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Study of Nugget and Heat Affected Zone in Resistance Spot Welding

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Abstract : This paper presents An experimental and qualitative study on the size of Nugget diameter and HAZ of weld Created by Resistance Spot welding of Titanium grade 2 - Inconel 625 using Copper interlayer. The average diameter of nugget, HAZ is taken as function of parameters like time variable, pressure, Heat (Current). Based on the collected data the graphs plotted between Nugget and HAZ size with other Variables. Linear Regression Analysis is performed and its feasibility is analysed while forming a direct relation between nugget, HAZ size with respect to Heat, pressure and time variable. Afterwards a comprehensive analysis is performed about the nature of surface and contour plot which relate between HAZ , nugget diameter with heat, pressure using Response Surface Method (RSM) analysis, welding parameters for maximum and minimum size of nugget and HAZ is found.
Keywords - Copper, Inconel 625, Resistance Spot Welding (RSW), Regression Analysis, Response Surface Methodology (RSM), Titanium Grade - 2..

1. INTRODUCTION

An Titanium, Inconel and its alloys are widely used in rockets, nuclear power plant, automotive, marine and railway industry for high performance structural applications because of many desirable properties such as high strength to weight ratio, resistant to stress corrosion cracking, superior cryogenic properties, and good weldability and formability. RSW is considered to be a remarkable and potentially useful welding technique for joining Ti-alloys, Al-alloys, etc. RSW process involves interactions of thermal, electrical, mechanical, and metallurgical phenomena. Nickel-based superalloy Inconel 625 was developed as a solid solution-strengthened alloy having molybdenum and niobium on its nickel–chromium matrix, and the high strength can be retained without any precipitation heat treatment, also widely used inaeronautical, aerospace, chemical, petrochemical, and marine applications due to its good mechanical properties, process ability, weldability, and resistance to high temperature corrosion on prolonged exposure to aggressive environments. The requirement of RSW for each spot welding is not performed on the same condition because of the alignment of sheets and electrodes as well as the different surface condition. For that reason, a spot welding process needs the optimum process condition that can afford allowance in parametric values for good quality of welding. Regression analysis and RSM is performed in order to determine the best set of welding parameters , such that the linear regressive relation predicts experimental values of the dependent variable as accurately as possible. RSM surface and contour plots gave the idea of specific zones and overall nature of curve on variois welding control parameters, hence we can judge and chose the best suited set of parameters as per requirement.

2. NEED OF THE STUDY.

In automobile industry itself on a daily basis millions of spot weld is made of different sizes, indentation depth. A survey of literature shows that a series of various welding input parameter are responsible for weld profile, size etc. RSW is an inexpensive way of joining sheet metals and comprised of many features like easy to weld, very narrow and guided weld zones which gives edge over methods of welding process. Further, using linear regression analysis , RSM techniques, neural networks intelligence simplified predictor relation has been formulated, as well as different specific zones of welding control parameters has been spotted which could give optimum results. In the present paper a copper interlayer sandwiched between Titanium-Inconel sheets specimen has been used for evaluation and study. Thus a method needs to be developed to simplify the analysis of this process and interrelate the outcome result with input variables. These kinds of developed model save lots of time and relatively accurate in their prediction. So that the manufacturer or an engineer can directly choose the requisite size or can guess the welding control parameters for getting specific resultant spot weld.

3. MATERIALS AND SOFTWARE TOOLS

The base materials used to made spot weld joint are Titanium grade 2, Inconel 625 alloy and copper interlayer sandwiched inbetween. The software tools used to performe regression analysis and RSM are Microsoft-excel and Minitab

3.1 Titanium grade-2
Titanium and its alloys have been considered as one of the best engineering metals for use in industrial applications. Currently, there has been an interest in the development of titanium alloy because of their unique properties such as low density, high specific strength, and excellent corrosion resistance; thus, they are widely used in aerospace and chemical industries. During welding, titanium alloys pick up oxygen and nitrogen from the atmosphere easily. An effective way to reduce the formation tendency of intermetallic compounds in dissimilar welding of Titanium with other base metal is the use of solid-state welding process such as ultrasonic spot welding, friction stir welding. Titanium Grade 2 may be considered in any application where formability and corrosion resistance are important, and strength requirements are moderate. Ti Grade 2 can be processed by conventional techniques such as hot rolling, forging.

3.2. Inconel 625
The solid solution-strengthened nickel-based superalloy Inconel 625 was created as a material with relatively high concentrations of chromium, molybdenum, carbon, and niobium. a lot of industries use it, including aerospace, marine, chemical. Strength of Inconel alloy 625 is derived from the stiffening effect of molybdenum of its nickel-chromium matrix. Thus, precipitation hardening treatments are not required. This combination of elements also is responsible for superior resistance to a wide range of corrosive environments of unusual severity as well as to high-temperature effects such as oxidation and carburization. High tensile, creep, and rupture strength; outstanding fatigue and thermal-fatigue strength; oxidation resistance; and excellent weldability and braze ability are the properties of INCONEL alloy 625 that make it interesting to the many field.

3.3. Copper interlayer
Copper is a soft, non-ferrous metal that can be easily bent, cut, shaped and joined using several welding processes. Since it is ductile and highly malleable, copper is also used as the major element in hundreds of different alloys, including brass, bronze, and nickel copper. The most common alloying elements used for copper alloys are aluminium, nickel, zinc, tin and most copper alloys can be successfully joined using welding, brazing or soldering processes. The exact process chosen depends largely on whether you are welding pure copper or an alloy.

3.4. Regression analysis
Regression analysis is a statistical tool for the investigation of relationships between variables. we study the relationship, called the regression function,between one variable y, called the dependent variable, and several others x, called the independent variables.Our primary goal is to determine the best set of parameters coefficients, such that the model predicts experimental values of the dependent variable as accurately as possible calculated values y which should be close to experimental values. Microsoft Excel ANOVA is a widely used software tool for calculation of regression relation in technical and experimental field.Excel contains the solver function, which is ideally suited to fitting data with non-linear functions via an iterative algorithm, which minimizes the sum of the squared difference between data points and the function describing the data. The most commonly used measure of the closeness of fit is least squares fit method, this is based on the principal that the magnitude of the difference between the data points and the curve is a good measure of how well the curve fits the data. Regression analysis is widely used for prediction and forecasting, where its
use has substantial overlap with the field of machine learning. In some situation's regression analysis can be used to infer causal relationships between the independent and dependent variables.

3.4. Response Surface Methodology
The purpose of considering RSM model in engineering is to establish a relationship, albeit approximate, between dependent and independent variables that can be used to predict response values for given settings of the control variables. To determine, through hypothesis testing, significance of the factors whose levels are represented and find optimum settings of the result in the maximum (or minimum) response over a certain region of interest. RSM become very important tool in the optimization of different food processes such as extraction, drying, blanching, enzymatic hydrolysis, food industry and levels of the factors significantly influences the successful application .Several researchers used response surface methodology to optimize the process parameters in casting, welding and machinability

4. EXPERIMENTAL DETAILS & RESEARCH METHODOLOGY

Experimental set up are used to develop resistance spot weld joints in dissimilar metal joining process, thereafter investigation methods employed to find relation between welding parameters and size of nugget and HAZ.
For preparing the weld joints the materials taken are commercially available titanium, Inconel and copper interlayer.
Dimensions of base materials and interlayer :

Sl. No	Materials	Dimension
1	Titanium grade 2	150×20×1 mm
2	Inconel 625 alloy	150×20×1 mm
3	Copper interlayer	100 micron (0.1mm) thickness

The RSW process is performed on commercially available spot welder machine (Electroweld company).
Maximum Power rating of welding machine = 50 kVA
Weld time, Hold time and Squeeze time can be varied on the machine.
Pressure force depend upon compressor setting which can be manually changed.
Electrode tip is round in nature and diameter of 5 mm size.

Weld time – It is the time during which welding current is applied to the metal sheets. The weld time is measured and adjusted in cycles of line voltage.
Squeeze time – It is the period of time programmed into the weld controller, typically between the command to close the electrode and beginning of weld time.
Hold time – It is the time during which electrode force is maintained after the current flow ends.

4.1 Methedology

4.2 Experimental Data

All together 27 observations are made by changing the parameters and afterwards nugget diameter and HAZ size are measured and plotted correspondingly. A table is prepared encapsulating the data for the nugget size and HAZ size corresponding to the other welding parameters time variation, heat % , pressure corresponding to given welding parameters

Table 4.1 Nugget and HAZ size at different welding parameters

No.	TIME VARIATION	HEAT %(max of 50 kVA)	PRESSURE (psi)	NUGGET (mm)	HAZ (mm)
1	time1	40	35	4.06	6.41
2	time 1	40	50	4.638	6.68
3	time 1	40	80	4.053	6.16
4	time 1	60	35	4.731	7.26
5	time 1	60	50	4.23	7.16
6	time 1	60	80	3.92	6.44
7	time 1	80	35	4.08	8.23
8	time 1	80	50	4.13	7.32
9	time 1	80	80	4.456	8.07

10	time 2	40	35	4.629	7.3
11	time 2	40	50	4.063	6.65
12	time 2	40	80	4.373	6.74
13	time 2	60	35	4.52	7.61
14	time 2	60	50	4.024	7.06
15	time 2	60	80	4.843	8.39
16	time 2	80	35	4.585	8.42
17	time 2	80	50	4.469	7.5
18	time 2	80	80	4.96	8.48
19	time 3	40	35	4.461	7.82
20	time 3	40	50	4.381	7.24
21	time 3	40	80	4.45	7.917
22	time 3	60	35	4.751	7.806
23	time 3	60	50	4.053	8.06
24	time 3	60	80	4.283	7.08
25	time 3	80	35	4.77	6.18
26	time 3	80	50	4.8	8.345
27	time 3	80	80	4.85	8.59

The different set of time configuration chosen for the welding purpose vary in between different squeeze time, hold time, weld time.

Table 4.2 Different time zone values for welding

No.	Squeeze time	Weld time	Forge time
Time 1	30	15	11
Time 2	35	20	13
Time 3	40	25	15

1 second = 50 cycles
The rated working frequency of welding machine is 50 Hz , so that in one second all together there is 50 cycles of AC current flows through the machine.

5. RESULTS AND DISCUSSION

A graph is drawn representing the size of nugget and HAZ as a function of different variable welding parameters as pressure, time, heat (%)

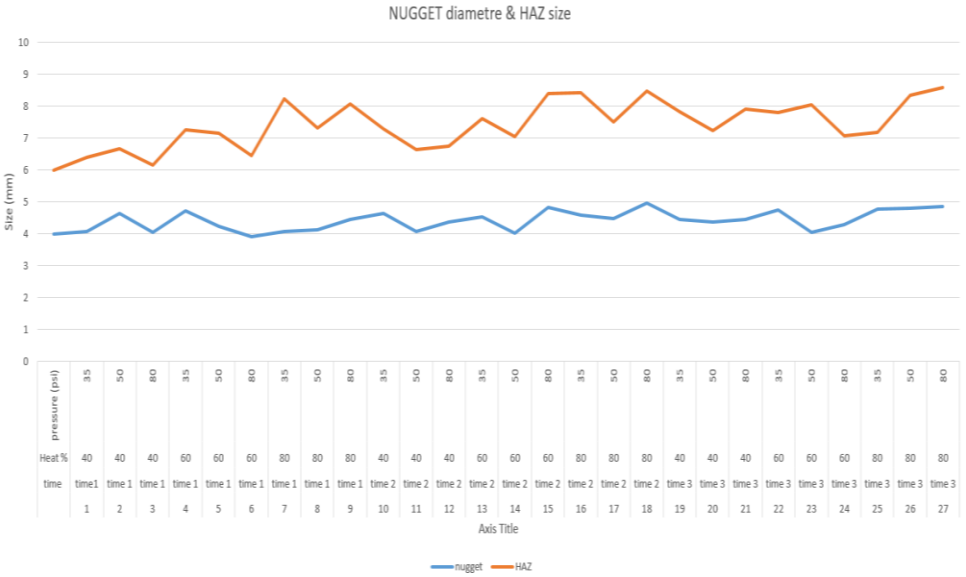

Figure 5.1 Graph representing the size of nugget and HAZ with welded parameters

Based on the observation one can conclude that there is relation between the size of HAZ and time variable as we can see that between 1st weld size and 10th weld where only change happening is time constant , in which we observe that size of nugget and HAZ increases whereas in the 19th weld there is decrease in size of nugget and HAZ size , So we can conclude with increase in time first weld size increases and then afterwards it decreases.
Now if we analyse the 1st, 4th, & 7th now from the table we find that nugget size increases at first and then afterwards it decreases , with increase in heat that is basically with increase in power or current. Next if we look at the size of 27th and 1st weld we see that with overall increase in all parameters of welding like Heat power, pressure & time factor the net size of nugget and HAZ both increases. But contrary to that we observe that size of HAZ is constantly increasing. So we can conclude that nugget size behave at first it size increase and then afterwards it size decreases with reaching at optimum welding parameter whereas HAZ is constant increasing function with increase in the value of welding parameters.

Regression Analysis is performed base on the table Where linear equation of nugget & HAZ is formed as a function of variable heat (power percentage).
Heat percentage or percentage of maximum current power is the main factor in determining the nugget size and HAZ size while performing linear regression analysis.
The linear relation for nugget aftet performing linear regression analysis is as follows

$$N = 4.154 + 0.004745 \times (H)$$

Where N - nugget diameter in (mm)
H- % of Maximum power 50KVA

The linear relation for HAZ after performing linear regression analysis is as follows
$$A = 6.2 + 0.021 \times (H)$$

Where A - HAZ average diameter size in (mm)
H- % of Maximum power 50KVA
The above are given linear relation between nugget diameter and HAZ as a function of fraction of maximum heat(%).

Using RSM analysis on MiniTab Software a surface curve is plotted between the Nugget as primary process parameter and other Variable Pressure, heat. From the surface curve Sketched by software in 3-D axis Nugget-Pressure- Heat. We can observe that nugget size is going in decreasing order that is from higher value to lower value for 40 to 60 psi and heat of 40 to 60% percentage. After that We achieved the minimum Size of nugget of 4.2 mm around 60 psi and 50% heat. Afterwards again with further increase in pressure and percentage of heat Nugget size increases In two- dimensional Contour plot of Nugget vs pressure , Heat which can be verified after analysing the darker curve sections. So we can say that Nugget with respect to force, and heat in the form of electric current behave like Concave orientation that's first decreasing then increasing function.

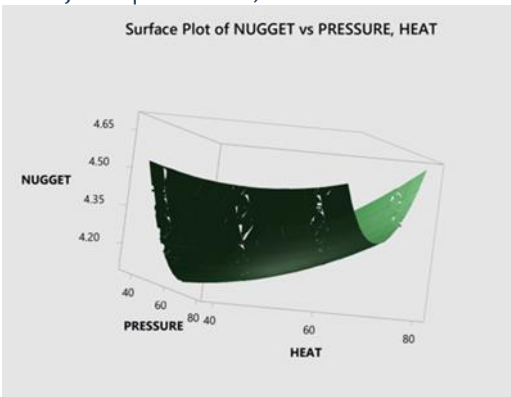

Figure 5.1 Surface plot of Nugget vs Pressure, heat

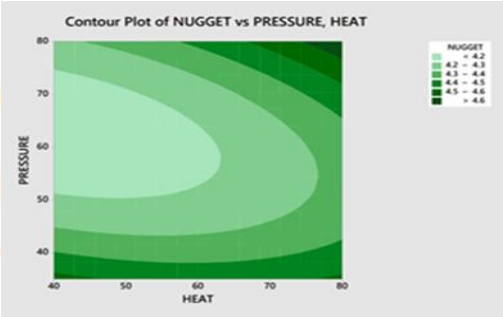

Figure 5.2 Contour plot of Nugget vs pressure, heat

Theoretically as we know that the size of Heat Affected Zone (HAZ) Will go on increasing with successive increment of Heat in form of electric orient, because HAZ is the main surrounding region where all the energy coming from spot welding Machine is absorbed.

In the surface plot of HAZ vs Pressure, Heat we can observe that with increase in both heat and pressure successively there is overall Continuous increase in HAZ size But with further analysis we can also observe that If we take the heat constant then HAZ size behave in concave Manner that is with increase in pressure it first behave as a decreasing function then afterwards it act like an increasing function.

From the Contour plot data we can observe that the maximum HAZ occurs at the respective Maximum values of both pressure and Heat 80 psi and 80% of heat. The minimum size of HAZ occurs around 60-70 psi and 40% heat.

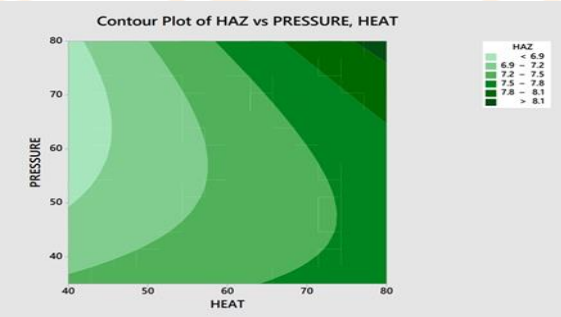

Figure 5.3 Contour plot of HAZ vs pressure , heat

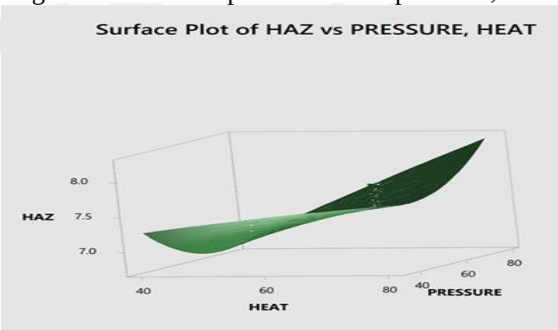

Figure 5.4 Contour plot of HAZ vs pressure , heat
(Pressure-psi, Nugget- mm, Heat - % of 50kVA)

In the following given surface plot and contour plot we can observe that the minimum HAZ Occurs at least given set of time and at highest pressure of 80 psi. And maximum HAZ size happen to be at maximum weld time profile and highest pressure.

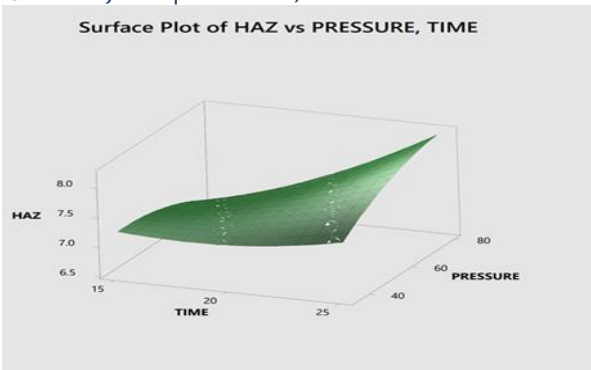

Figure 5.13 Surface plot of HAZ vs pressure , heat

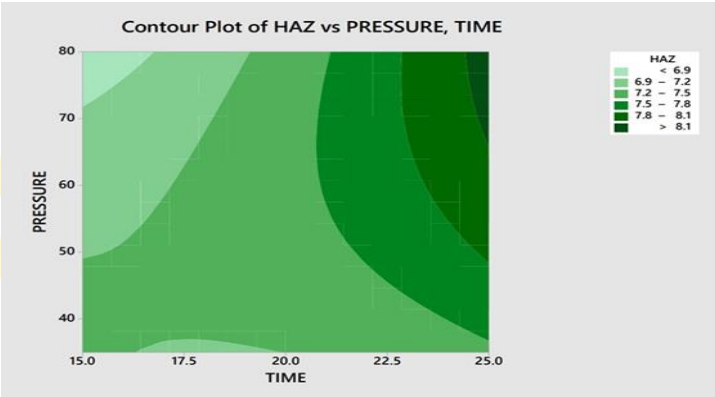

Figure 5.14 Contour plot of HAZ vs pressure , heat
(Pressure-psi, HAZ- mm)

Table 5.2 Summary report of nugget, HAZ with respect to welding control parameters :

Output parameters	**Pressure (psi)**	**Heat (% of max)**	**Time**	**Inference**
Nugget	40-60	40-60	-	Decreasing
	60	50	-	Minimum
	60 >	50 >	-	Increasing afterwards
HAZ	60-70	40	-	Minimum
	80	80	-	Maximum (limit of welding machine)
	80	-	Maximum time	Maximum
	80	-	Minimum time	Minimum

As from the table and surface plot observation it is found that the combination of both pressure and heat play a companion role in formation of nugget profile, higher the current more will be the pressure made by electrodes will impact on workpiece intermediary molten state of nugget. With further increase in current nugget increases until expulsion happen. The above HAZ surface plot resembles similarity with the surface curve of energy absorption-force- current and energy-time-current, given by Yue [1]. Both the output surface curve in the paper shows regular increase in energy absorption with respect to increment in current, time and electrode force. With increase in time the stability factor of welded nugget increase which give higher strength to spot weld made.

CONCLUSION AND FUTURE SCOPE

Regression analysis and RSM proves to be an effective way of study of nugget size and HAZ. In industry or automobile where many spot weld joints with various change in requirement is to be made, so linear regresaive predictor could be well used to employed. Also RSM surface and contour plots gave the idea of specific zones and overall nature of curve on variois welding control parameters , hence we can judge and chose the best suited set of parameters as per requirement.

The linear regressive equation for Nugget and HAZ are :

$N = 4.154 + 0.004745 \times (H)$

$A = 6.2+ 0.021 \times (H)$

Where A - HAZ average diameter size in (mm)
N - nugget diameter in (mm)
H- % of Maximum power 50KVA

Further based on analysis given points could be concluded.

- Heat percentage or current power come out as the main factor in determining the size nugget size and HAZ size compare to other variables and we can say that the output linear regressive relation is feasible for both variables.
- Linear regression analysis for nugget and HAZ showed with some degree of probability error while finding linear dependencies with time variable and pressure.
- It is observed that nugget size is going in decreasing order that is from higher value to lower value for 40 to 60 psi and heat of 40 to 60% percentage. After that the minimum Size of nugget of 4.2 mm around 60 psi and 50% heat. Afterwards again with further increase in pressure and percentage of heat Nugget size increases. With increase in both heat and pressure successively there is overall Continuous increase in HAZ size.
- The welding current, followed by the welding time and the welding compressor pressure, had a substantial impact on the heat input generation and nugget - HAZ formation. The surface and contour plot of nugget in RSM shows that first nugget size decrease, goes to minimum and then overall we see increase in nugget diameter with increase of welding current and pressure. Displays the largest . Though a deeper penetration could be made possible with increase in power and force such that the highest welding current generated expulsion.

Many new parameters like shear strength, hardness, fatigue strength can be also analysed and their feasibility, maximum and minimum parameters could be found, using linear regression and RSM for spot weld joints with interlayer. RSM analysis augmented with neural network artificial intelligence could also be incorporated in the study of dissimilar joints in analysing as well as developing models as tool predictor, can also be carried out. Its powerful and useful tool in optimization in various manufacturing process as it helps in minimising the number of experiments and helps in finding most responsive parameter. Increasing the set of control variables and output parameters further multiple linear regressive analysis with more sophisticated data set for weld joints of many new materials like aluminium, titanium could be collected at a single point and a comparative analysis could be performed of the set of output relations and behaviours of surface plot curve for each weld joints of given material.

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