# Optimization of AZ61 Mg Alloy Resistance Spot Welding using Response Surface Method

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**Abstract:** The purpose of this study is to investigate the effect of resistance spot welding (RSW) parameters on nugget size and ultimate strength of Magnesium alloy sheets AZ61 under tensile-shear test. In this study microstructural examination and hardness measurements were carried out on the welded samples. The results show that the weld nugget zone is divided into two separate parts: the equiaxed dendritic zone (EDZ) perched at the center of the weld nugget and the columnar dendritic zone (CDZ) situated around the fine-grained zone having it surrounded. The effect of the following three parameters: electric current, welding time and electrode force on the dimensions of the weld nugget and the welded ultimate strength is investigated. The response surface method (RSM) is employed to examine the effects of welding parameters and to attain optimum parameters. The analysis of variance (ANOVA) results of RSM model shows that however the tensile-shear strength and nugget size are improved with increasing the welding current and welding time, the welding current is the most influential parameter. In addition, the optimal values for the welding parameters are calculated to achieve the maximum nugget size and the ultimate strength of welded joint. Finally, a regression model is proposed in order to predict the peak load and the nugget size as function of the mentioned welding parameters.

**Keywords:** AZ61 Mg Alloy, Optimization, Resistance Spot Weld, Response Surface Method

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## 1 INTRODUCTION

In spite of significant advances in welding, resistance spot welding (RSW) is still the most commonplace welding process for metal sheets. Owing to its straightforward application, low cost and short duration of connection required; the process could be applied to virtually all sorts of metals including steels, aluminum and magnesium. Generally, strength and quality of a resistance spot welding joint depend entirely to the dimensions of the weld nugget. In fact, the diameter of the weld nugget admittedly plays a pivotal role on the performance and life span of a welded structure. Magnesium alloys, as the lightest material holding a superior resistance, has an immense potential to be utilized in reduction of structural weight. Magnesium and its alloys, as one of the green engineering materials, are one of the promising materials in decreasing weight of the structures, engineering components as well as automobile bodies in the present century. According to the 2020 perspective, the average magnesium used in an automobile will rise to 158.7kg [1]. On average, approximately 5000 weld nuggets exist in an automobile [2] considering the tendency to apply magnesium alloys to the automobile bodies; the way magnesium sheets are welded has grown of paramount importance in the solidity of the automobile bodies. Due to their distinctive specifications, magnesium alloys are amongst the most demanding metals in welding. Since they are sensitive to hot cracks during welding, you cannot weld magnesium alloys through the implementation of the analogous knowledge and information which used to be effective on welding steel and aluminum alloys.

In accordance with the declared content, it is essential to study spot welding of magnesium alloys, ultimate strength of these joints, where the effect of welding parameters on the weld quality is of crucial prominence. Kramer et al. [3] analyzed the influence of the electrode force on the dimensions of the weld nugget and the mechanical strength on Mg alloy AZ61. They observed that with the increase of the electrode force, the diameter of the weld nugget decreases due to the reduction in contact resistance between the sheet conjunctions. Behravesh et al. [4] studied the microstructure of the welded area in RSW joints. The results have shown that however the heat affected zone (HAZ) does not melt, the temperature is so high that the recrystallization phenomenon was happened in this zone. Hao et al. [5] studied the characteristics and features of the RSW of the AZ91 and AZ31 alloys, discerned that different behavior were observed during welding magnesium alloys AZ31 and AZ91 derives from their metallurgical differences. This study indicated that in welding magnesium alloys, increasing the electrode forces individually, the same as welding other metals is not effective in controlling the melt spraying. Afshari and et al. [6] investigated the effect of the RSW parameters on the peak load and nugget diameter of Al 6061-T6 joints. They presented a formula to calculate the peak load under the tensile-shear test. Niknejad et al. [7] examined the effect of aluminum content on the mechanical properties and microstructure of Magnesium alloys. They concluded that through increasing the aluminum content, the secondary phase deposition ($Mg_{17}Al_{12}$) (β) increases in HAZ and FZ's weld nugget. Babu et al. [8] investigated the microstructure specifications and deformation behavior of AZ31 alloy resistance spot welded joints. They realized that in the HAZ, as the grain boundaries melt, the boundaries reduce and the zone's grains grow larger compared to other zones. In this zone, due to the formation of dendritic structure and grain growth, the ultimate strength declines compared to the base metal in these zones. Sun et al. [9] discovered that the weld nugget of Magnesium alloys features a great capacity in terms of solidification crack and during welding AZ31 alloy when the welding electric current is higher than 15 kA; the cracks become visible at the weld nugget. These cracks grow more in the cross section of the weld nugget and in the perpendicular direction of the sheet conjunctions and the grain boundaries. Liu et al. [10] studied the impact of the electric current on the mechanical properties and microstructure of AZ31 alloy and utilized two types of alloys (AZ31-SA and AZ31-SB). They perceived that owing to the conversion of columnar dendritic zone (CDZ) to equiaxed dendritic zone (EDZ), via rising the electric current, the fracture load ($F_c$) and fracture toughness ($K_c$) enhance the mechanical properties.

The literature review indicates that however there are some studies on importance of welding parameters effects on the nugget size and the peak load of welded joints, the optimization of this process is rare. The purpose of this work is to study and optimization of the resistance spot welding process of magnesium alloy AZ61. For this purpose, through the implementation of varied experimental tests, the microstructure of the welded zone, the solidity variation of different peak loads, the impact strength as well as the dimensions of the weld nugget were investigated. Also, through the employment of the response surface methodology (RSM), the influences of welding parameters such as welding current, welding time and electrode force on ultimate strength as well as the dimensions of the weld nugget were studied and optimal parameters were provided to increase the joint strength.

## 2 MATERIALS AND METHODS

AZ61 Magnesium sheet with 1.2 mm thick, in the dimensions of 100 × 25 and according to the AWS-D17.2 standard, is used to weld the test sample for tensile-shear quasi static testing according to the "Fig. 1". The welding is implemented via the machine manufactured by Novin Sazan Company with CU08 controller and copper electrode. After welding the samples, STM250 machine manufactured by Santam Company is used to carry out the tensile-shear testing. Three welding parameter levels (welding current, welding time and electrode force) were selected to examine the influence on the peak load and diameter of the weld nugget. "Table 1" demonstrates the parameters extracted from the design of experiments (DOE), the tests are conducted in consonance with the table and the results (nugget size and peak load) are presented.

**Table 1** Resistance spot welding parameters

| No. | Welding | Welding | Electrode | Nugget | Pick |
|---|---|---|---|---|---|
| 1 | 16 | 10 | 1130 | 6.00 | 2096 |
| 2 | 16 | 16 | 1130 | 6.15 | 2200 |
| 3 | 12 | 10 | 848 | 3.45 | 1801 |
| 4 | 12 | 16 | 848 | 3.64 | 1947 |
| 5 | 12 | 16 | 1130 | 6.45 | 1850 |
| 6 | 16 | 13 | 990 | 6.14 | 2233 |
| 7 | 12 | 13 | 990 | 3.47 | 1826 |
| 8 | 16 | 16 | 848 | 6.29 | 2311 |
| 9 | 14 | 13 | 990 | 5.13 | 2086 |
| 10 | 12 | 10 | 1130 | 3.31 | 1662 |
| 11 | 14 | 13 | 990 | 5.10 | 2083 |
| 12 | 14 | 13 | 990 | 5.14 | 2086 |
| 13 | 14 | 13 | 990 | 5.12 | 2085 |
| 14 | 14 | 13 | 990 | 5.14 | 2090 |
| 15 | 14 | 10 | 990 | 4.85 | 1950 |
| 16 | 14 | 13 | 990 | 5.10 | 2084 |
| 17 | 14 | 16 | 990 | 5.13 | 2110 |
| 18 | 14 | 13 | 1130 | 5.00 | 2033 |
| 19 | 16 | 10 | 848 | 5.96 | 2157 |
| 20 | 14 | 13 | 848 | 4.93 | 1982 |

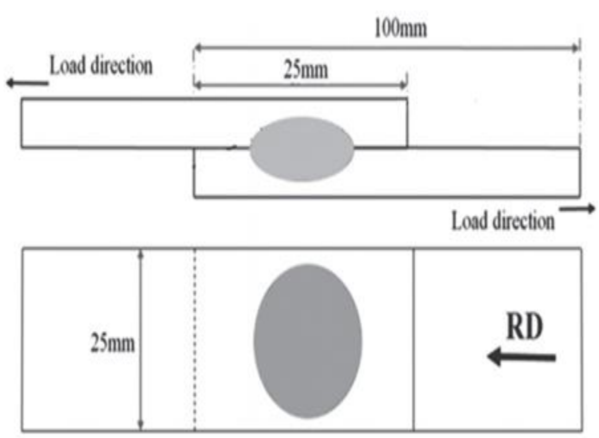



**Fig. 1** Schematic of the welded samples.

The optical microscope Leitz Metallux 3 is utilized to investigate the microstructure and to measure the diameter of the weld nugget after cutting and preparing the samples (polishing and mounting). FM-700 machine manufactured by FUTURE-TECH Company enjoying pyramidal teeth with an apex angle of 136 degrees as well as 100 grams of load is used to run hardness test and to extract the hardness profile in different areas of the weld nugget.

The upper and lower limits of each parameter are opted for pursuant to attain the minimum diameter of the weld nugget recommended by AWS standard as well as eschewing the melt spraying. Each test sample is duplicated twice in order that the measurement values for diameter of the weld nugget and peak load of a sample could be implemented under equal parameters. Afterwards, the results, parameters interactions and their optimal values were obtained through the utilization of this table and RSM.

## 3 RESULTS AND DISCUSSION

### 3.1. Microstructure of the Weld Zones

Since the quality and intensity of RSW is overly dependent on the diameter of the weld nugget, examining the microstructure of this area of joint is of great importance. These areas are susceptible to any sorts of cracks or defects caused by welding giving rise to reduction in terms of quality and peak load. Figure 2 shows the microstructure of welded zone of the alloy AZ61 in sample 8.

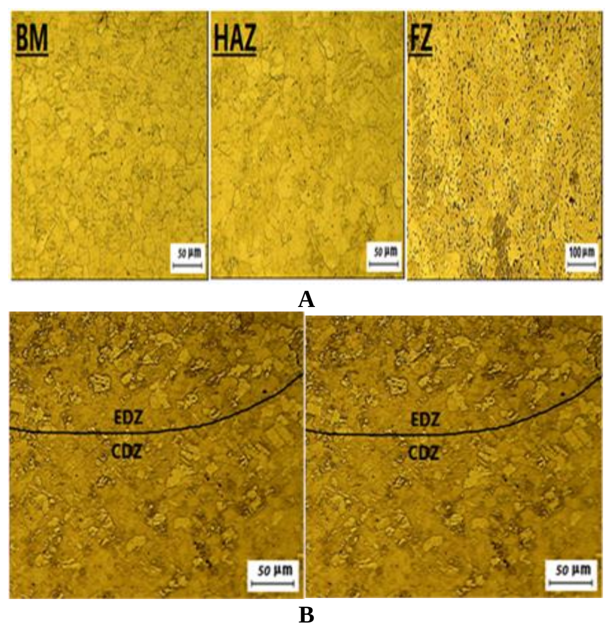



**Fig. 2** The microstructure of different zones of the weld nugget.

The structural change in the zone affected by the temperature and weld nugget relative to the base metal is observable in this figure. "Fig. 2" (A) illustrates 3 different microstructures in welded zone: base material (BM), heat effected zone (HAZ) and fusion zone (FZ). In "Fig. 2" (B), two different zones in terms of microstructure are separated from each other. The fine-grained zone positioned above the figure forms equidaxed dendritic zone (EDZ) due to the high temperature, the weld nugget zone or the fusion zone is placed in this area as well. The coarse-grained zone wherein the grain boundaries are exposed to heat and the crystallization phenomenon occurred in this zone of the microstructure which brought about the formation of the Columnar Dendritic Zone (CDZ) [4]. As a matter of fact, formation of the CDZ and EDZ is contingent on the freezing condition [8] and on the understanding that electric current of the welding rises Columnar-to-Equiaxed Transition (CET) transpires and the width of CDZ decreases [10].

Totally, the mechanical properties of the EDZ are better than the CDZ, thus increase of EDZ will enhance the mechanical properties [11-12]. The secondary phase deposition ($Mg_{17}Al_{12}$) in the grain boundaries, particularly in the HAZ region, leads to reduction in strength and mechanical properties of the welded joint [7].

### 3.2. Tensile-shear Test

There are several approaches to study the mechanical properties and ultimate strength; however, tensile-shear testing is one of the simplest approaches, which in a short time reflects the strength resistance of the welded joint. Normally, three failure modes exist for RSW in tensile-shear testing as follows:

1. Interfacial Failure (IF)
2. Pullout Failure (PF)
3. Through Thickness Failure (TTF)

According to the conducted studies, it is perceived that the failure mode for AZ61 and AZ80 alloys is PF and as to the AZ31 alloy, it is IF [7]. The failure load in the second and third type of failure (PF and TTF) is overly dependent on the diameter of the weld nugget as well as the thickness of the sheet [13-14]. The image of the sample 7 before and after the failure (PF) is illustrated in "Fig. 3".

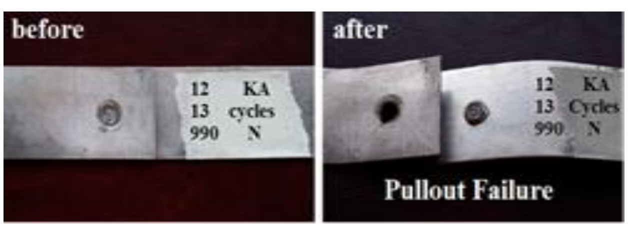



**Fig. 3** Image of sample 7 before and after failure under the tensile-shear test.

### 3.3. Hardness Measurement Test

Typically, in RSW the lowest hardness values are reported at the boundary between BM, HAZ and FZ [4], [8]. In "Fig. 4", the hardness profiles for various weld zones are displayed for sample No. 8. As it could be seen in this figure, by dint of the grain growth of the microstructure in the HAZ, the hardness level diminishes in this zone causing the peak load to decrease. In accordance with "Fig. 4", the maximum hardness quantity exists in the base metal zone varying from 65 to 67 micro Vickers since the dimensions of the grains as well as the work hardening are better in this zone [8]. It is important to mention that similar hardness profiles were observed for the other samples.

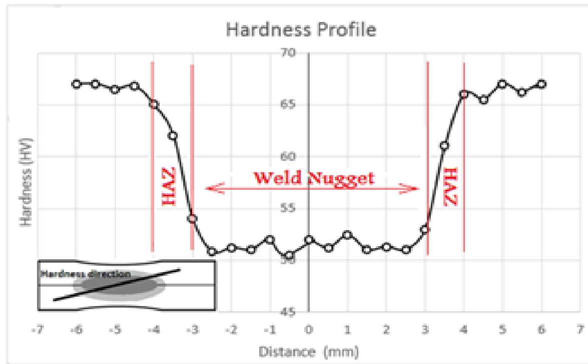



**Fig. 4** Profile hardness of sample No. 8.

### 3.4. Nugget Diameter

It is essential to measure the diameter of the weld nugget in RSW for it is directly related to the peak load. In "Fig. 5", the measurement result for diameter of the weld nugget in sample No. 8 is presented.

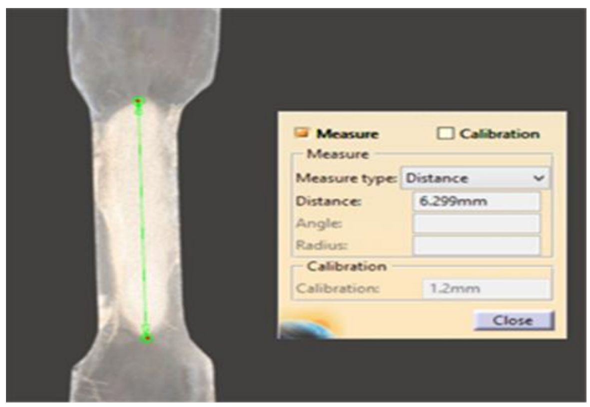



**Fig. 5** The measured nugget diameter for sample 8.

As it could be observed, the diameter of the weld nugget is 6.30 mm. Moreover, according to "Table 1", the results presented for measuring the diameter of the weld nugget are only acceptable between the range of the minimum and maximum diameter ($3\sqrt{t}$ to $6\sqrt{t}$) which indicates that these values are verified [1].

### 3.5. Optimization

In the welding process, there are numerous input parameters at various levels, each of which may affect the final property (the strength or dimensions of the weld nugget) in some way. It would be quite costly and time consuming to implement trial and error method to be cognizant of the impacts left on the final product by each of these parameters. Eventually, the final results comprise both high error rates and non-reflection of the combined effect of the parameters on the final answer. The Response Surface Methodology (RSM) is a combination of mathematical and statistical techniques advantageous in modeling and analysis of the response variable affected by several input parameters and its purpose is to optimize the response variable [15].

However, there are many influential parameters in RSW, according to the previous experience and studies, the most effective parameters in this process are welding current, welding time and electrode force. It is indispensable to control and optimize these factors in order to achieve the maximum pick load. MiniTab 16 software is employed to fulfill this cause. After designing the matrix experiments and carrying out the experimental tests, through the implementation of RSM, each parameter is analyzed in three levels. “Table 2” illustrates the parameters as well as the levels studied.

**Table 2** Welding parameters and their levels

| Factors | Levels | | |
|---|---|---|---|
| Welding Current (KA) | 12 | 14 | 16 |
| Welding Time (Cycles) | 10 | 13 | 16 |
| Electrode Force (N) | 848 | 990 | 1130 |

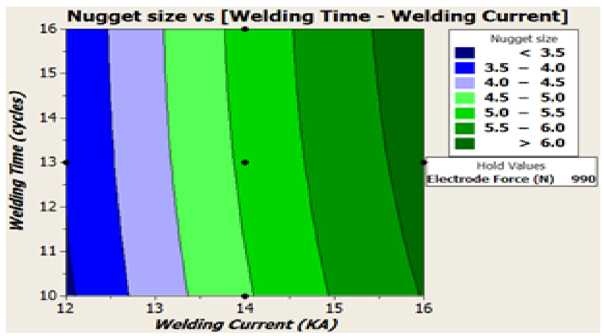
In this study, Central Composite Design (CCD) enjoying three independent variables without blocks and replicates are utilized. The response obtained from the software based on Y equation is predicted as follows:

$$Y = B_0 + \sum_{i=1}^{k} B_i\ x_i + \sum_{i=1}^{k} B_{ii}\ x_i^2 + \sum\sum_{i<j} B_{ij}\ x_i x_j \quad (1)$$

Where $B_0$ is a fixed coefficient, $B_iX_i$ is a linear main effect, $B_{ii}X_i$ is a non-linear effect, $B_{ij}X_iX_j$ is the interaction effect of factors and ε is remaining or error [15]. With respect to the above, the results acquired from the presented equation in the colored contours palpably displayed the impacts and interactions of the parameters on the diameter of the weld nugget and the pick load.

Figure 6-A shows the relationship between welding current and welding time with the diameter of the weld nugget. As it could be observed, at a fixed force of 990 N and within a welding current range of 16 kA, weld nugget’s diameter range 6 mm dramatically rises by the increase of the welding time. Also, in cases that the welding time is fixed in 13 cycles, the growth of weld nugget’s diameter (> 6 mm) commences in current range of 15.5 kA and the influence of the electrode force on the growth of weld nugget’s size is insignificant as if merely in the range of 990 N, a slight change was observed in the growth of weld nugget’s diameter (> 6 mm) and it has increased the size of the area.

In general, it could be noted that under this condition, the electrode force leaves a minor impact on the growth of weld nugget’s size as shown in “Fig. 6-B”. In the final condition, when the welding current is fixed at 14 kA, weld nugget’s growth (> 6 mm) starts at the range of 15.5 cycles as though by increasing the electrode force, the dimensions of the well nugget area higher than 6 mm increases and as displayed in “Fig. 6-C”, in 942 N, the dimensions of this area reaches its top. Providing that the current is fixed at 14 kA, at a force of 942 N, even if the welding time is 15 cycles, accessibility to a weld nugget size over 6 mm is viable.

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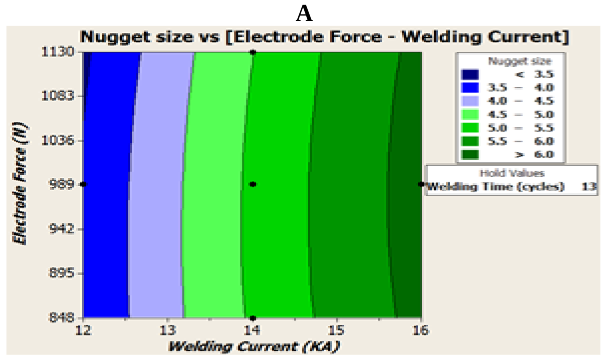


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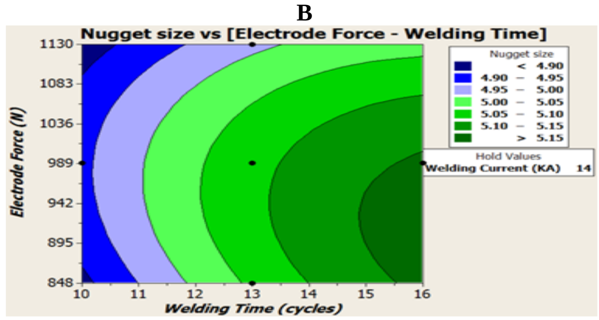


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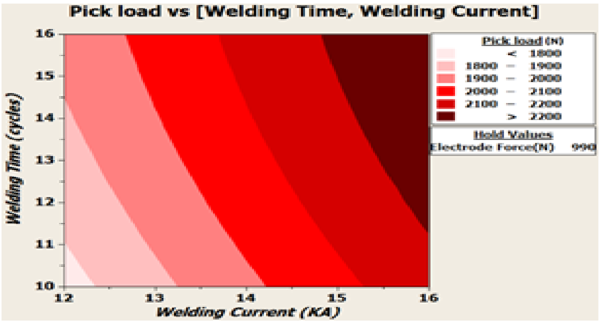
**Fig. 6** Interaction of welding parameters on diameter of the weld nugget diagram.

“Fig. 7” displays the effect of the welding parameters on the ultimate strength of welded joints under the tensile-shear test. The similar effects of the welding parameters are seen when comparing “Figs. 6 and 7”. This similar effect indicates the relation between the nugget size and the strength of the welded joints.

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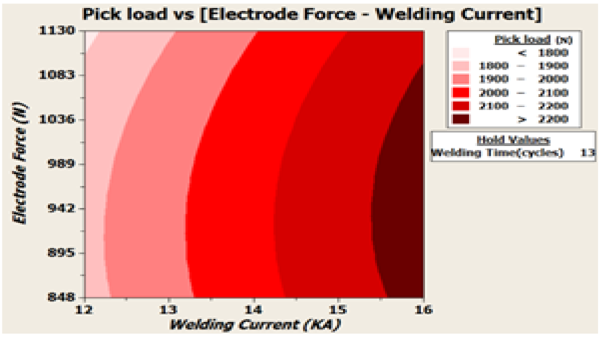


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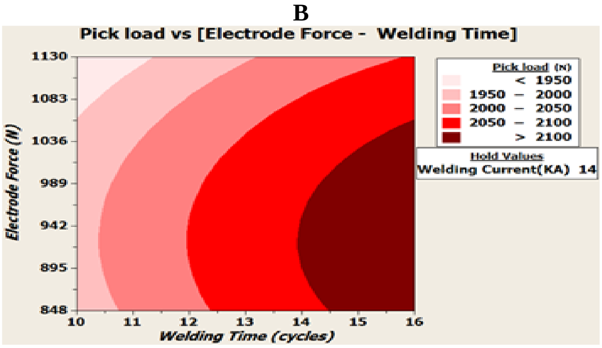


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**Fig. 7** The interaction of welding parameters on peak load diagram.

Given the above, finding an appropriate approximate relation between the input parameters and the response variable (weld nugget size and peak load) sought. Thus, regression function is employed for modeling these relationships. The equations for the response variable (weld nugget size and peak load) are estimated according to "Eqs. (2) and (3)".

$$D = -4.55+0.661X_1+0.0363X_2-0.000250\,X_3 \qquad (2)$$

$$P = 619+95.5X_1+25.1X_2 - 0.252\,X_3 \qquad (3)$$

Where, $X_1$, $X_2$ and $X_3$ represent welding current, welding time and electrode force, respectively. Moreover, *D* and *P* represent diameter of weld nugget and peak load, respectively. After determining the impact of each parameter on the response variable, optimization of these parameters is imperative to achieve the largest diameter of the weld nugget. Figure 8 illustrates the optimization results and as it could be deduced, the optimized values for welding current, welding time and electrode force parameters are 16 kA, 16 cycles and 947.7 N respectively which under these welding parameters, the achievable diameter is 6.26 mm.

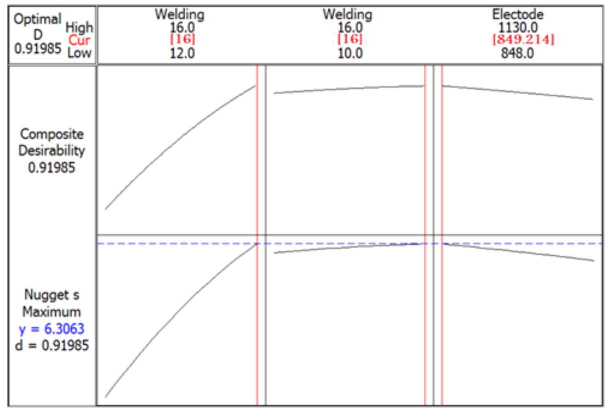


**Fig. 8** Optimization of welding parameters.

So as to verify the diameter of the weld nugget (6.26 mm) acquired from the optimal parameters (according to "Fig. 11"), the regression function ("Eq. (2)") is utilized in which the diameter of the weld nugget is predicted 6.36 mm. This prediction contains an error rate of 1.6% which is a quite trivial. "Table 3" presents the confidence interval (CI) as well as the total squared error for this prediction. As it could be discerned, 95 percent of the confidence interval (CI) is acceptable for this prediction based upon which the decision could be made.

**Table 3** The confidence interval (CI) for the predicted nugget diameter

| | Goal | Lower | Upper | Target |
|---|---|---|---|---|
| Nugget size | Max. | 3.28 mm | 6.30 mm | 6.30 mm |

## 4 CONCOLUSION

In this study, the impact of welding parameters including: electric current, welding time and electrode force on diameter of the weld nugget and the peak load have been investigated. Moreover, the microstructures of the welded zone as well as the hardness variation in each zone have been studied. Eventually, through the implementation of response surface methodology, optimum parameters are presented to reach the maximum diameter size of the weld nugget in the peak load. The results of this study are as follows:

1. Investigating the microstructure of the weld nugget zone proves that the zone is divided into two separate

parts: the equiaxed dendritic zone (EDZ) perched at the center of the weld nugget and the columnar dendritic zone (CDZ) situated around the fine-grained zone having it surrounded. The reason for the loss of mechanical properties in this zone is the secondary phase deposition (Mg17Al12) at the grain boundary of these zones, which give rise to a dramatic decrease in the peak load.

2. Due to the grain growth of the microstructure in the HAZ, the hardness level declines in this zone and causes the peak load to decrease. Furthermore, the maximum amount of hardness is found in the base metal zone owing to the better grain size and the work hardening available.

3. A regression model was developed to estimate the peak load and diameter of the weld nugget. It was observed that a great dependency exists between the response variable and the input variables. Besides, according to the coefficients of the equations' independent variables, it was determined that the welding current and welding time parameters have the largest effect on the peak load.

4. The optimal values for welding current, welding time and electrode force parameters predicted are 16 kA, 16 cycles and 147.7 N respectively to achieve the maximum nugget size and ultimate strength of welded joint.

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