NUMERICAL MODELING AND STUDYING THE EFFECTS OF RESISTANCE SPOT WELDING PARAMETERS ON TENSILE-SHEAR STRENGTH IN AUTOMOTIVE SHEETS

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ABSTRACT

The main aspect of this paper is offering DOE approach for applying in spot resistance welding. In study, tensile-shear strength of welded sheet is chosen to analyze mechanical property as an important attribute. Firstly, Cause & Effect diagram is drawn and 7 parameters including 6 process factors plus sheet thickness are selected. Consequently, max/min limits on changing of parameters are determined. DOE (Design Of Experiment) which is widely adopted method for numerical modeling of complicate process is employed to offer the best experiment pattern (matrix) and processing the experiment data. For arranging the parameters in order of importance, DOE screening pattern called Placket-Burman is applied and four highly influential parameters are selected. In Consequence, a fractional factorial DOE pattern is employed to model the behavior of tensile-shear strength as a function of four selected parameters (thickness, current, time & pressure). Obviously, final equation is verified by ample experiments. Future, related graphs and surfaces are plotted to interpret the behavior. This model including interactions between parameters and is capable to predict strength reliably.

1 INTRODUCTION AND CONCEPTS

Resistance spot welding is most widely applied for joining sheet materials such as parts in automotive body, home appliance and so on.

The process employs shaped copper alloyed electrodes to apply pressure and convey electrical current through the work pieces. Heat is developed mainly at the two sheets interface and eventually causing the work pieces being welded. Spot welding offers a number of advantages over other techniques including high speed, ease of automation, energy efficiency, productive in mass production and lower safety hazards.

Several different process parameters affect on weld specifications.Therefore, proper arrangement of parameters for achieving the best result is always challenging where upon, in many cases, experimental tests prior to weld are necessary. In other word, weld specifications are tested by changing actual amounts of factors to be optimized. [3]

Obviously, there are many organized experimental method for conducting and analyzing controlled test to evaluate the effect of input parameters on outputs. One of the most reliable and common method which is adopted for numerical modeling of complicate process, is DOE (Design Of Experiment). With today's ever-increasing complexity of processes and models, DOE refers to experimental methods applies to quantify indeterminate measurements of factors and their interactions statistically through observance of controlled changes made methodically as directed by mathematically systematic patterns. In brief, DOE offers minimized controlled experiment pattern and then the actual data of performing the pattern are statistically processed to find the best regression fit for creating mathematical function as a model. In this study mainstay, a fractional factorial DOE pattern (matrix) including 27 experiments is employed for modeling the tensile-shear strength of spot welds as a function of four main selected parameters of welding process. In consequence, the behavior of model is interpreted and some studies are included as well.[9]

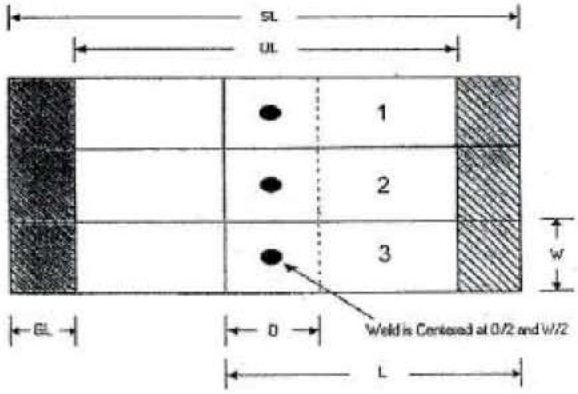
2 ASSUMPTION

In addition to appearance of weld nugget which often is the main criterion of acceptance in many cases, mechanical properties usually is the most important specification for assessing soundness of welded parts. Hence, many different tests are being applied for monitoring different aspects of weld mechanical properties. In this research, tension-shear strength is chosen for assessing mechanical property over other mechanical specifications. [1]

According to main objective of this research, study has been conducted through automotive body sheets and following input data are considered:

- Base metal is a kind of low carbon steel with about 0.08 % C, 0.01 % Si, and 0.3 % Mn with no more than 0.3 % S, P which is addressed by AISI 1008, ASTM A620 or named ST-14. [1]
- Thickness range is 1.5 mm to 2.5 mm which is common in main parts of automotive body. [1]
- Joint design and dimensions of test coupons are in accordance with ANSI/AWS/SAE D 8.9 (Dimensions is illustrated in figure 1).[5]
- Electrodes have been shaped the way ASTM A-class shaped with 7 mm diameter circle tip and made of Cr-Copper alloy (ASTM classes are illustrated schematically in figure 2). [2]
- Welding machine is fully automatic with 50 Hz input current (each cycle is 20 ms or 0.2 S) and enable to apply precisely any setting levels of all parameters. [1]
- Tension-shear strength tests have been done by accurate Instron machine under 1 Cm/min strain rate and the term "Strength" here indicates maximum force load before tearing or any failure in weld/HAZ. Because nuggets diameter keep constant (7 mm), all strengths are expressed by Kg/spot. [1]

- Normality test for parameters have been performed and the results demonstrate normal behaviour. [1]



Thickness	L	W	O	SL	UL	GL
0.60-1.29	105	45	35	175	95	40
1.30-3.00	138	60	45	230	105	62.5

Note: all dimensions are in mm

Fig. 1 Dimensions of test coupons [5]

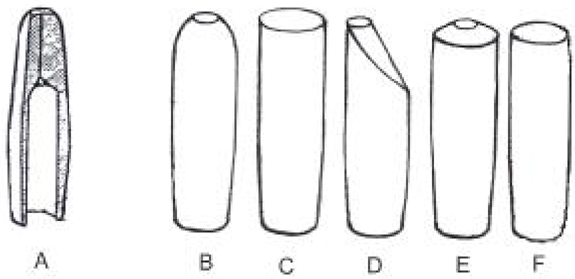


Fig. 2 Schematic shape of ASTM classes for electrode tips [2]

3 RESEARCH STEPS

3.1 PRIMARY SELECTION OF PARAMETERS

Drawing Cause & Effect diagram is one of the most effective ways to identify factors; they have effect on a process output. This diagram is formed by 6 main branch including 5 M & 1 E (Machine, Material, Method, Man-power, Measurement and Environment) and in each branch many items can be added regarding their effects on output. Here tensile-shear strength has been studied as output and diagram in figure 3 has been drawn for factors (Man-power, Measurement and Environment have been neglected because of their insignificant effects in comparison with others).[7]

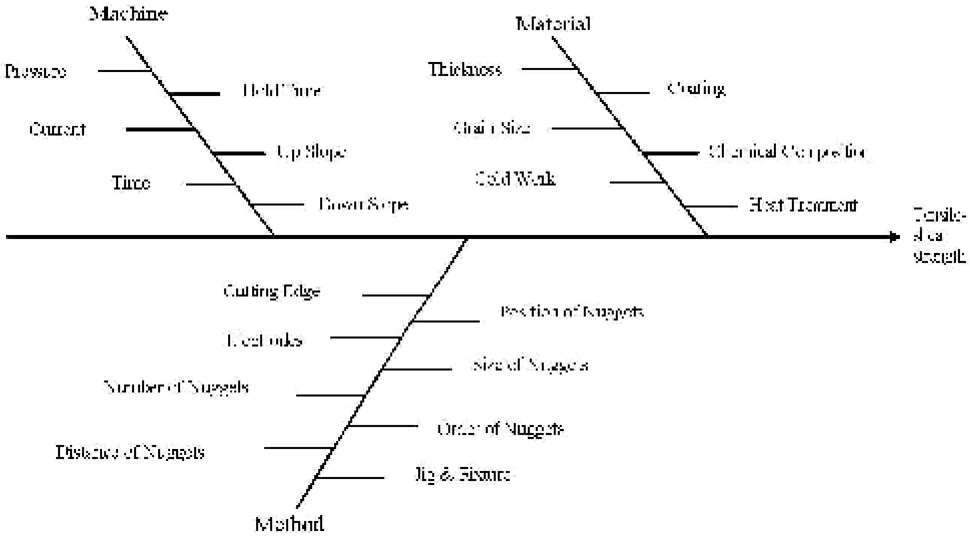


Fig. 3 Cause & Effect diagram[1]

From Cause & Effect diagram, six factors of machine plus thickness have been selected while other factors are taking under control to cut their noise effects on the results. [1]
If the respond or output depends on only one factor, a few easy experiments are capable to reveal the effect of that factor. Whereas if multiple factors affect output, the easiest method for analyzing is the changing of specific factor while other factors are constant. This is called OFAT (One Factor AT a Time) approach.[7] The main problem with this approach is that no interactions between factors are analyzed. In this study, OFAT has been applied to determine proper range (max/min) of some parameters. [7]

For determining max/min of current and time, Lobe curve has been plotted.[2] In this matter, for each fixed time, a minimum possible amount of current has been applied and the current gradually has been increased up to having a weak joint. This current has been noted as minimum required current. Consequently, In order to determine the maximum allowable current, the current has been increased up to getting nugget out of shape and metal run-out happens in weld (OFAT of current). [1] This task repeats for other amounts of time (OFAT of time).[1] Finally Lobe curve can be plotted by connecting these max/min noted points to each other. Sample Lobe curves for thickness of 1.5 and 2.5 mm are illustrated in figure 4 and 5 respectively in which pressure is 3 Bar.[1]

Here, the current is expressed in percentage of kilo volt ampere in which the average value of welding voltage had been 2.2 V.[1] Therefore the amounts of current are obtainable in Ka.

By Lobe curves, it is deducible that, the range of 20 to 30 %Kva for current and 20 to 30 cycles for time is the suitable range for modeling.[1]

To put in a nut shell, selective ranges for these seven parameters are as following:

- Thickness: 1.5 to 2.5 mm

Assumed for automotive body mainstay.[1]

- Upslope: 0 to 9 cycles (0 to 1.8 S)

Whole applicable range of welding machine.[1]

- Down slope: 0 to 9 cycles (0 to 1.8 S)

Whole applicable range of welding machine.[1]

- Hold time: 10 to 30 cycles (0.2 to 0.6 S)

Applying the minimum hold time is necessary for shaping sound weld nugget but excessive time has no effect on weld soundness and just increase the process time ineffectively. This range has been chosen by OFAT of hold time while other parameters are keeping in the mid-range.[1, 3]

- Pressure: 1-5 Bar (Electrode diameter is 7 mm constant)

This parameter is highly influential and a lot of suggestion ranges of pressure are available in reference book. Depends on other factors, this range has been picked from the expanded range of references.[1, 6]

- Current: 20 to 30 %Kva

From Lobe curve.[1]

- Time: 20 to 30 cycles (0.4 to 0.6 S)

From Lobe curve.[1]

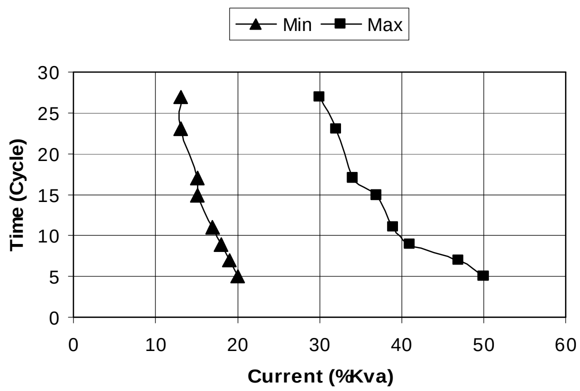


Fig. 4 Lobe curve for thickness of 1.5 mm[1]

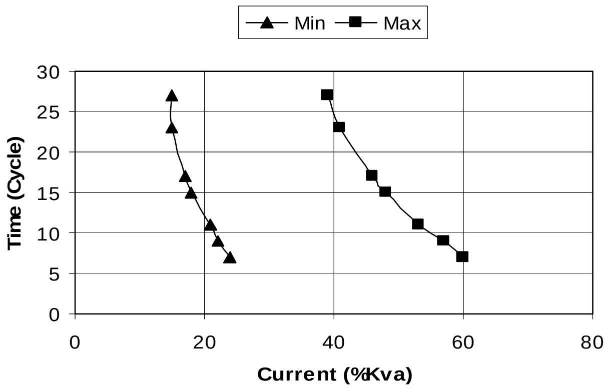


Fig. 5 Lobe curve for thickness of 2.5 mm[1]

3.2 SCREENING TO IDENTIFY THE MOST HIGHLY INFLUENTIAL PARAMETERS

DOE approach suggests some screening patterns including few experiments for quick assessment of effect of factors on output. Of course this few experiments are not enough for modeling because of low resolution of suggested pattern but these screening matrix can arrange parameters in order of priority of their effects on output.[8] Here, the most well-known DOE software, Echip Ver 6.4, has been employed to process data.[10] Suggested screening pattern of Echip has been Placket-Burman pattern including 12 experiments with 2 levels for each factor.[8, 10] This pattern including each run-result (tensile-shear strength) is indicated in table1 and the amounts of each level of factors are indicated in table 2.[1]

Table 1 Placket-Burman pattern and each run- result[1, 8]

Run	Thickness	Current	Time	Pressure	Upslope	Downslope	Hold time	Strength (Kg/spot)
3	1	-1	1	1	-1	1	1	2130
2	-1	1	-1	1	1	1	1	1985
12	-1	-1	-1	-1	-1	-1	-1	1712
1	1	1	1	-1	1	1	-1	2212
10	-1	1	1	1	-1	-1	-1	2099
8	1	1	-1	-1	-1	1	-1	2280
5	-1	-1	-1	1	1	1	-1	1545
4	-1	1	1	-1	1	-1	1	2177
9	1	1	-1	1	-1	-1	1	2050
6	-1	-1	1	-1	-1	1	1	1712
7	1	-1	-1	-1	1	-1	1	2200
11	1	-1	1	1	1	-1	-1	2015

Table 2 Amounts of each level for Placket-Burman pattern [1]

Factor	Thickness	Current	Time	Pressure	Upslope	Downslope	Hold time
Level +1	2.5	30	30	5	7	7	25
Level -1	2	25	25	3	3	3	15

ANOVA-process (Analyze Of Variance) on data has arranged factors as shown in figure 6.[1,10] It is obvious that four most influential parameters are thickness, current, time and pressure in order and these four parameters are selected for modelling in consequence.[1, 10]

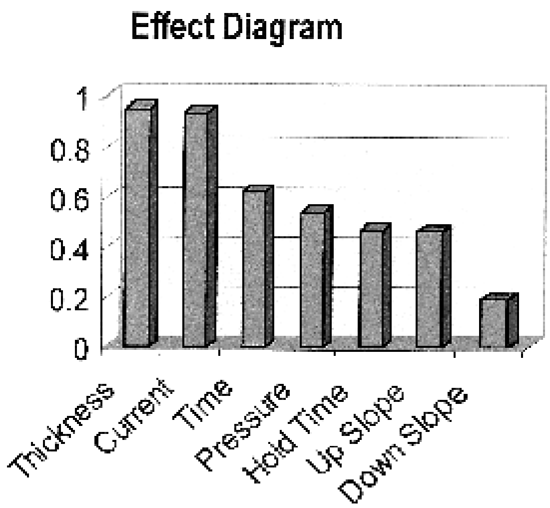


Fig. 6 Effects diagram from screening [1]

3.3 MODELLING AND FINAL EQUATION

In this step, mathematical equation should be obtained in which strength is defined by a function of four selected parameters. Obviously, model should be accurate enough to estimate strength in proper and acceptable tolerance. Therefore 3 levels for each factor are examined to use curves instead of lines with higher accuracy.[8] In regard to proper resolution of model, a fractional factorial pattern including 27 experiments has been suggested by DOE.[9, 10] This pattern including each run-result is indicated in table 3 and the amount of each level of factors is indicated in table4.[1, 10]

Table3 Fractional factorial pattern and each run-result [1, 9, 10]

Run	Thickness (mm)	Current (%Kva)	Time (Cycle)	Pressure (Bar)	Strength (Kg/spot)
15	1	-1	0	0	1152
1	-1	-1	-1	-1	1272
17	0	0	0	1	1664
4	-1	-1	-1	0	1252
18	1	-1	0	1	980
2	0	1	-1	-1	1690
23	0	-1	1	0	1620
22	-1	0	1	0	1308
27	1	1	1	1	1940
24	1	1	1	0	2264
12	1	-1	0	-1	1438
14	0	0	0	0	1764
21	1	1	1	-1	2084
5	0	1	-1	0	1652
20	0	-1	1	-1	1712
19	-1	0	1	-1	1460
16	-1	1	0	1	1360
26	0	-1	1	1	1316
25	-1	0	1	1	1354
6	1	0	-1	0	1416
13	-1	1	0	0	1392
3	1	0	-1	-1	1464
10	-1	1	0	-1	1436
9	1	0	-1	1	1192
11	0	0	0	-1	1776
8	0	1	-1	1	1476
7	-1	-1	-1	-1	1032

Table 4 Amounts of each level for fractional factorial pattern [1]

Factor	Thickness	Current	Time	Pressure
Level +1	2.5	30	30	5
Level 0	2	25	25	3
Level -1	1.5	20	20	1

Data has been processed by multiple variable regressions and finally model equation is generated by Echip. [10] This equation is shown as a table format in table 5 in which first column from left indicates different combination of factors and next column including related coefficients.[1, 10]

Table 5 Model equation [1, 10]

Combination of factors	Coefficients
1 (constant)	1764
I	42.1865
T	32.6829
P	-40.9795
D	263.306
IxT	-8.3065
IxP	5.55166
IxD	58.3325
TxP	0.62963
IxD	160.8
PxD	-37.8129
IxTxP	0.0340937
I^2	-13.8467
P^2	-11
I^2xP^2	1.72956
T^2xP^2	1.47395
P^2xD^2	-97.4565
I^2xT^2xP^2	-0.141958
I^2xT^2xP^2xD	-0.0608
I^2xT^2xP	-0.0538292
IxPxD	10.3082

I (%Kva) denote the actual amount of Current-25
T (Cycle) denote the actual amount of Time-25
P (Bar) denote the actual amount of Pressure-3
D (mm) denote the actual amount of Thickness-2

For using this table, all coefficients should be multiplied by related combinations of factors respectively in each raw and the sum of multiplied-results is the amount of strength in kilogram per spot.[1]

In this regression, adjusted R squared is 0.97 that reveals a very good fitting of model with actual data.[1, 10]

3.4 Verifying the model

Reliability is one of the most important aspects of deploying any kinds of models such as numerical ones. In this respect, the final model is verified in three steps.[7] Firstly comparison between actual results of each experiment pattern run and model prediction which is shown in table 6.[1] Secondly, five other combinations of factors (in contrast with applied pattern) apply and test performing results compare with model prediction. This comparison is shown in table 7.[1] And thirdly, the conditions for two extreme points, here refer to maximum and minimum of strength, have been computed by Echip.[10] And prediction of model has been compared with actual amounts of factor. This comparison including predicted and actual strength is shown in table 8.[1]

Table 6 Comparison between actual results of each run and model prediction for strength (Kg/spot) [1]

Run	Prediction	Actual
15	1192.72	1152
1	1272.00	1272
17	1638.04	1664
4	1252.00	1252
18	997.39	980
2	1696.20	1690
23	1577.98	1620
22	1393.76	1308
27	1940.00	1940
24	2264.00	2264
12	1451.05	1438
14	1764.00	1764
21	2084.00	2084
5	1673.01	1652
20	1699.30	1712
19	1437.55	1460
16	1342.61	1360
26	1299.26	1316
25	1361.85	1354
6	1330.24	1416
13	1351.28	1392
3	1462.24	1464
10	1422.95	1436
9	1210.11	1192
11	1801.96	1776
8	1492.74	1476
7	1032.00	1032

Table 7 Comparison between actual results of each run and model prediction, for strength in different setting of factors (Kg/spot) [1]

Thickness	Current	Time	Pressure	Prediction	Actual
2	30	20	1	1692.20	1650
2.5	25	25	3	1895.65	1810
1.5	21	27	2	1346.92	1283
2	26	24	4	1723.88	1684
2.5	23	28	5	1838.01	1757

Table 8 Comparison between predicted and actual strength (Kg/spot) for maximum and minimum points [1]

Condition	Thickness	Current	Time	Pressure	Prediction	Actual
Maximum	2.5	28	29	3.5	2349.30	2307
Minimum	2	20	22	5	874.06	894

These three comparisons demonstrate that equation of model is capable to predict strength reliably.[1]

4 STUDY THE BEHAVIOR OF MODEL

Up to here, a verified numerical model of behavior has been achieved and it is necessary to interpret the behavior of model scientifically. For this reason, two kinds of graph are employed including 3D graphs in which vertical axis (z) shows strength versus two parameters out of four (x & y axes) when two other parameters are fixed, and 2D graphs in which strength are shown as iso-strength counters.[1]

Current and time are two main parameters in resistance spot welding. The relation between strength and these two parameters is shown in figures 7 and 8.[1]

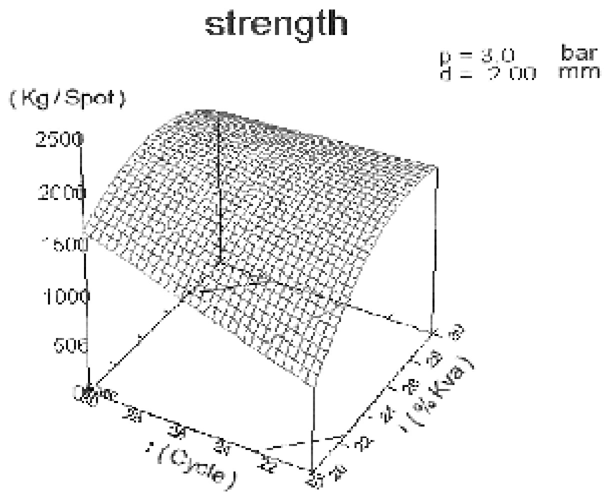


Fig. 7 3D-plot of strength vs. current & time for pressure of 3 Bar & thickness of 2 mm [1]

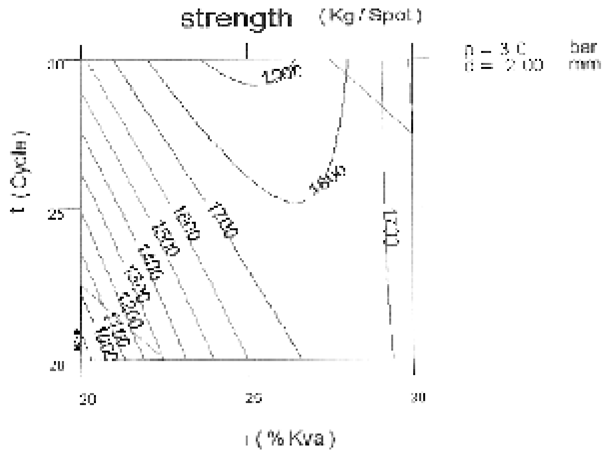


Fig. 8 2D-plot of strength vs. current & time for pressure of 3 Bar & thickness of 2 mm [1]

In these figures, strength increase slightly to reach a peak and decline by current changing. These trends remain the same for each amount of time in the range. However, higher time reduces the amount of current for getting to the maximum point.[1]

For instance, peak point is about 28 %Kva for 20 cycles different from 25 %Kva for 30 cycles (figure 8).[1]

Apparently, increasing time causing higher strength but it is supposed to get the maximum point just as current trend.[1]

In these figures, the highest strength is about 1900 Kg/spot in 30 cycle and nearly 26 %Kva.[1]

It is understandable that increasing or decreasing rate changes between one region and another. Here, for example, more tight counter lines in lower current and time demonstrate high gradient in contrast to less packed lines in higher ones.[1] This gradient is considerable in lower amounts of current and time in particular for current but gradient decreases as approach the peak.[1] Gradient is important in mass production where upon much closer tolerance of strength will be obtained if process parameters are selected from low gradient region (unpacked line).[4] This aspect is noticeable, for instance, in automotive body assembly lines.

For studying the influence of pressure, figures 9 & 10 are plotted for pressure in 1 Bar and figures 11 & 12 are plotted for pressure in 5 Bar.[1]

A noticeable decline is seen in high current and time for both pressures where upon peak can be considered for time trend in high amounts of current and it is much more considerable for pressure of 5 Bar. Strength can reach to more than 2000 Kg/spot in 1 Bar whereas increasing the pressure decreases the maximum achievable strength to nearly 1900 Kg/spot and totally it is deducible that surface shifting-down results from pressure increasing.[1]

For studying the condition in different thickness, figures 13 & 14 for thickness of 2.5 mm and 15 & 16 for thickness of 1.5 mm are plotted.[1] It should be mentioned that inner area of triangle in these shapes have been resulted from actual tests but outer area have been extrapolated from model by Echip.[1]

In figures 13 & 14, the most noticeable point is high achievable strength of more than 2200 Kg/spot, which it is supposedly related to higher strength of higher thickness.[2] In these figures, peak point happens in high amounts of time therefore it seems that in low amounts of time, weld situation is hypo-peak of current trend.[1]

Conversely, in figures 15 & 16 for thickness of 1.5 mm, it seems that weld situation is hyper-peak of both current and time in particular for time because strength decreasing arises from both current and time increasing.[1]

In Case, Echip is capable to plot relation between strength versus any combination of parameters as well for any other interpretation.[10]

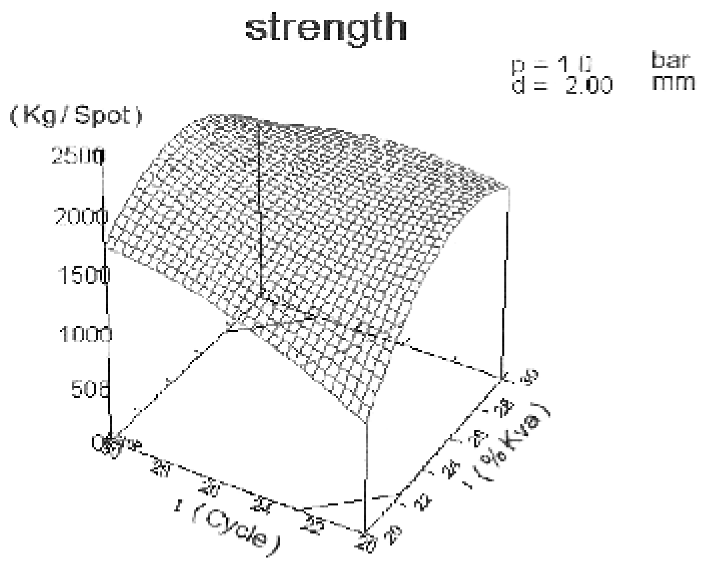


Fig. 9 3D-plot of strength vs. current & time for pressure of 1 Bar & thickness of 2 mm [1]

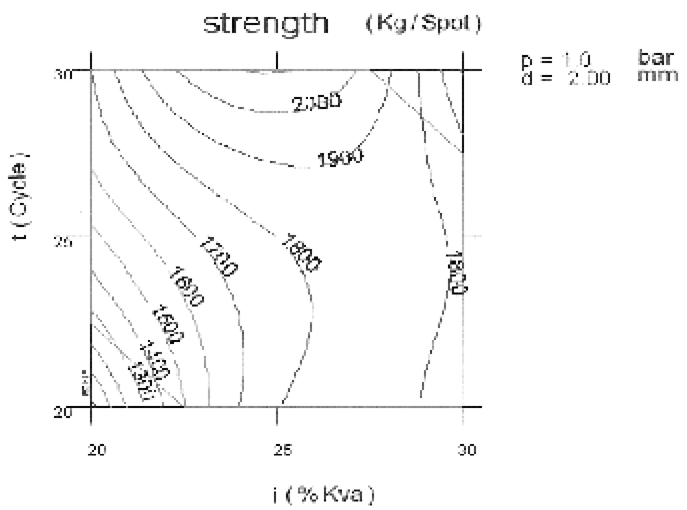


Fig. 10 2D-plot of strength vs. current & time for pressure of 1 Bar & thickness of 2 mm [1]

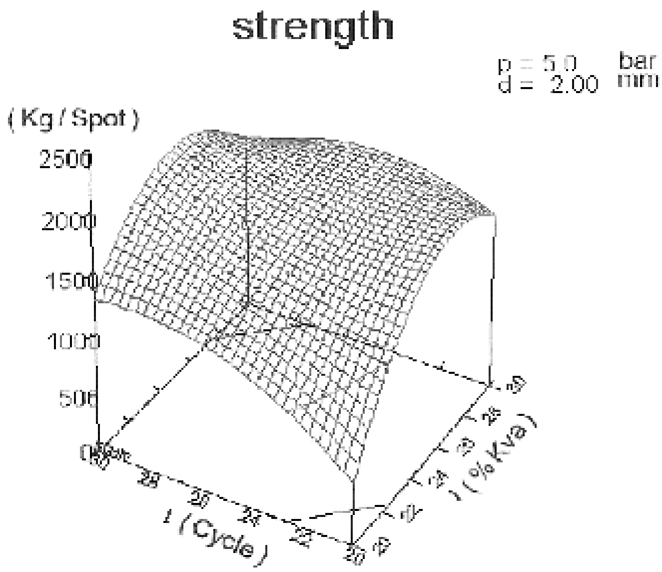


Fig. 11 3D-plot of strength vs. current & time for pressure of 5 Bar & thickness of 2 mm [1]

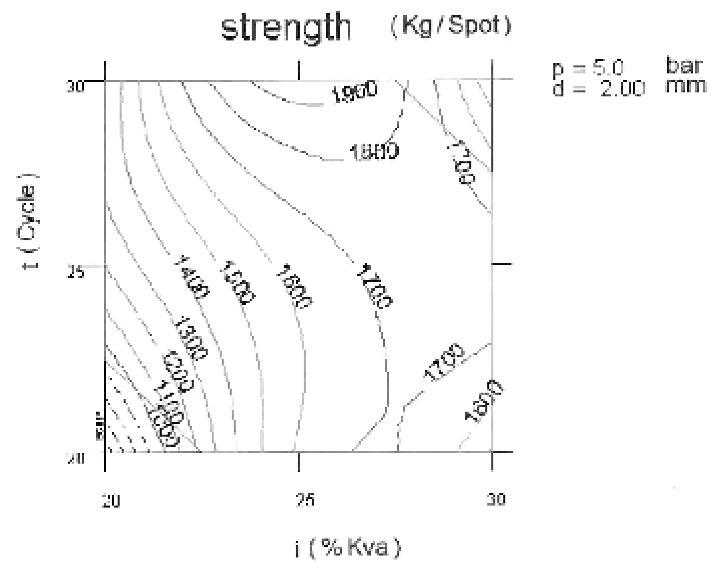


Fig. 12 2D-plot of strength vs. current & time for pressure of 5 Bar & thickness of 2 mm [1]

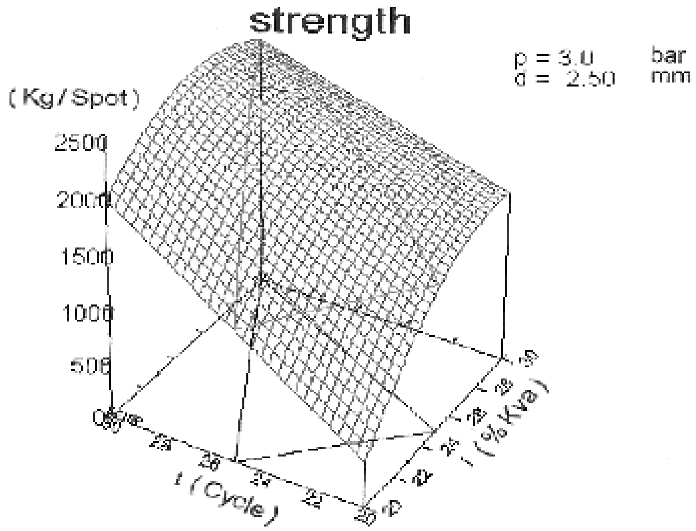


Fig. 13 3D-plot of strength vs. current & time for pressure of 3 Bar & thickness of 2.5 mm [1]

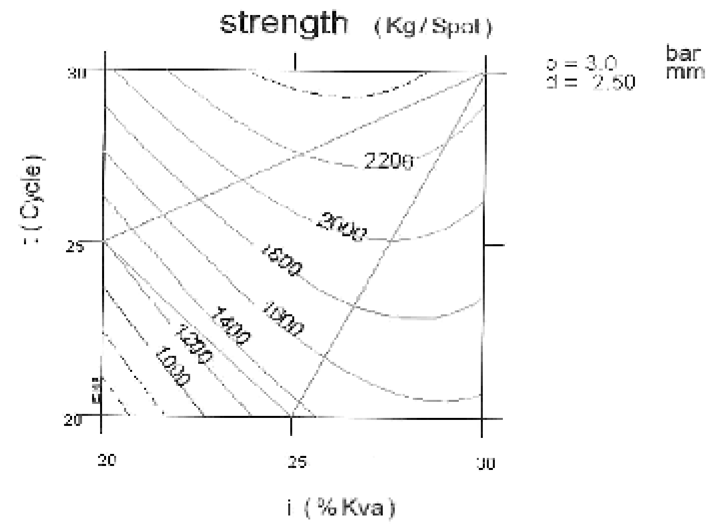


Fig. 14 2D-plot of strength vs. current & time for pressure of 3 Bar & thickness of 2.5 mm [1]

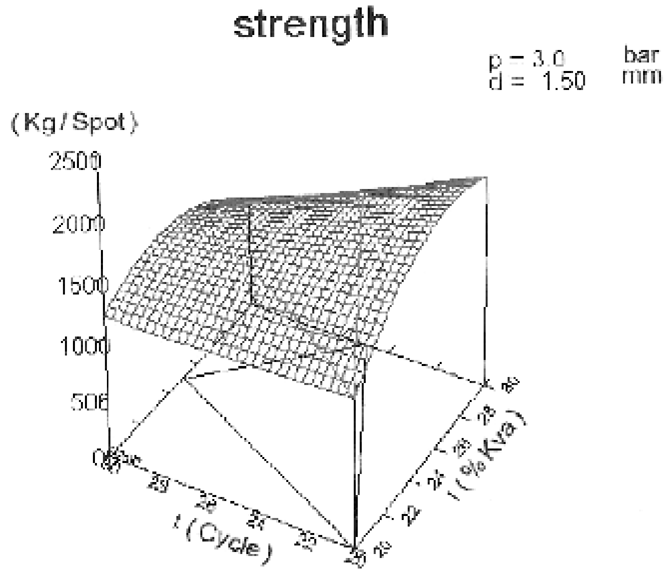


Fig. 15 3D-plot of strength vs. current & time for pressure of 3 Bar & thickness of 1.5 mm [1]

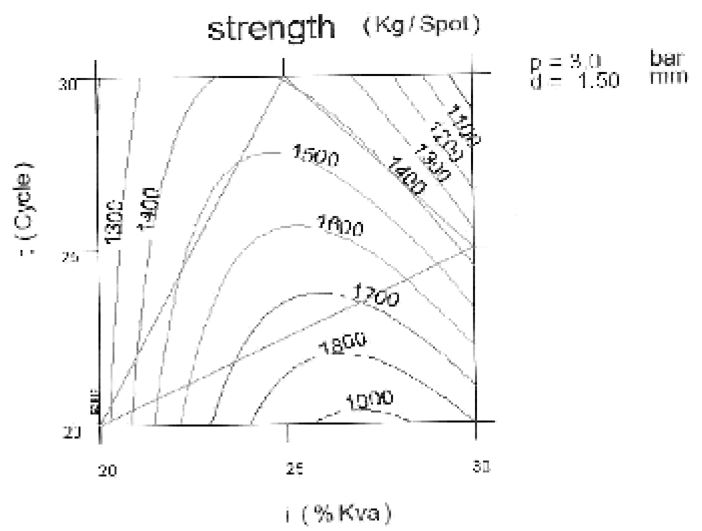


Fig. 16 2D-plot of strength vs. c
urrent & time for pressure of 3 Bar & thickness of 2 mm [1]

5 CONCLUSION

Overall, the main aspect of this paper is offering DOE approach for applying in spot resistance welding. In fact, DOE concepts are employed and all problems are solved in practice to achieve a systematic approach whereupon users can obtain effective and reliable numerical model through it. In brief, these approach steps are summarized as following: [1]

- Choosing attribute.
- Drawing Cause & Effect diagram.
- Selecting parameters for quick assessment of their effects.
- Determining max/min limits for parameters (In case, using OFAT or Lobe curve)
- Applying DOE screening pattern to arrange parameters in order of importance.
- Selecting important parameters for all-out modeling.
- Applying best DOE modeling pattern to obtain mathematical equation.
- Verifying the model.

According to these steps, here, chosen attribute is tensile-shear strength[3] and quick assessment has been performed by Placket-Burman pattern[8, 10] on six process factors plus thickness out of other factors from Cause & Effect diagram.[1] Thickness, current, time and pressure have been selected for modeling and mathematical equation has been obtained by a fractional factorial pattern[9, 10] performing. Consequently, verifying the model is done by three different kinds of comparison between actual results and model prediction. Also behavior has been interpreted scientifically.[1]

Two aspects are important in model behavior. One of them is the amount of strength another one is strength gradient.[1] It is preferred in mass production that strength is chosen from low gradient area to obtain closer tolerance.[4]

This model including interactions between parameters and is capable to predict strength reliably as a function of thickness, current, time and pressure.[1]

The main advantage of numerical modeling over other techniques is being practical oriented.[8] Therefore all unconsidered and noise factors are included in result and model are much closer to practice with common sense as well.[8]

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