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Application of Taguchi method for optimization of resistance spot welding of austenitic stainless steel AISI 301L

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Abstract

This study presents a systematic approach to determine effect of process parameters on indentation as a primary & initial measure of weld quality and subsequently tensile strength, nugget diameter and penetration. To achieve the objective an attempt has been made to select important welding parameters like welding current, weld cycle, hold time & cool cycle using quality tools, available literature and on scientific reasons. On the selected parameters, Experiment have been conducted as per Taguchi method and fixed the levels for the parameters. The experiment has four factors and all factors are at two levels. To have wide spectrum of analysis and variability with time, L32 Orthogonal Array (OA) experiments are conducted. Optimum welding parameters determined by Taguchi method improved indentation which in turn confirms the value of nugget size, tensile strength and penetration. Analysis of variance (ANOVA) and F-test has been used for determining most significant parameters affecting the spot weld parameters.

Keywords: Welding parameters; Taguchi Method; Resistance spot welding (RSW); Orthogonal array; ANOVA

1. Introduction

The use of resistance welding for stainless steel railcar fabrication was a fascinating feat of engineering linked to the creativity and vision of Edward Gowan Budd (1870-1946), founder of the Edward G. Budd Manufacturing Co., Philadelphia. His company was the first to produce all-steel automobile bodies and also one of the first to use resistance spot welding. AISI 301L austenitic stainless steel has been very widely used for rail vehicles carbody design for many years owing to its corrosion resistance, low life cycle cost, high strength to weight ratio and fire resistance. Resistance spot welding is the most widely used form of the electric resistance welding process in which faying surfaces are joined in one or more spots. The RSW process fundamentally consists of four stages which are squeeze cycle, weld cycle, hold cycle and off cycle. Welding spatters and Indentation are primary measures for the quality of spot. Weld spatters are visible and indentation can be measured using dial gauge as a first and primary measure of weld quality. The automotive industry has introduced the three-layer weld configuration, which represents new challenges compared to normal two-sheet lap welds. New researches are going on for four sheets welding.

2. Literature Review

Indentation is the indent created on the sheet surfaces by electrodes under electrode force during welding. It is a direct indicator of the existence of a weld, and sometimes that of the amount of penetration of a weld. Because it is very difficult to eliminate unless special electrodes and procedures are used, certain indentation is allowed in most practices. Excessive indentation is not allowed considering its implication in surface finish of the assembled structure, and the load-bearing capacity of the weld. If the surface is exposed to customers of the final products, a deep indentation may create an unfavorable impression. Too much indentation may also create a weak link between a weld and its parent metal sheets because of a reduced thickness in the sheet near the wall of indentation. This is especially true when multiple sheet stackups, such as three-sheet stack-ups, are welded, with the outermost sheet as a thin one. The indentation depth is often more than the thickness of the outer sheet, resulting in little joining strength for the sheet attached to the inner ones. Excessive indentation often results from excessive heating, i.e., improper welding schedules, and it is usually related to other types of discontinuities. For instance, expulsion and surface melting (resulting in surface cracking and holes) are often associated with large indentation. Excessive indentation may also induce excessive separation. By correctly choosing welding parameters and welder setup, indentation can be controlled to achieve sufficient penetration and strength (Zhang, Senkara 2006: 61). Welding solution provider M/s. Rautaruukki corporation recommends that Indentation must be less than 20 % of work piece thickness, preferably less than 10 %(Ruukki,2012). Bračun et al (2005) has found that indentation is one of the indicator of spot welding quality. Increasing welding current leads to alter failure mode from interfacial failure mode to pullout mode (Pouranvari 2011:40). As per JIS 3140, 1989 indentation on the weld surface on the side for which evenness is specified shall not exceed 10% of the sheet thickness of the side or 0.15 mm whichever is greater. Quantitative relationships can be used to to link a weld's geometric and mechanical attributes to its strength under tensile-shear loading using finite element method (Zhou 2003). Finite Element Analysis can be used to study the nugget dia in the case of RSW (Thakur 2010). Kachhoriya et al (2012) has used regression modeling to get the highest ultimate strength in the range in case of RSW of low carbon mild steel. Response surface methodology has been used for predicting the weld zone development for the resistance spot welding of low carbon steel of 1 mm thickness(Muhammad 2012). Neural network-based approaches also used to model TIG welding (Dutta,2007). Limited research has been carried out for resistance spot welding of AISI 301L using three or more sheets. Three-Sheet Spot Welding of Advanced High-Strength Steels for automotive application has been studied and the mechanism of nugget formation has been identified to initiate between the two high-strength steels from where it develops and grows into the sheets. Depending on the heat input, the nugget might grow close to or in some cases even slightly penetrate into the thin, low-carbon steel. (Nielsen 2011). Uijl from Tata Steel R & D has written a technical white paper regarding a case study of a complicated geometry with welding of 3 sheets of 3 different materials considering shunt welds which was simulated and validated against experimental results. The work presented in this paper shows that the use of simulation software based on a 2D axi-symmetric approach can be used to simulate 3D effects, such as shunt welds (Uijl, Tata Steel). The influence of nugget diameter on the mechanical properties and the failure mode of resistance spot welding of AISI 301 L has been studied and found that the fatigue life of spot welds under the fixed loads increased with the nugget size, which was especially evident for the spot welded thin sheets (Liu 2012).

3. Scope of the study

Material Used: Austenitic Stainless Steel grade 301L

Welding process: Direct resistance spot welding as per JIS E 4049 - 1990

Thickness of material (in mm): 2 + 2 + 1.5 + 2

Application of the process: Railway car body manufacturing

4. Objective of the study

1) Optimization of process parameters to get indentation upto 25% of sheet thickness (maximum 0.5 mm).
2) Effect of optimized parameters on nugget diameter, tensile strength and penetration.

4.1 Hypothesis

1) H_{A1}: Tensile strength is more than 1920 Kgf (As per JIS Z-3140)
2) H_{A2}: Nugget diameter is more than 7.1 mm
3) H_{A2}: Penetration is more than 20%

4.2 Experimental Factors: Weld current, Weld Cycle, Hold Time & Cool Time

4.3 Control Factors: Electrode tip dia (6 mm as per JIS Z 3221), Electrode force (700 Kgf)

4.4 Noise Factors: Ambient Temperature, Variation in machine output, Operator Fatigue etc.

4.5 Welding Machine used:

Model No. PC9841A002, Serial No. 0315-0012, Make: Nawootec

5. Methodology used

5.1 Experiment Design: Taguchi L 32 orthogonal array (Four factors and two levels)

The designed parameters are given in table.1

5.2 Experimentation

The indentation at old level before conducting the taguchi experiment is given in table.2

The results of indentation after conducting the taguchi experiments are given in table table.3

Indentation values given in the table 2 & 3 are average values of the spot indentation on the samples.

6. Analysis & Results

Software used for analysis is Minitab 14

6.1 Analysis of indentation before conducting experiment

Figure 1 shows that average indentation is 0.87 mm and data follows normal distribution because p value is more than 0.05. Figure-2 shows that point no.9 is above control limit but no special cause identified.

6.2 Analysis of indentation after conducting experiment

Figure 3 shows that residuals follow normal distribution and do not show any pattern with time and fitted value.

Figure 4 & 5 shows significant factors which are

a) Weld Cycle
b) Interaction between Weld Current & Weld Cycle
c) Interaction between Weld Current, Weld Cycle & Hold Time

Figure 6 (a) shows that p- value is less than to 0.05 for Weld Cycle, Interaction between Weld Current & Weld Cycle and Interaction between Weld Current, Weld Cycle & Hold Time which are the significant factors.

Figure 6 & 7 shows that there is a significant change in indentation when the weld cycle is changed from 50 to 60.

As per figure 8, new levels of weld parameters for minimum indentation are

i) Weld Cycle = 50 Cycles
ii) Weld current = 9.5 Kamp
iii) Hold time = 70 Cycles

7. Validation

08 nos. of experiments are conducted to validate the results at new levels of weld parameters for minimum indentation. The results of the experiments are as follows:-

The analysis and results of experiment data in table-4 are as follows:-

7.1 Comparison of indentation at new and old levels

7.1.1 Test for Equal Variances: Old and New levels

95% Bonferroni confidence intervals for standard deviations

	N	Lower	StDev	Upper
Old levels	8	0.0896325	0.143272	0.328161
New levels	8	0.0281650	0.045020	0.103117

F-Test (normal distribution)
Test statistic = 10.13, p-value = 0.007

7.1.2 Two-Sample T-Test and CI: Old and New levels

Two-sample T for Old and New Method.

	N	Mean	StDev	SE Mean
Old levels	8	0.869	0.143	0.051
New levels	8	0.3138	0.0450	0.016

Difference = mu (C15) - mu (C16)

Estimate for difference: 0.555000
95% CI for difference: (0.432560, 0.677440)
T-Test of difference = 0 (vs not =): T-Value = 10.45, P-Value = 0.000, DF = 8

Figure 9 shows that indentation at new level is below 0.4 mm

Test of equal variance and two sample t –test shows that the p-value is less than 0.05 which depicts that new levels of welding parameters are better than old levels

7.2 Check for tensile strength at new level

7.2.1 One-Sample T test:

Test of mu = 1920 vs > 1920 (as per JIS Z-3140)

Variable	N	Mean	StDev	SE Mean	95% Lower Bound	T	P
Tensile strength	8	2470.75	135.48	47.90	2380.00	11.50	0.000

One sample t-test shows that p-value is less than 0.05 and figure-10 shows that the alternate hypothesis H_{A1}: Tensile strength is more than 1920 Kgf is accepted.

7.3 Check for nugget diameter at new level

7.3.1 One-Sample T test:

Test of mu = 7.1 vs > 7.1 (as per JIS Z-3140)

Variable	N	Mean	St. Dev	SE Mean	95% Lower Bound	T	P
Nugget diameter	8	10.6950	1.0628	0.3758	9.9831	9.57	0.000

One sample t-test shows that p-value is less than 0.05 and figure-11 shows that the alternate hypothesis H_{A2}**:** Nugget diameter is more than 7.1 mm is accepted.

7.4 Check for penetration at new level:

7.4.1 One-Sample T test

Test of mu = 20 vs > 20 (as per JIS Z-3140)

Variable	N	Mean	StDev	SE Mean	95%Lower Bound	T	P
Penetration	8	50.3125	12.6574	4.4751	41.8341	6.77	0.000

One sample t-test shows that p-value is less than 0.05 and figure-12 shows that the alternate hypothesis H_{A2}: Penetration is more than 20% is accepted.

8. Conclusions

This paper has presented an investigation on the optimization and effect of welding parameters on indentation of spot welded AISI 301L stainless steel. The level of importance of the welding parameters on indentation is determined by ANOVA (main effect plots). Based on ANOVA method, the highly effective parameters on indentation are found as weld cycle, interaction between weld current & weld cycle and interaction between weld current, weld cycle & hold time whereas weld current, hold time and cool time were less effective factors. An optimum parameter combination for the nominal indentation was obtained using the cube plot. The experimental results confirmed the validity of Taguchi method for optimizing the process parameter in resistance spot welding.

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List of Tables:

Table-1, Factors and levels

S.No.	Factors	Low	High
1.	Weld Current	9.5 KA	10 KA
2.	Weld Cycle	50 Cycles	60 Cycles
3.	Hold Time	70 Cycles	80 Cycles
4.	Cool Time	70 Cycles	80 Cycles

Table-2, Initial Indentation before conducting the experiment

S.No.	Indentation	S.No.	Indentation (in mm)
1	0.71	11	0.68
2	0.78	12	0.73
3	0.83	13	0.98
4	0.98	14	1.12
5	0.79	15	1.06
6	0.8	16	0.94
7	0.9	17	0.85
8	1.16	18	0.77
9	1.3	19	0.76
10	0.88	20	0.97

Table-3, Experimental data for indentation

S. No.	Weld Current	Weld Cycles	Cool Time	Hold Time	Indentation (in mm)	S.No.	Weld Current	Weld Cycles	Cool Time	Hold Time	Indentation (in mm)
1	9.5	50	70	70	0.22	17	10	50	70	70	0.37
2	9.5	50	70	70	0.25	18	10	50	70	70	0.32
3	9.5	60	70	70	0.44	19	10	60	70	70	0.43
4	9.5	60	70	70	0.39	20	10	60	70	70	0.30
5	9.5	50	80	70	0.25	21	10	50	80	70	0.58
6	9.5	50	80	70	0.20	22	10	50	80	70	0.35
7	9.5	60	80	70	0.51	23	10	60	80	70	0.40
8	9.5	60	80	70	0.42	24	10	60	80	70	0.35
9	9.5	50	70	80	0.28	25	10	50	70	80	0.34
10	9.5	50	70	80	0.25	26	10	50	70	80	0.28
11	9.5	60	70	80	0.36	27	10	60	70	80	0.50
12	9.5	60	70	80	0.36	28	10	60	70	80	0.34
13	9.5	50	80	80	0.34	29	10	50	80	80	0.34
14	9.5	50	80	80	0.27	30	10	50	80	80	0.29
15	9.5	60	80	80	0.33	31	10	60	80	80	0.34
16	9.5	60	80	80	0.33	32	10	60	80	80	0.32

Table-4, Experimental data at new levels of welding parameters

	Indentation (in mm)	Tensile Strength (in Kgf)	Nugget Diameter (in mm)	Penetration (%)
1	0.39	2529	10.93	35.5
2	0.29	2614	11.25	47.5
3	0.32	2591	10.02	49
4	0.25	2413	10.73	36.5
5	0.35	2581	12.96	43
6	0.28	2250	9.92	71.5
7	0.29	2478	9.8	56.5
8	0.34	2310	9.95	63

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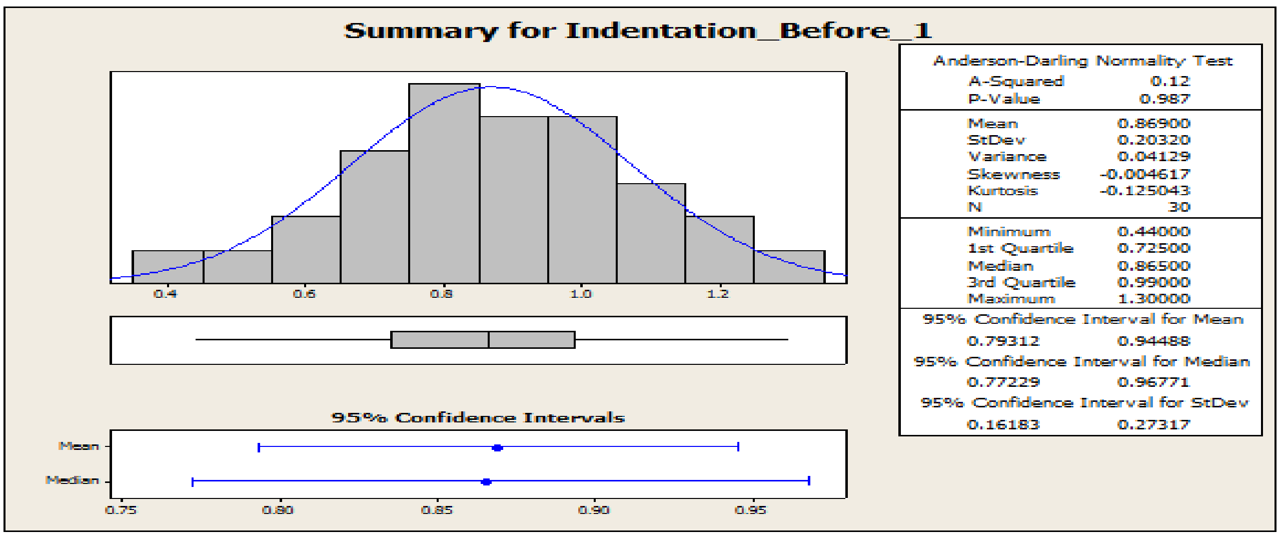


Figure.1 Normality plot for indentation before experiment

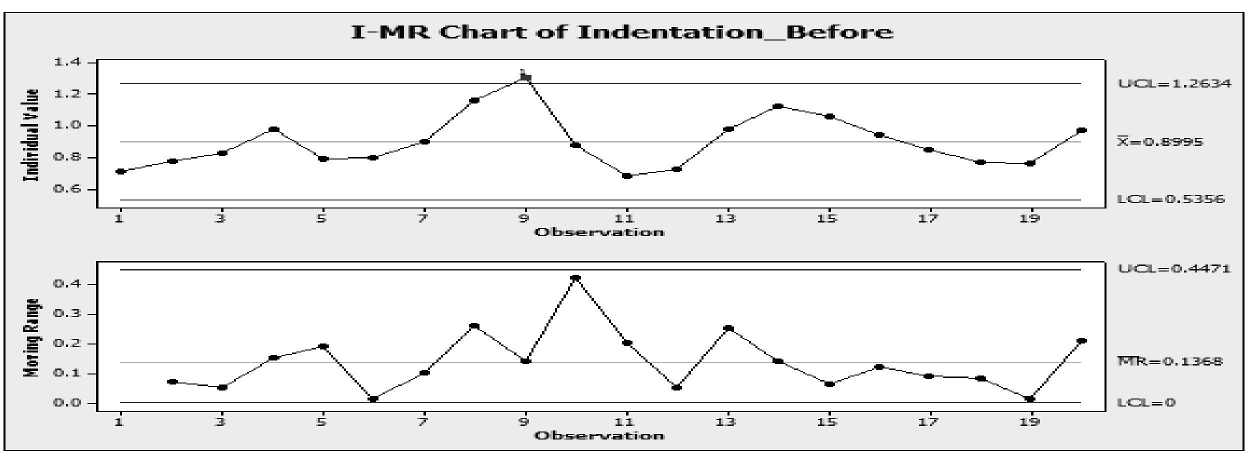


Figure-2, Check for any special cause for chronological data

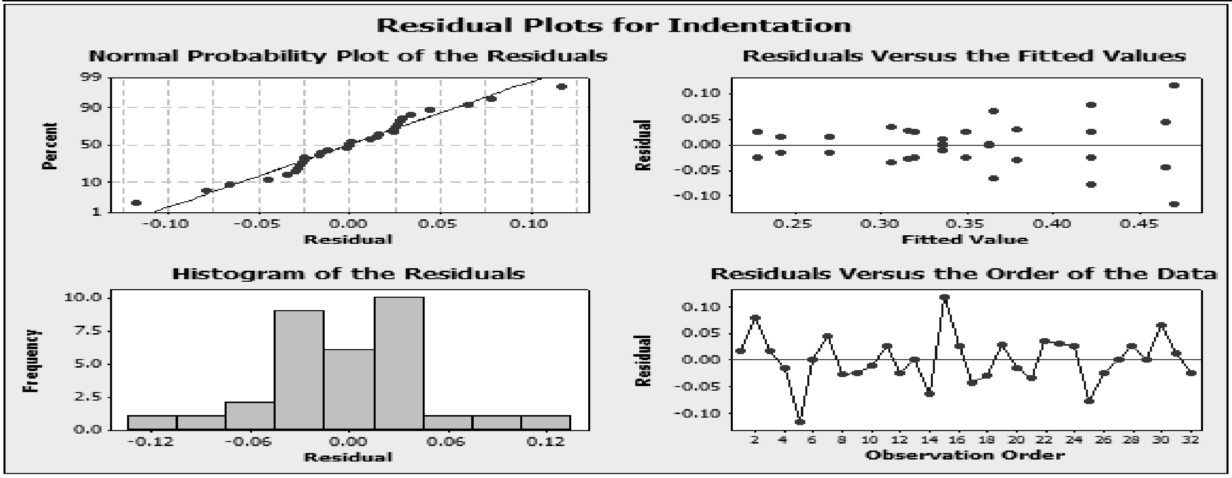


Figure-3, Check for the adequacy of the model

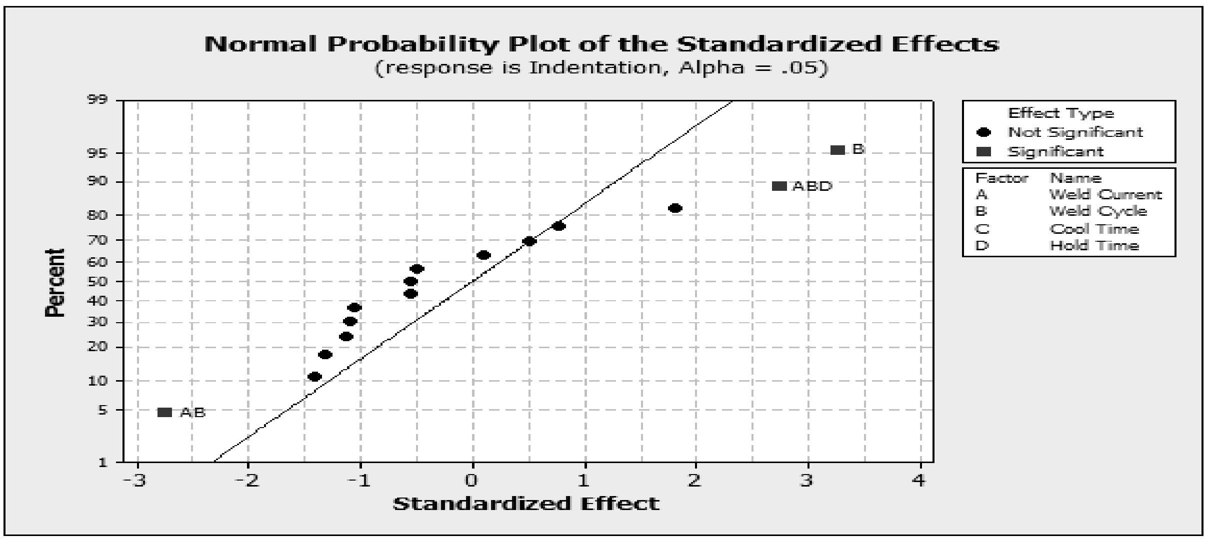


Figure-4, Determination of large effects by Normal probability plot

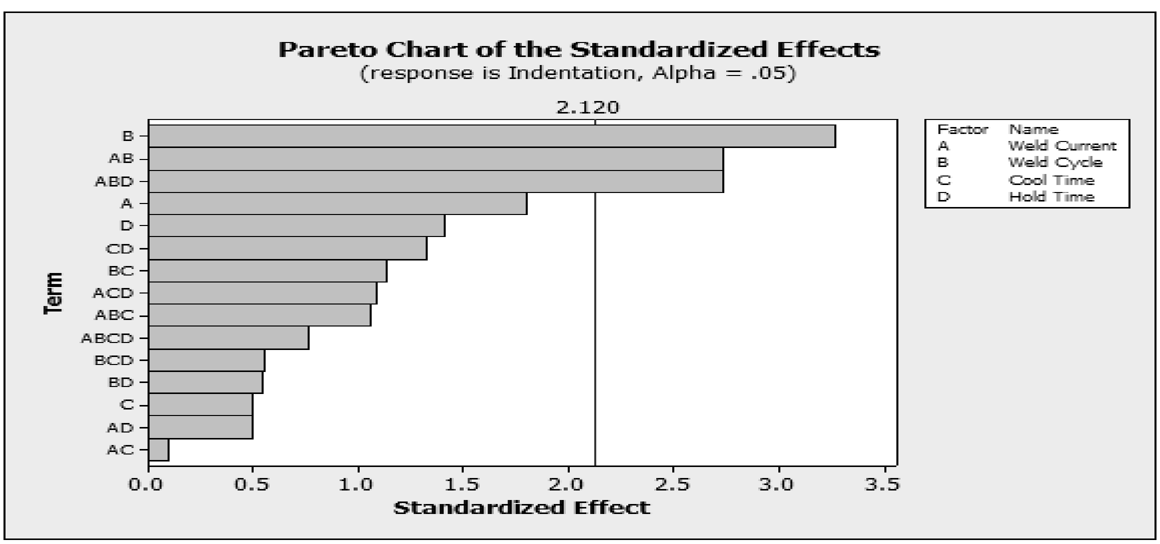


Figure-5, Determination of large effects by Pareto chart

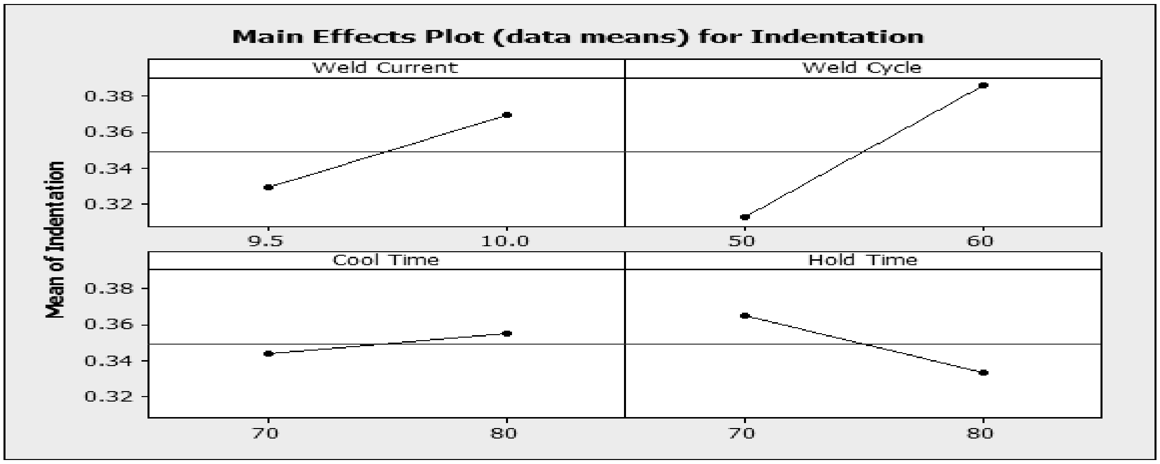


Figure-6, Main effects plots (data means) for indentation

•Term	Effect	Coef	SE Coef	T	P
•Constant		0.34925	0.01125	31.05	0.000
•Weld Current	0.04063	0.02031	0.01125	1.81	0.090
•Weld Cycle	0.07350	0.03675	0.01125	3.27	**0.005**
•Cool Time	0.01125	0.00563	0.01125	0.50	0.624
•Hold Time	-0.03175	-0.01587	0.01125	-1.41	0.177
•Weld Current*Weld Cycle	-0.06162	-0.03081	0.01125	-2.74	**0.015**
•Weld Current*Cool Time	0.00212	0.00106	0.01125	0.09	0.926
•Weld Current*Hold Time	-0.01112	-0.00556	0.01125	-0.49	0.628
•Weld Cycle*Cool Time	-0.02550	-0.01275	0.01125	-1.13	0.274
•Weld Cycle*Hold Time	-0.01225	-0.00612	0.01125	-0.54	0.594
•Cool Time*Hold Time	-0.02975	-0.01487	0.01125	-1.32	0.205
•Weld Current*Weld Cycle*Cool Time	-0.02387	-0.01194	0.01125	-1.06	0.304
•Weld Current*Weld Cycle*Hold Time	0.06162	0.03081	0.01125	2.74	**0.015**
•Weld Current*Cool Time*Hold Time	-0.02437	-0.01219	0.01125	-1.08	0.295
•Weld Cycle*Cool Time*Hold Time	-0.01250	-0.00625	0.01125	-0.56	0.586
•Weld Current*Weld Cycle*Cool Time* Hold Time	0.01712	0.00856	0.01125	0.76	0.458

S = 0.0636273 R-Sq = 70.35% R-Sq(adj) = 42.55%

Figure 6 (a), p-value of effects

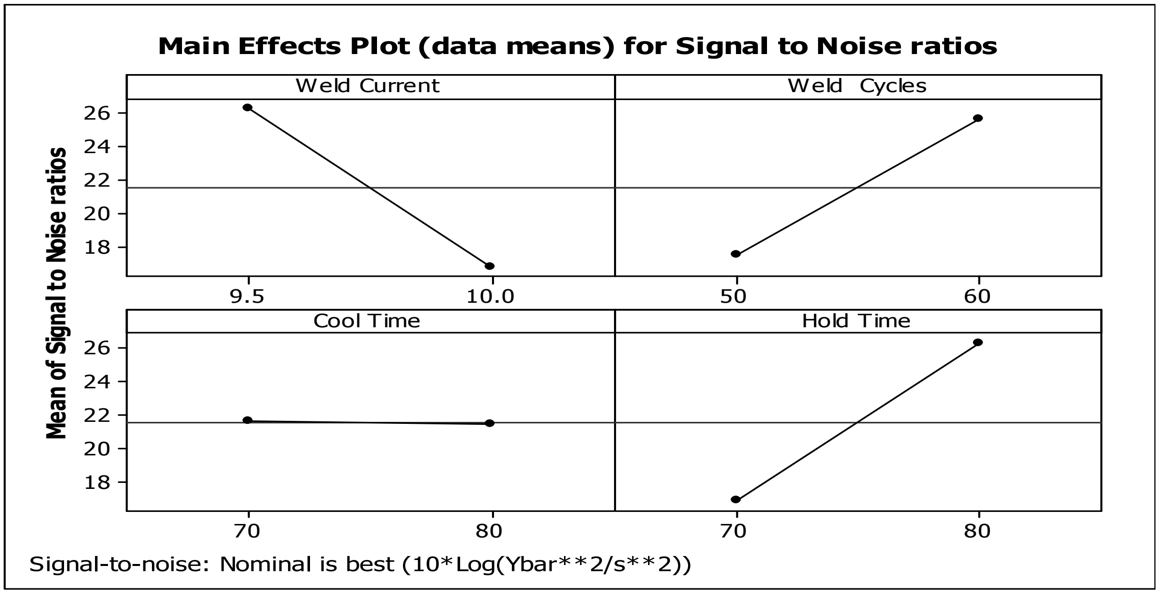


Figure-7, Main effects plots (data means) for for Signal to Noise ratio

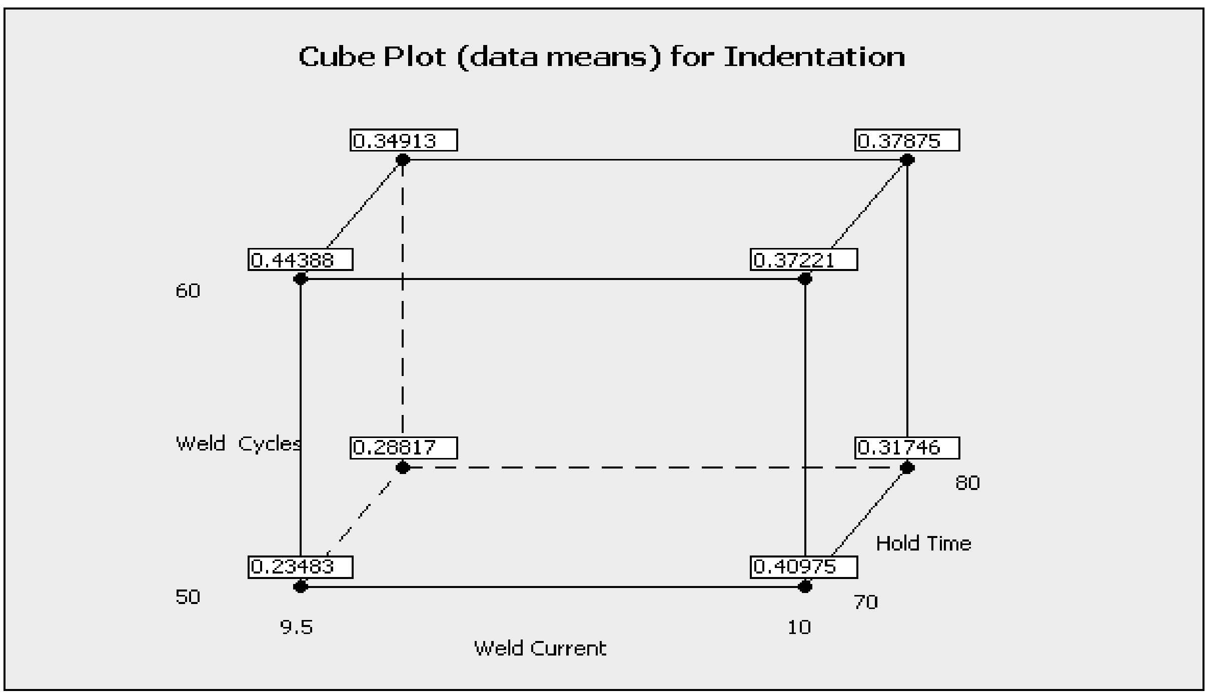


Figure-8, Cube plot (data means) for indentation

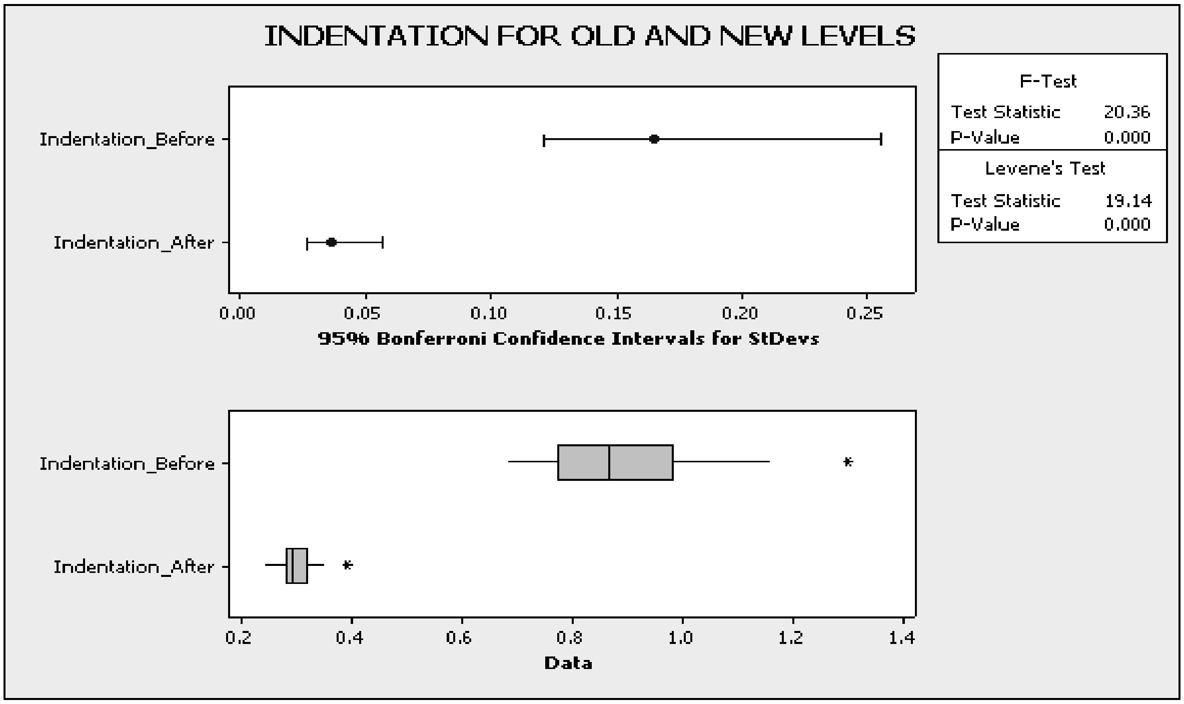
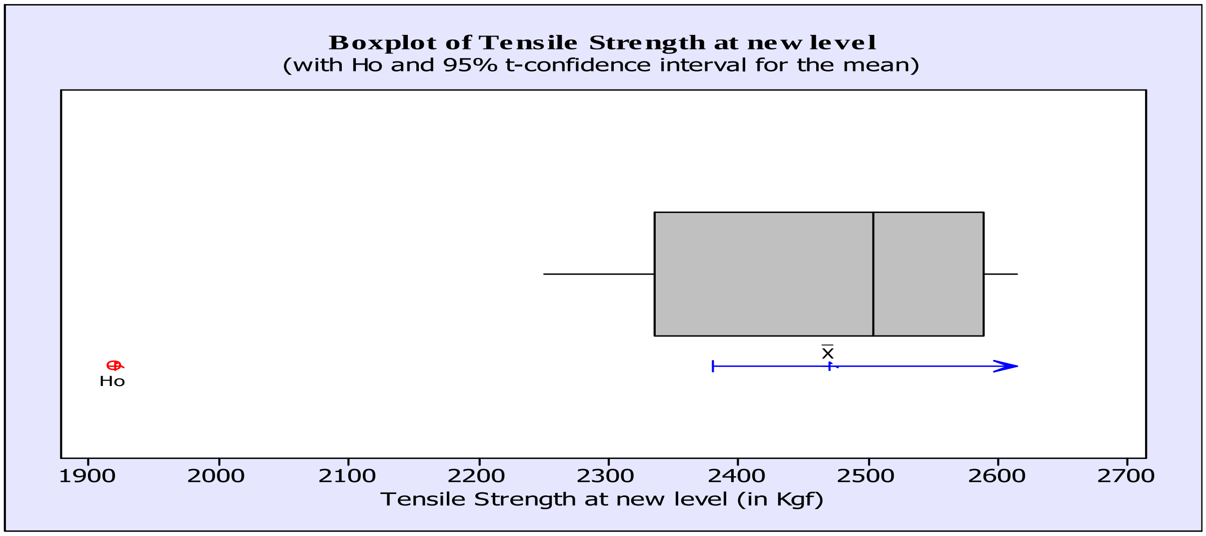


Figure-9, Box plot for indentation at new and old levels of welding parameters



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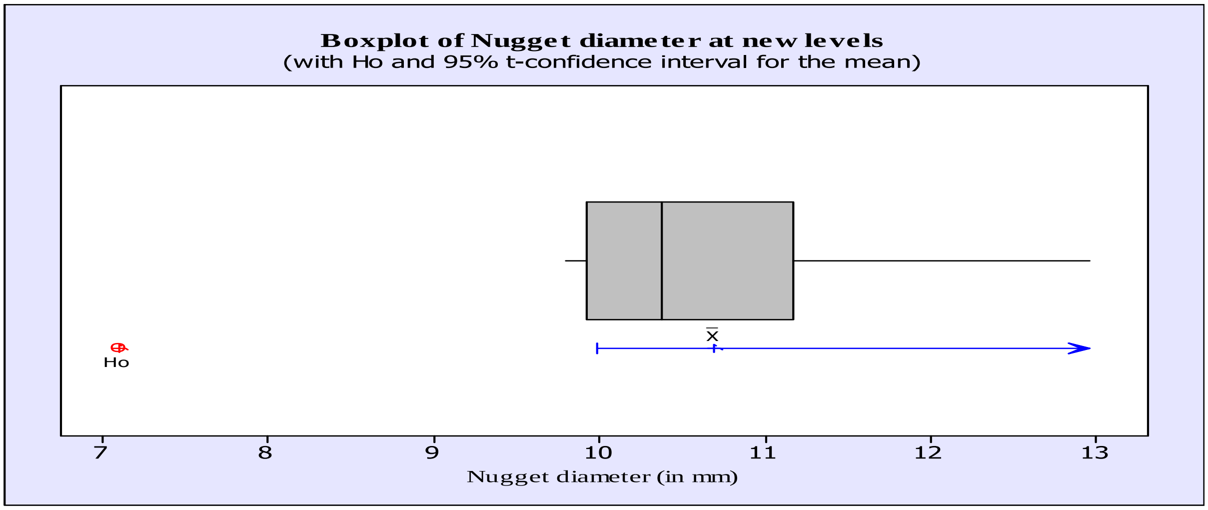

Figure-11, Box plot for nugget diameter at new levels of welding parameters

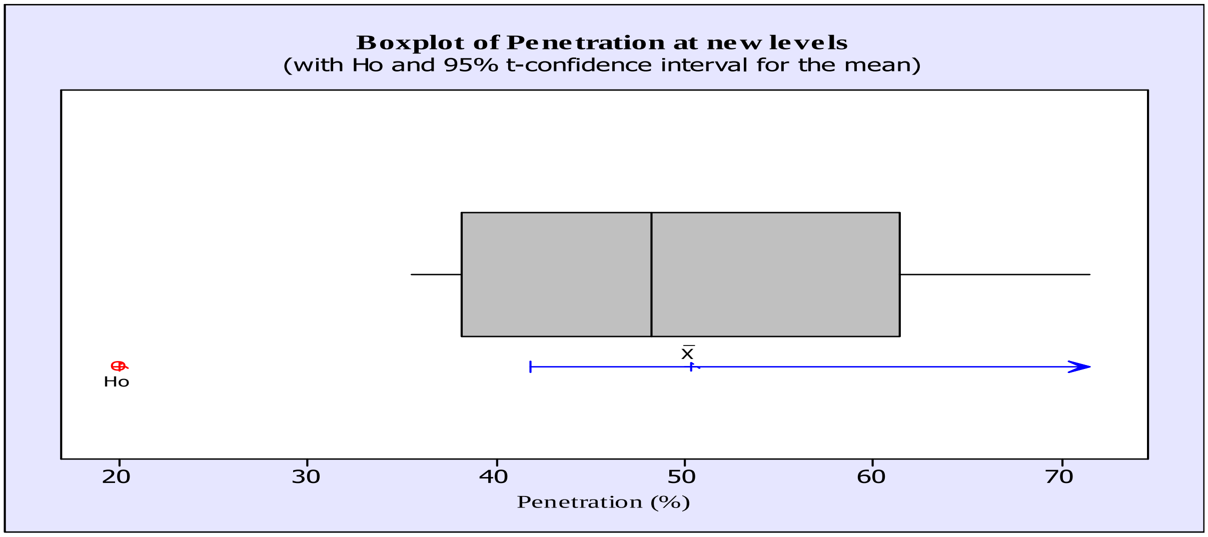

Figure-12, Box plot for penetration at new levels of welding parameters