in the table 1.

Tab.1 - L9 Experimental Layout with Mean value of response.

Sl No	Input Parameter			Mean Responses	
	A	B	C	Tensile Strength (Mpa)	Weight loss (gm)
1	1	2	2	163.0	0.392
2	1	3	3	147.0	0.569
3	2	1	2	136.5	0.531
4	2	2	3	172.0	0.524
5	2	3	1	167.0	0.532
6	3	1	3	136.0	0.527
7	3	2	1	199.0	0.501
8	3	3	2	193.5	0.527
9	1	2	2	163.0	0.573

SALT FOG CORROSION

The Magnesium alloys is hypersensitive to corrosion in the combative environment. The corrosion of magnesium alloys is highly depended on the presence of chlorine ion content and pH value of the corrosive solution. The metallurgical factor such as the chemical composition of the alloying elements, grain size, shape and distribution of secondary phases or intermetallic compound particles, inclusions, solute-aggregated grain boundaries (GBs), crystallographic orientations and dislocation density are the main factors which affects the corrosion of an alloy. The general corrosion, galvanic corrosion, pitting corrosion, filiform corrosion, IGC, EFC, stress corrosion cracking (SCC), corrosion fatigue (CF) etc. are the different modes of corrosion seen in Magnesium alloys.

From the fabricated FSW joints the corrosion specimens of size 50 mm x 16 mm x5 mm were sliced and polished with different grade of emery paper, cleaned with acetone, distilled water and dried in warm air [11-13] is shown in figure 1. The polished specimens were subjected to salt fog corrosion test of pH value 7, the temperature at 360 C and 5% concentration of NaCL and exposed to the corrosive environment for 72 hours and the photograph of the salt fog corroded sample is shown in the figure 2..Localized corrosion is prone to occur under low pH value or acidic and neutral solution.

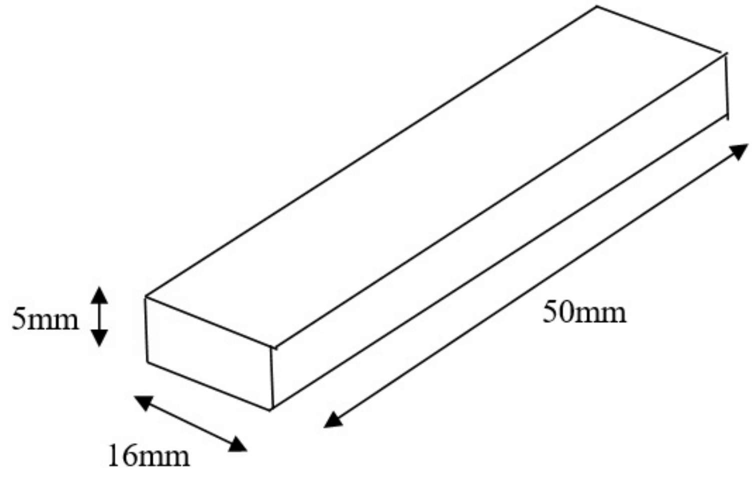


Fig.1 - Dimensions of the salt fog sample.

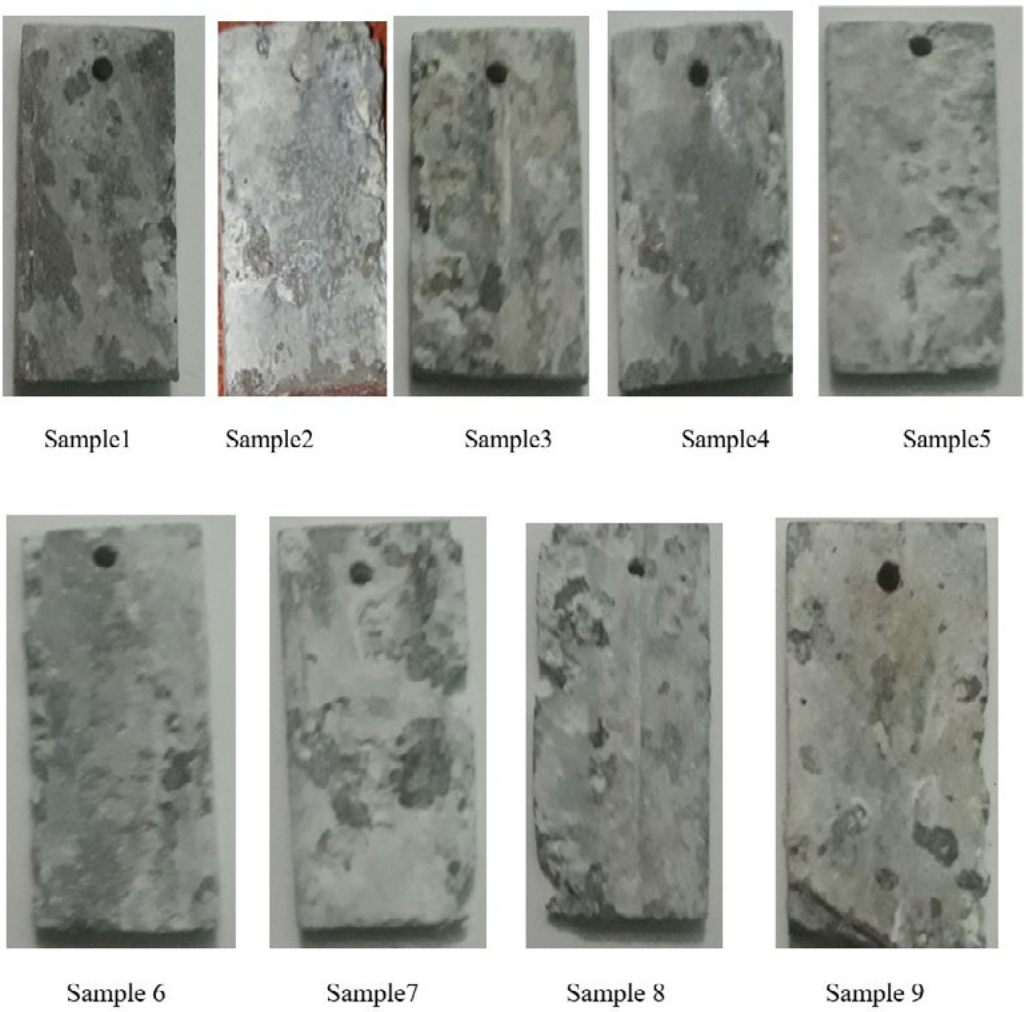


Fig.2 - Photograph of the salt fog corroded samples.

The three different types of corrosion such as Galvanic corrosion, Pitting corrosion and Filiform corrosion can be visualized in the micro structure of the corroded samples of dissimilar Magnesium welds.

Generally Galvanic corrosion initiates from the different size of the grains of an alloy. The welded samples has different zones like base metal AZ31 ,HAZ, TMAZ, Nugget, Base metal of ZM 21 as well as the interfacing zone. As the different zones had different grain size the galvanic corrosion accelerates in the presence of neutral NaCL solution, Al acts as the cathode initially in the Al-Mg galvanic coupling. The dissolution of magnesium the solution turns into alkaline and the Al turns into anode due the alkalized effect. The average grain size of Magnesium alloy AZ 31 and ZM 21 are 70µm and 40 µm respectively as the base metal AZ 31 is prone to corrosion than the ZM21 is witnessed in the photograph of the corroded sample as well as in the microstructure of the base metal sides. Basically the Magnesium alloys are non-corrosive in the alkaline medium, but the presence of Cl- in the solution will increases the rate of corrosion. The segregation of $Mg(OH)_2$ and MgO as dis-continuous layer layers in the alkaline medium forms the absorption sites of anions for Cl-. Beyond the self-corrosion potential the alpha Magnesium dissolves and forms the hemispherical pits is seen in the microstructure of the corroded samples. The reactions happened in the anode and cathode are summarized in the following equations

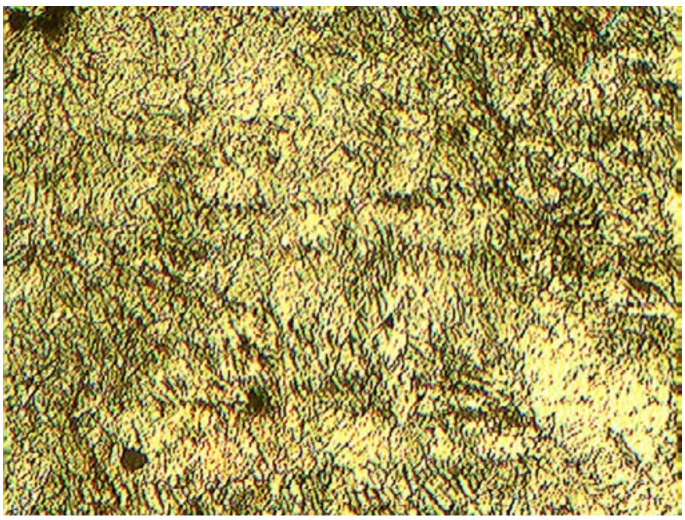
Anodic Reaction $$Mg \rightarrow Mg^{2+} + 2e^{-} \quad 1)$$

Cathodic Reaction $$2H_2O + 2e^{-} \rightarrow 2OH + H_2 \uparrow \quad 2)$$

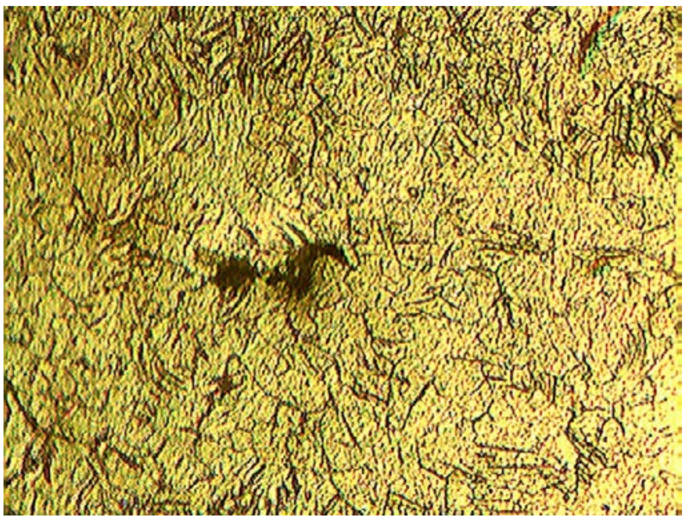
Total Reaction $$Mg^{2+} + 2H_2O \rightarrow Mg(OH)_2 + H_2 \uparrow \quad 3)$$

Pitting corrosion is also affected by the grain size. The corrosion morphology changes from pitting to homogeneous or uniform corrosion in the nugget region of the weldments due to the presence of refined grains of size of 5.46 µm which is clearly captured and seen in the nugget region microstructure.

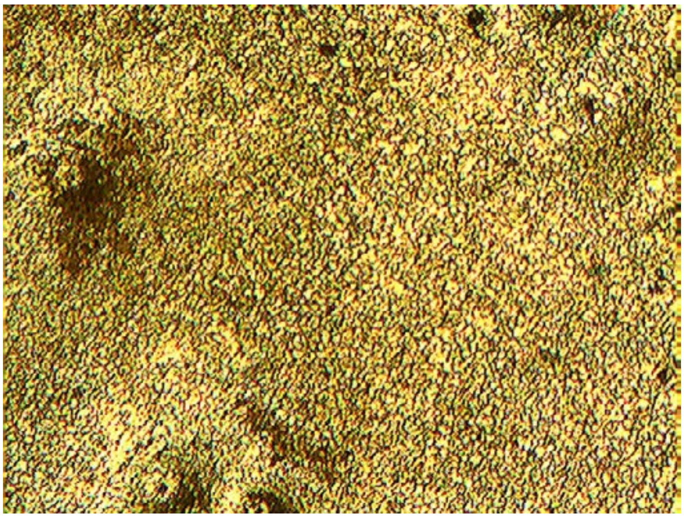
The filiform corrosion and the pitting corrosion occur simultaneously in the Magnesium alloys when exposed to air and NaCl in the salt fog corrosion test. The filiform corrosion initially originates from the active spot of the pitting corrosion and extend itself forward through the active corrosive area of the metal surface. And it is mainly due to the evolution of hydrogen rather than oxygen absorption. The microstructure of the different zones of the FSW corroded metal surfaces is shown in the figure 3.



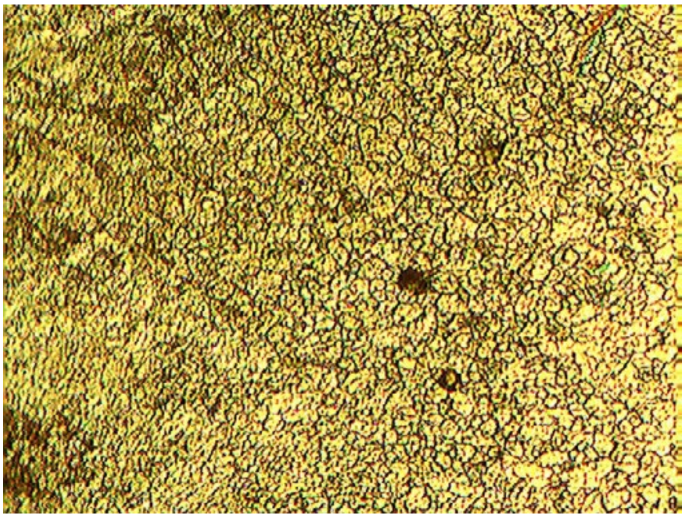
Base metal ZM21 side – 100X



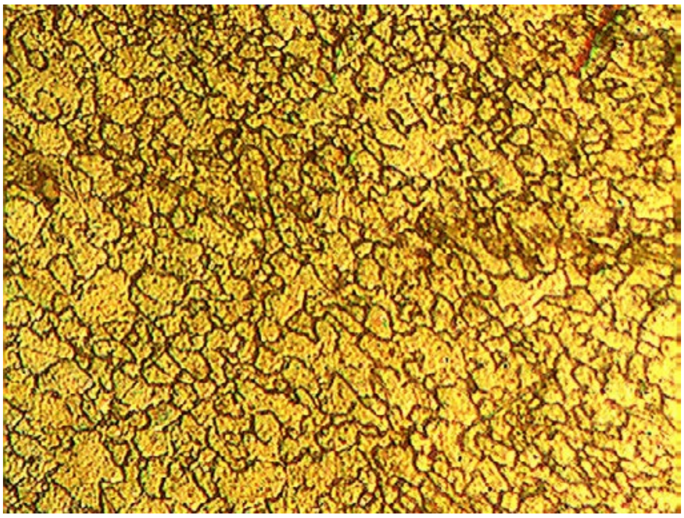
Base metal ZM21 side – 200X



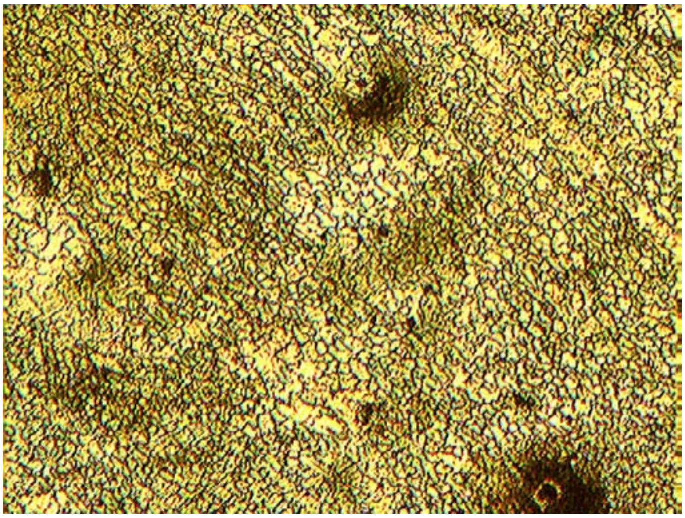
Interface region of ZM21 side with nugget region-100X



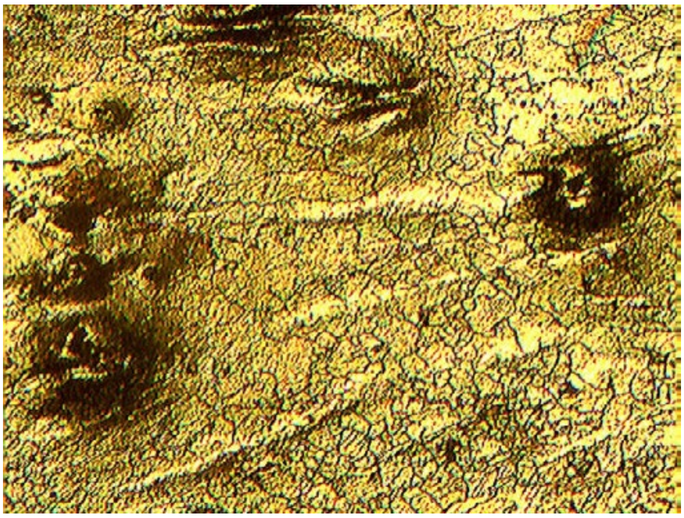
Nugget region -100X



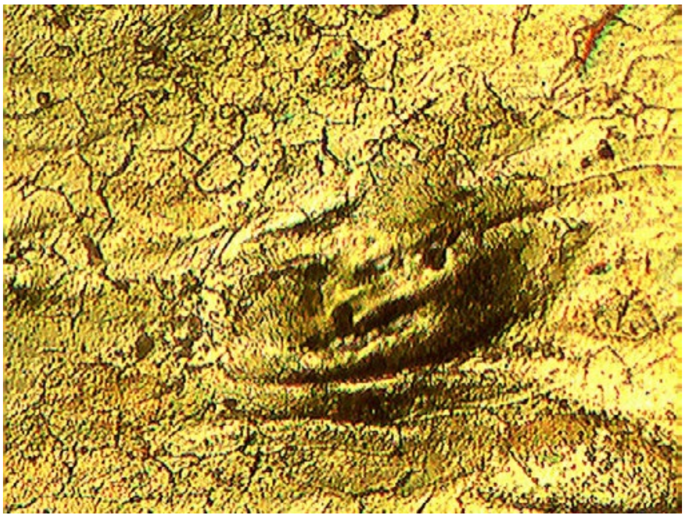
Nugget region -200X



Interface of AZ31B with nugget – 100X



Base martial AZ31B -100X



Base martial AZ31B -200X

Fig.3 - The microstructure of the different zones of the FSW corroded metal surface.

The main purpose to conduct the salt fog corrosion test is to find the material loses as the welds are exposed to the corrosive environment. Maximization of the tensile strength and minimization of the material loses are the two different responses considered for the multi response optimization. The conflicting quality characteristic function (ie. maximization and the minimization) mathematically makes interesting in optimizing the objective function and it being the novelty of this investigation.

GREY RELATION ANALYSIS

The grey relational analysis based on grey system theory. Grey relational analysis is an efficient tool for such multi-response analysis. It can be used for solving the interrelationships multi response problems [14-15]. In grey relational analysis the first step is to perform the grey relational generation by normalising the responses in the range between 0 and 1 to avoid the different scales and units problem of the responses considered. As the response tensile strength of the joint is fall under the larger the better category the normalisation is done by using the equation 4.The weight loses due to the salt fog corrosion test is the minimizing function it is normalised by using the equation 5.The normalised values of the responses are reported in the table no 2. Then calculate the grey relational coefficient from the normalized data using the equation 6 which correlates between the desired and actual experimental data. The overall grey relational grade is then computed by averaging the grey relational coefficient corresponding to each performance characteristic. The grey relation co efficient, the average and the ranking is shown in table no 3. Overall evaluation of the multiple performance characteristics is based on the calculated grey relational grade. Thus the optimization of the multiple response characteristics is converted into single grey relational grade. The optimal level of the process parameters is the level with the highest grey relational grade. Analysis of variance (ANOVA) is performed to find the statically significant process parameters. With the grey relational analysis and statistical analysis of variance, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the analysis. [16-18].

STEPS IN GREY RELATIONAL ANALYSIS

Step 1

Larger-the-better performance characteristic is normalized as follows:

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad 4)$$

Lower-the better performance characteristic, is normalized as follows:

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad 5)$$

Where, $x^*_i(k)$ is the value after grey relational generation

min $x^0_i(k)$ is the smallest value of $x^0_i(k)$

max $x^0_i(k)$ is the largest value of $x^0_i(k)$

Tab.2 - Normalized values of the response

Sl No	Responses		Normalised value of the	
	Tensile Strength (MPA)	Weight loss (gm)	Tensile Strength	Weight Loss
1	163	0.392	0.428571	1
2	147	0.569	0.174603	0.022099
3	136.5	0.531	0.007937	0.232044
4	172	0.524	0.571429	0.270718
5	167	0.532	0.492063	0.226519
6	136	0.527	0	0.254144
7	199	0.501	1	0.39779
8	193.5	0.527	0.912698	0.254144
9	163	0.573	0.428571	0

Step 2

The grey relational co efficient [$\xi_i(k)$] can be calculated as follows:

$$\xi_i(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{oi}(k) + \zeta \Delta_{max}} \quad 6)$$

Where, $x^*_0(k)$ denotes the reference sequence

$x^*_j(k)$ denotes the comparability sequence

$\xi \varepsilon [0-1]$ is the distinguishing co efficient; 0.5 is widely accepted

$\Delta 0i = \left\| x^*_0(k) - x^*_i(k) \right\|$ is the difference in absolute value between $x^*_0(k)$ and $x^*_j(k)$

$\Delta_{min} = \min_{\forall j \in i} \min_{\forall j \in k} \left\| x^*_0(k) - x^*_i(k) \right\|$ is the smallest value of $\Delta 0i$

$\Delta_{max} = \max_{\forall j \in i} \max_{\forall j \in k} \left\| \left\| x^*_0(k) - x^*_i(k) \right\| \right\|$ is the largest value of $\Delta 0i$

Step 3

The grey relational grade is obtained as:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \quad 7)$$

where, n is the number of performance characteristics.

Tab.3 - Grey relational co efficient, Grey relational grade and Ranking

Sl No	Grey Relational Co Efficient		Grey Relational Grade	Ranking
	Tensile Strength (MPA)	Weight loss (gm)		
1	0.466667	1	0.733333	1
2	0.377246	0.338318	0.357782	9
3	0.335106	0.394336	0.364721	8
4	0.538462	0.406742	0.472602	4
5	0.496063	0.392625	0.444344	5
6	0.333333	0.40133	0.367332	7
7	1	0.453634	0.726817	2
8	0.851351	0.40133	0.626341	3

The mean value of grey relation grade is 0.4995.

OPTIMUM LEVELS OF THE FACTOR

The optimum levels of the factors are determined by computing the level average of the grey relational grade. The higher the grey relation grade implies the better quality characteristics irrespective to its quality function considered (maximization / minimization). The higher value of the level averages indicates the optimum level of the factor. The average grey relational grade and the optimum levels of the factors are listed in Table 4. The optimum levels of the process parameters based on grey relation grade is $A_3B_1C_1$.

Tab.4 - The average grey relational grade at each level

Process Parameter	Average Grey Relational Grade			Max-Min
	Level 1	Level 2	Level 3	
Rotational speed	0.4853	0.4281	**0.5844***	0.1563
Tool pin Profile	**0.6443***	0.4762	0.3774	0.2669
Axial load	**0.5757***	0.4101	0.5120	0.1655

* Indicates the optimum level of the factor

ANALYSIS OF VARIANCE (ANOVA)

The Analysis of variance is performed to find statistically the significant factor. In F test high value of F of a factor indicates gives the clear picture of the significant factors and its contribution towards the response. The ANOVA for Grey Relation Grade is calculated and listed in table 5.

In our investigation, all the three process parameters are statistically significant. The tool pin profile is the most significant factor followed by the axial load and the rotational speed of the tool. And they contribute 57 %, 22% and 20% respectively.

Tab.5 - Analysis of variance for means

Source	DoF	Seq SS	Adj SS	Adj MS	F	% Contribution
A	2	0.037520	0.037520	0.018760	11.66	19.56
B	2	0.109254	0.109254	0.054627	33.97	56.96
C	2	0.041832	0.041832	0.020916	13.01	21.81
Residual Error	2	0.003217	0.003217	0.001608		1.68
Total	8	0.191823	0.191823			100

PREDICTED OPTIMUM CONDITION

Based on the experiments, the optimum level setting is A3B1C1. The additive model to evaluate the predicted tensile strength is taken from the literature. The average Grey Relational Grade values of the factors at their levels are taken from Table 4 and the predicted Grey Relational Grade given below:

Grey Relational Grade (predicted)

$= A_3+B_1+C_1-2T$

$= 0.5844+0.6443+0.5757-2*0.4995$

$= 0.8054$

Where, A 3 - Average Grey relation grade value of rotational speed at 3rd level

B1 - Average Grey relation grade value of Tool pin Profile at 1st level

C1 - Average Grey relation grade value of Axial Force at 1st level

T - Overall Average Grey relation grade

CONFIRMATION RUN

The confirmation experiments were carried out by setting the process parameter at optimum levels. The rotational speed, Tool Profile, and axial force were set at 2100 rpm, Hexagonal Toot pin and 3kN respectively. Three tensile specimens were subjected to tensile test and the average value of the Friction Stir welded of dissimilar Magnesium alloys was 186 MPa with 0.4125 gm weight loss. The confirmation experimental results are given in Table 6. The grey relation grade values of the initial, predicted and confirmation run experiments is shown in Table 7.

Tab.6 - Experimental results for the optimized parameter

Ex. No	A, Rotational speed (rpm)	B, Tool pin Profile	C, Axial force (kN)	Tensile Strength Mpa	Weight Loss gm
1	2100	Hexagonal	3.0	186	0.4125

Tab.7 - Grey relation grade values of initial, predicted and confirmation run

Setting Level	Initial Data	Optimal Machining Parameter	
		Prediction	Experiment
	$A_1B_1C_1$	$A_3B_1C_1$	$A_3B_1C_1$
Tensile Strength (Mpa)	163		186
Input power (Watts)	0.392		0.4125
Grey Relational Grade	0.733333	0.8054	0.76159

Improvement in the grey relation grade is 0.028257.

CONCLUSION

1. The L9 Taguchi orthogonal designed experiments of Friction Stir Welding on Dissimilar Magnesium alloys AZ 31 and ZM21 were successfully conducted.
2. The FSW process parameters are optimized towards the tensile strength of the joint and weight loss at salt fog corrosion test using grey relation analysis. The optimal levels of the rotational speed, Tool pin Profile, and axial force is 2100 rpm, hexagonal pin profile and 3 kN respectively.
3. The tool pin profile is the highly significant factor among the process parameter considered.

REFERENCES

[1] Jiang HM, Li SH, Wu H, Chen XP. Numerical simulation and experimental verification in the use ozf tailor-welded blanks in the multi-stage stamping process. J Mater Process Technology, 2004;151:316–20.

[2] Panda SK, Kumar DR, Kumar H, Nath AK. Characterization of tensile properties of tailor welded IF steel sheet and their formability in stretch forming. J Mater Process Technology 2007;183:321–32.

[3] Behler K, Berkmanns J, Ehrhardt A, Frohn W. Laser beam welding of low weight materials and structures. Mater Des 1997;(18/46):261–7.

[4] Liao Y-C, Yu MH. Effects of laser beam energy and incident angle on the pulse laser welding of stainless steel thin sheet. J Mater Process Technol 2007;190:102–8.

[5] Cao X, Jahazi M, Immarigeon JP, Wallace W. A review of laser welding techniques for magnesium alloys. J Mater Process Technol 2006;171:188–204.

[6] Zhang ZD, Liu LM, Shen Y, Wang L. Mechanical properties and microstructures of a magnesium alloy gas tungsten arc welded with a cadmium chloride flux. Mater Charact 2008;59:40–6.

[7] Kolodziejczaka P, Kalita W. Properties of CO2 laser-welded butt joints of dissimilar magnesium alloys. J Mater Process Technol 2009;209:1122–8.

[8] Y U Sirong , CHEN Xianjun , HUANG Zhiqiu , LIU Yaohui ,(2010), "Microstructure and mechanical properties of friction stir welding of AZ31B magnesium alloy added with cerium",Journal of Rare Earths, Vol. 28, No. 2, Apr. 2010, p. 316.

[9] S.Vijayan S.Prasath and S. R. Koteswara Rao (2016), "Optimization of Friction stir .welding process parameters for joining ZM21 to AZ31 of dissimilar Magnesium alloys using Taguchi Technique", La Metallurgia Italiana, Vol.5, pp.25-33.

[10] D. Thirumalaikumarasamy*, K. Shanmugam, V. Balasubramanian (2014), "Influence of chloride ion concentration on immersion corrosion behaviour of plasma sprayed alumina coatings on AZ31B magnesium alloy",Journal of Magnesium and Alloys 2 (2014) 325-334.

[11] A. Dhanapal, S. Rajendra Boopathy, V. Balasubramanian(2012), "Influence of pH value, chloride ion concentration and immersion time onccorrosion rate of friction stir welded AZ61A magnesium alloy weldments",Journal of Alloys and Compounds 523 (2012) 49– 60.

[12] A. Dhanapal , S. Rajendra Boopathy , V. Balasubramanian (2011), "Developing an empirical relationship to predict the corrosion rate of friction stir welded AZ61A magnesium alloy under salt fog environment",Materials and Design 32 (2011) 5066–5072.

[13] Deng J. (1989), 'Introduction to grey system', Journal of Grey System, Vol. 1, pp. 1-24.

[14] Jeyapaul R., Shahabudeen P. and Krishnaiah K. (2006), 'Simultaneous optimization of multi-response problems in the Taguchi method using genetic algorithm', International Journal of Advanced Manufacturing Technology, Vol. 300, pp. 870-878.

[15] Gopalsamy B.M., Mondal B. and Ghosh S. (2009), 'Optimisation of machining parameters for hard machining: grey relational theory approach and ANOVA', International Journal of Advanced Manufacturing Technology, DOI 10.1007/s00170-009-2054-3.

[16] Noorul Haq A., Marimuthu P. and Jeyapaul R. (2007), 'Multi response optimization of machining parameters of drilling Al/SiC metal matrix composite using grey relational analysis in the Taguchi method', International Journal of Advanced Manufacturing Technology, DOI 10.1007/s00170-007-0981-4.

[17] Vijayan S., Raju R. and Rao S.R.K. (2011), 'Multi-Objective Optimization of Friction Welding Process Parameters on Aluminum Alloy AA 5083 Using Taguchi Based Grey Relation Analysis', Materials and Manufacturing Processes, Vol. 25, No. 11, pp. 1206-12.

[18] Rong-Chang Zeng, Zheng-Zheng Yin, Xiao-Bo Chen and Dao-Kui Xu, "Corrosion Types of Magnesium Alloys ",http://dx.doi.org/10.5772/intechopen.80083.