# Multi-objective Optimization of Setting of Resistance Spot Welding Machine using Taguchi's Quality Loss Function

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**ABSTRACT**

Resistance Spot Welding (RSW) is widely used in the industry particularly automobile industry as a predominant technique for sheet metal assembly. Although used for several decades, RSW has a major problem of large variation in weld quality. For setting RSW machine parameters, welding operators in the industry, generally use trial and error method for getting the desired quality (Weld Indentation, Weld Strength or there combinations) of the weld. With the change in work-shift, each time the machine parameters are reset, thereby wasting time & material and adversely affecting the productivity. It appears that optimum setting in the parameters of RSW machine may improve the quality of the product.

The paper reports the experimental Multi Objective Optimization of setting of RSW machine using Taguchi's Quality Loss Function, to get the desired quality of the weld. Also the results of multi-objective optimization are compared with the results of single objective optimization.

**Keywords :** Multi Objective Optimization, single objective optimization, Resistance Spot Welding, Weld Indentation, Weld Strength, Taguchi's Quality Loss Function.

## INTRODUCTION

Resistance spot welding is a process of joining two or more metal parts by fusion at discrete spots at the sheet interface. Resistance to current flow through the metal sheet generates heat and raises temperature at sheet interface till the metal fuses and forms a nugget. This process is completed within a specified cycle time (one cycle corresponds to $1/50^{th}$ of a second when referred to the power supply frequency of 50 cycles per second). The two main industries that widely use this process are the automobile industries and the aircraft industries.

The main quality requirements of the product are the Weld Indentation (depth of depression on sheet surface caused by welding electrode) and Weld Strength (related to weld joint failure load in tension). The quality of weld depends on the setting of the control parameters like welding electrode force (electrode force), diameter of the welding electrode contact surface (electrode diameter), squeeze time, weld time, hold time and weld current, of the spot welding machine and on the noise factors like axial misalignment, angular misalignment, poor fit up, electrode wear and electrode temperature.

Generally the welding operators in the industry, for setting spot welding machine parameters, use trial and error method. With the change in work shift, each time the machine parameters are reset, thereby wasting time and material and adversely affecting the productivity.

Literature review [1, 2] in this area reveals that, no theoretical model is available to arrive at the optimum setting of the RSW machine, satisfying multiple objectives to get desired weld quality. It is necessary to arrive at the optimum setting by planning and executing extensive experimentation. Antony [3] has suggested a multi-objective optimization technique using Taguchi quality loss function to simultaneously optimize the multiple quality characteristics in manufacturing processes.

In the present paper the Taguchi methodology has been applied to optimize the RSW machine setting for multiple quality characteristics such as Weld Indentation and Weld Strength. Also the results of multi-objective optimization are compared with the results of single objective optimization.

## EXPERIMENTATION

The experiments were performed on a 50 KVA, SPM-SP-258, special dual head spot welding machine, which is manufactured by mechelonic engineers pvt. Ltd., Mumbai India.

In the present experimentation, the control parameters identified are Electrode Force, Weld Current, Squeeze Time, Weld Time, and Hold Time, to investigate their effects on the quality characteristics (Weld Indentation, and Weld Strength).The input and fixed parameters used in the present study is shown in Table 1.

### Levels of parameters

As per the literature review and experience of welding operators in the industry, range for each variable (control factor) are decided. Then as per [4, 5], four levels are identified for each control factors as shown in Table2.

### Selection of Orthogonal Array (OA)

Selection of the orthogonal array is based on the calculation of the total degree of freedom of all the factors. Orthogonal arrays are special matrix in which entries are at various levels of input parameters, and each row represents individual treatment condition [5, 6]. In orthogonal array, for any pair of column all combinations for each factor level occur and they occur in equal number of times (this is called balancing property).

Degree of freedom related to a process can be calculated as [5]:

dof = (number of levels - 1) for each factor + (number of levels - 1) (number of levels - 1) for each interaction + 1.

In present case of five parameters at four different levels assuming no interaction between factors the degree of freedom is calculated as:

dof = ( 4 1 ) 5 + 1 = 16

Hence, a standard $L_{16}$ OA as suggested by Taguchi [5] is selected which is given in Table 3.

### Conduction of experiments and observations

The electrode diameter selected is 6 mm as per ISO standard for new electrodes, for producing test samples. The test samples, composed of two 50.8 mm wide by 152.4 mm long coupons, are spot-welded as shown in fig.1, with a square overlap area. These sample dimensions follow the recommendation by SAE [7] and have sufficient widths to not to affect the strength of the weld [8]. Three sets of experiments are conducted to get responses as per the orthogonal array selected.

Using comparator with dial indicator, indentation at the spot of weld is measured for all the samples produced. Actual strength of the weld is found out by destructive test on Universal Testing Machine. Table 4 gives the average values of weld indentations and weld strength.

### Computation of quality loss for each quality characteristic

In Taguchi method [9, 10], a quality loss or mean square deviation (MSD) function is used to calculate the deviation between the experimental value and the desired value. The MSD is different for different types of problems e.g.

for Smaller-the-better type problem

$MSD=(y_1^2+y_2^2+...)/n$............ (1)

and for Higher-the-better type problem

$MSD=(1/y_1^2+1/y_2^2+.)/n$............(2)

Where, $y_1$, $y_2$... $y_n$ are results of the experiments (responses), and n is the number of repetitions of $y_i$. In present case the Weld Indentation is smaller-the-better (SB) type and Weld Strength is higher-the-better (HB) type. The quality loss values for each quality characteristic against different experimental runs are given in Table 5.

### Computation of normalized quality loss for each quality characteristic

Let $L_{ij}$ be the quality loss for the $i^{th}$ quality characteristic at the $j^{th}$ trial condition or run in the experimental design matrix. As each quality characteristic has different unit of measurements, it is important to normalize the quality loss [3]. The normalized quality loss can be computed using:

$y_{ij} = L_{ij} / L_i$ .......................... (3)

Where, $y_{ij}$ = Normalized quality loss value for $i^{th}$ experimental run and $j^{th}$ quality characteristic, $L_i$ = maximum quality loss for the $i^{th}$ quality characteristic among all the experimental runs. Therefore, $y_{ij}$ varies from a minimum of zero to a maximum of 1. The computed normalized quality loss for Weld Indentation and Weld Strength is given in Table 6.

### Computation of total normalized quality loss (TNQL)

For computing the total normalized quality loss ($Y_j$) corresponding to each trial condition, we must assign a weighting factor for each quality characteristic considered in the optimization process. If $w_i$ represents the weighting factor for the $i^{th}$ quality characteristic, p is the number of quality characteristics and $y_{ij}$ is the loss function associated with the $i^{th}$ quality characteristic at the $j^{th}$ trial condition, then $Y_j$ can be computed using:

$$Y_j = \sum_{i=1}^{p} w_i y_{ij} \qquad (4)$$

In present case, p = 2, and assuming unequal weights i.e. $w_1$ = 0.6 for Weld Indentation, and $w_2$ = 0.4 for Weld

Strength, the total normalized quality loss in each experimental run is shown in Table 7.

**Computation of multiple S/N ratio (MSNR)**

After the total normalized quality loss ($Y_j$) corresponding to each trial condition has been calculated, the next step is to compute the multiple S/N ratio at each design point. This is given by:

$\eta_i = -10 \log10 (Y_j)$ ..................(5)

The multiple S/N ratios along with total normalized quality losses in each trial condition are shown in Table 7.

In single quality optimization using Taguchi methodology, steps of calculating the normalized quality loss and total normalized quality loss are omitted, and in place of a multiple S/N ratio, separate S/N ratios corresponding to each quality characteristics is computed where the $Y_j$ are the quality loss values of different quality characteristics. Other steps are same as in multi-objective optimization.

**Determination of factor effects and optimal settings**

Next step is to determine the average effect of each factor on multiple quality characteristic at different levels. This is equal to, the sum of all S/N ratios corresponding to a factor at particular level divided by the number of repetition of factor level.

The factor levels corresponding to maximum average effect are selected as optimum level. The average factor effect has been shown in Table 8 and response plot is shown in Figure 2. The optimum setting of parameters is $A_4 B_1 C_4 D_3 E_1$.

**Analysis of variance (ANOVA)**

A better feel for the relative effect of the different factors can be obtained by the decomposition of the variance, which is commonly called ANOVA. It is a computational technique to estimate quantitatively the relative significance (F-ratio), and also the percentage contribution (PC) of each factor. The sum of squares (SS) and mean sum of squares or variance (V) for each factor, and error (EP) obtained by pooling of factors C and D are computed first, to evaluate the F value and PC [5]. The degree of freedom (df) for each factor is calculated as:

df = number of level 1

The ANOVA given in Table 9 shows the contribution of different factors as: Electrode Force (72.911%), Weld Current (11.637%), Squeeze Time (1.9435%), Weld Time (2.977%) and Hold Time (10.532%).

**Confirmation Experiment**

Conducting a verification experiment is a crucial final step of a robust design. Its purpose is to verify that the optimum conditions suggested by the matrix experiment do indeed give the projected improvement. The confirmation experiment is performed by conducting a test with optimal settings of the factors and levels previously evaluated. The predicted value of multiple S/N ratio at optimum level ($\eta_o$) is calculated by following formula:

$$\eta_o = \eta_m - \sum_{i=1}^{k} (\eta_i - \eta_o) \text{.................(6)}$$

Where, k is the no. of factors and $\eta_m$ is the mean value of multiple S/N ratios in all experimental runs, $\eta_i$ are the multiple S/N ratios corresponding to optimum factor levels.

The predicted value of multiple S/N ratio and that from confirmation test are shown in Table 10. The improvement in multiple S/N ratio at the optimum level is found to be 3.9521 dB. The value of Weld Indentation (mm) and Weld Strength (N) at this optimum level are 0.09 mm and 4140 N against the initial parameter setting of 0.18 mm and 2438.33 N.

**Comparison of multi-objective and single objective optimization results**

The results of single quality optimization for Weld Indentation and Weld Strength are summarized in Table 11 to Table 15 and response plot is shown in Fig. 3 and Fig. 4. The results of multi-objective optimization (MOO) and single-objective optimization (SOO) using Taguchi methodology has been compared in Table 16. The results show that the quality values at optimum settings are different in each case. The results of MOO basically depends on weights assigned to quality values e.g. in present case the most important quality assumed was Weld Indentation with weight 0.6, and result shows the quality loss of 10.294 %. Similarly the quality loss for optimum Weld Strength value obtained from MOO with respect to the value obtained from SOO is 8.877 %. Therefore, chance of quality loss is always there, when the aim is to optimize the multiple quality characteristics simultaneously. The multi-objective optimization is useful in the sense that at same optimum parameter level one can get the optimum quality value of multiple quality characteristic at the same time rather than a single optimum quality characteristic.

**CONCLUSIONS**

The conclusions drawn from above results are summarized as:

1. The Taguchi's quality loss function can be used to optimize the multiple quality characteristics. A significant increase in S/N ratio (3.9521 dB) has been registered at optimum parameter setting in the present experimental investigation. Also,

both the quality characteristics (Weld Indentation and Weld Strength) have been considerably improved as compared to initial parameter settings of the experiment.

2. The optimum parameter values in the present operating conditions are: Electrode Force = 2.50 KN, Weld Current = 6.5 KA, Squeeze Time = 12 cycles, Weld Time = 15 cycles and Hold Time = 3 cycles.
3. The percentage contribution of factors in increasing order is: Electrode Force (72.911%), Weld Current (11.637%), Hold Time (10.532%), Weld Time (2.977%) and Squeeze Time (1.9435%).
4. The loss of quality is always possible during optimization of multiple quality characteristics at a time. The deviation of quality from its optimum value depends mainly on the weight assigned to it. Therefore, a careful selection of weights for different quality values plays a crucial role in multi-objective optimization.

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**Table 1:** Parameters of the Setting

| Control Factors | Symbols | Fixed Parameters |
|---|---|---|
| Electrode Force | Factor A | Electrode Diameter = 6 mm |
| Weld Current | Factor B | Axial misalignment |
| Squeeze Time | Factor C | Angular misalignment |
| Weld Time | Factor D | Plate thickness = 1.2 mm |
| Hold Time | Factor E | Plate material is CRC Steel |

**Table 2:** Levels of various control factors

| Control Factor | Level | | | | Unit |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| A. Electrode Force | 1.75 | 2.0 | 2.25 | 2.5 | KN |
| B. Weld Current | 6.5 | 7.2 | 8.0 | 8.5 | KA |
| C. Squeeze Time | 6 | 8 | 10 | 12 | Cycles |
| D. Weld Time | 11 | 13 | 15 | 17 | Cycles |
| E. Hold Time | 3 | 4 | 5 | 7 | Cycles |

**Table 3 :** $L_{16}$ Orthogonal Array.

| Expt. No. | Factor A | Factor B | Factor C | Factor D | Factor E |
|---|---|---|---|---|---|
| 01 | 1 | 1 | 1 | 1 | 1 |
| 02 | 1 | 2 | 2 | 2 | 2 |
| 03 | 1 | 3 | 3 | 3 | 3 |
| 04 | 1 | 4 | 4 | 4 | 4 |
| 05 | 2 | 1 | 2 | 3 | 4 |
| 06 | 2 | 2 | 1 | 4 | 3 |
| 07 | 2 | 3 | 4 | 1 | 2 |
| 08 | 2 | 4 | 3 | 2 | 1 |
| 09 | 3 | 1 | 3 | 4 | 2 |
| 10 | 3 | 2 | 4 | 3 | 1 |
| 11 | 3 | 3 | 1 | 2 | 4 |
| 12 | 3 | 4 | 2 | 1 | 3 |
| 13 | 4 | 1 | 4 | 2 | 3 |
| 14 | 4 | 2 | 3 | 1 | 4 |
| 15 | 4 | 3 | 2 | 4 | 1 |
| 16 | 4 | 4 | 1 | 3 | 2 |

**Table 4:** Experimental results

| Exp. No. | Weld Indentations (mm) | Weld Strength (Newton) |
|---|---|---|
| 01 | 0.1817 | 2438.33 |
| 02 | 0.2983 | 2988.33 |
| 03 | 0.2767 | 3040.00 |
| 04 | 0.3383 | 2218.33 |
| 05 | 0.1700 | 2691.67 |
| 06 | 0.2867 | 2593.33 |
| 07 | 0.1733 | 2538.33 |
| 08 | 0.2733 | 3381.67 |
| 09 | 0.1517 | 3440.00 |
| 10 | 0.1450 | 3721.67 |
| 11 | 0.1733 | 2751.67 |
| 12 | 0.2100 | 2380.00 |
| 13 | 0.0933 | 3206.67 |
| 14 | 0.1133 | 2985.00 |
| 15 | 0.1500 | 4491.67 |
| 16 | 0.2033 | 4250.00 |

**Table 5:** Quality loss for Weld Indentation and Weld Strength

| Exp. No. | Quality Loss (dB) | |
|---|---|---|
| | Weld Indentation | Weld Strength |
| 01 | 0.0324 | 1.682E-07 |
| 02 | 0.09 | 1.1198E-07 |
| 03 | 0.0784 | 1.0821E-07 |
| 04 | 0.1156 | 2.0321E-07 |
| 05 | 0.0289 | 1.3802E-07 |
| 06 | 0.0841 | 1.4869E-07 |
| 07 | 0.0289 | 1.552E-07 |
| 08 | 0.0729 | 8.7446E-08 |
| 09 | 0.0225 | 8.4505E-08 |
| 10 | 0.0196 | 7.2198E-08 |
| 11 | 0.0289 | 1.3207E-07 |
| 12 | 0.0441 | 1.7654E-07 |
| 13 | 0.0081 | 9.725E-08 |
| 14 | 0.0121 | 1.1223E-07 |
| 15 | 0.0225 | 4.9566E-08 |
| 16 | 0.04 | 5.5363E-08 |

**Table 6:** Normalized quality Loss for Weld Indentation and Weld Strength

| Exp. No. | Normalized quality Loss | |
|---|---|---|
| | Weld Indentation | Weld Strength |
| 1. | 0.2803 | 0.8277 |
| 2. | 0.7785 | 0.5511 |
| 3. | 0.6782 | 0.5325 |
| 4. | 1.0000 | 1.0000 |
| 5. | 0.25 | 0.6792 |
| 6. | 0.7275 | 0.7317 |
| 7. | 0.25 | 0.7638 |
| 8. | 0.6306 | 0.4303 |
| 9. | 0.1946 | 0.4158 |
| 10. | 0.1696 | 0.3553 |
| 11. | 0.25 | 0.6499 |
| 12. | 0.3815 | 0.8688 |
| 13. | 0.0701 | 0.4786 |
| 14. | 0.1047 | 0.5523 |
| 15. | 0.1946 | 0.2439 |
| 16. | 0.346 | 0.2724 |

**Table 7:** Total normalized quality Loss (TNQL) and multiple S/N ratio (MSNR)

| Exp. No. | TNQL | MSNR |
|---|---|---|
| 1. | 0.4992 | 3.01689 |
| 2. | 0.6876 | 1.62695 |
| 3. | 0.6199 | 2.07669 |
| 4. | 1.000 | 0.00 |
| 5. | 0.4217 | 3.7501 |
| 6. | 0.7292 | 1.3716 |
| 7. | 0.4555 | 3.41508 |
| 8. | 0.5505 | 2.59242 |
| 9. | 0.2831 | 5.48027 |
| 10. | 0.2438 | 6.12888 |
| 11. | 0.41 | 3.8725 |
| 12. | 0.5764 | 2.39279 |
| 13. | 0.2335 | 6.31771 |
| 14. | 0.2837 | 5.47114 |
| 15. | 0.2143 | 6.68881 |
| 16. | 0.3166 | 4.99504 |
| Mean MSNR ($\eta_m$) | | 3.6998 |

**Table 8:** Effect of factor levels on MSNR

| Factor | Mean MSNR (dB) | | | |
|---|---|---|---|---|
| | Level 1 | Level 2 | Level 3 | Level 4 |
| A | 1.680 | 2.782 | 4.469 | 5.868* |
| B | 4.049* | 3.649 | 4.013 | 2.500 |
| C | 3.314 | 3.615 | 3.905 | 3.970* |
| D | 3.574 | 3.602 | 4.238* | 3.390 |
| E | 4.607* | 3.879 | 3.039 | 3.270 |

*Optimum parameter level

**Table 9:** ANOVA table for Weld Indentation and Weld Strength

| Factor | SS | df | V | F | PC (%) |
|---|---|---|---|---|---|
| A | 40.869 | 3 | 13.623 | 14.2947 | 72.911 |
| B | 6.5232 | 3 | 2.1744 | 2.2816 | 11.637 |
| C | 1.0894* | 3 | 0.3631 | -- | 1.9435 |
| D | 1.6687* | 3 | 0.5562 | -- | 2.977 |
| E | 5.9035 | 3 | 1.9678 | 2.0648 | 10.532 |
| EP | 2.7581 | 6 | 0.4597 | -- | -- |
| Total | 56.054 | 15 | -- | -- | 100 |

* pooled factors

**Table 10 :** Result of confirmation experiment

| | Initial Setting | Optimum values | |
|---|---|---|---|
| | | Predicted | Experimental |
| Level | $A_1B_1C_1D_1E_1$ | $A_4B_1C_4D_3E_1$ | $A_4B_1C_4D_3E_1$ |
| Weld Indentation (mm) | 0.18 | -- | 0.09 |
| Weld Strength (N) | 2438.33 | -- | 4140 |
| MSNR | 4.0920 | 7.9325 | 8.0441 |

Improvement of MSNR = 3.9521 dB

**Table 11:** S/N ratio for Weld Indentation and Weld Strength in single quality optimization

| Exp. No. | S/N ratio (dB) | |
|---|---|---|
| | Weld Indentation | Weld Strength |
| 01 | 14.81 | 67.74 |
| 02 | 10.51 | 69.51 |
| 03 | 11.16 | 69.66 |
| 04 | 09.41 | 66.92 |
| 05 | 15.39 | 68.60 |
| 06 | 10.85 | 68.28 |
| 07 | 15.22 | 68.09 |
| 08 | 11.27 | 70.58 |
| 09 | 16.38 | 70.73 |
| 10 | 16.77 | 71.41 |
| 11 | 15.22 | 68.79 |
| 12 | 13.56 | 67.53 |
| 13 | 20.60 | 70.12 |
| 14 | 18.92 | 69.50 |
| 15 | 16.48 | 73.05 |
| 16 | 13.84 | 72.57 |
| Overall mean (m) | 14.399 | 69.568 |

**Table 12:** Effect of factor levels on Weld Indentation

| Factor | | Mean | MSNR (dB) | |
|---|---|---|---|---|
| | Level 1 | Level 2 | Level 3 | Level 4 |
| A | 11.47 | 13.18 | 15.48 | 17.46* |
| B | 16.80* | 14.26 | 14.52 | 12.00 |
| C | 13.68 | 13.98 | 14.43 | 15.50* |
| D | 15.63* | 14.40 | 14.29 | 13.30 |
| E | 14.83* | 13.99 | 14.04 | 14.70 |

*Optimum parameter level

**Table 13 :** Effect of factor levels on Weld Strength

| Factor | Mean MSNR (dB) | | | |
|---|---|---|---|---|
| | Level 1 | Level 2 | Level 3 | Level 4 |
| A | 68.46 | 68.89 | 69.62 | 71.31* |
| B | 69.30 | 69.67 | 69.90* | 69.40 |
| C | 69.34 | 69.67 | 70.12* | 69.10 |
| D | 68.22 | 69.75 | 70.56* | 69.70 |
| E | 70.70* | 70.22 | 68.90 | 68.50 |

*Optimum parameter level

**Table 14 :** Result of confirmation experiment for Weld Indentation

| | Initial Setting | Optimum values | |
|---|---|---|---|
| | | Predicted | Experimental |
| Level | $A_1B_1C_1D_1E_1$ | $A_4B_1C_4D_1E_1$ | $A_4B_1C_4D_1E_1$ |
| Weld Indentation (mm) | 0.18 | -- | 0.0816 |
| S/N ratio (dB) | 14.81 | 22.62 | 21.766 |

Improvement of S/N ratio = 6.956 dB

**Table 15:** Result of confirmation experiment for Weld Strength

| | Initial Setting | Optimum values | |
|---|---|---|---|
| | | Predicted | Experimental |
| Level | $A_1B_1C_1D_1E_1$ | $A_4B_3C_3D_3E_1$ | $A_4B_3C_3D_3E_1$ |
| Weld Strength (N) | 2438.33 | -- | 4543.33 |
| S/N ratio (dB) | 67.74 | 74.31 | 73.15 |

Improvement of S/N ratio = 5.41 dB

**Table 16:** Comparison of results from single objective and multi objective optimization

| | SOO results | | MOO results | |
|---|---|---|---|---|
| | Weld Indentation | Weld Strength | Weld Indentation & Weld Strength | Quality loss (%) |
| Level | $A_4B_1C_4D_1E_1$ | $A_4B_3C_3D_3E_1$ | $A_4B_1C_4D_3E_1$ | --- |
| Weld Indentation (mm) | 0.0816 | --- | 0.09 | 10.294 |
| Weld Strength(N) | ---- | 4543.33 | 4140 | 08.877 |

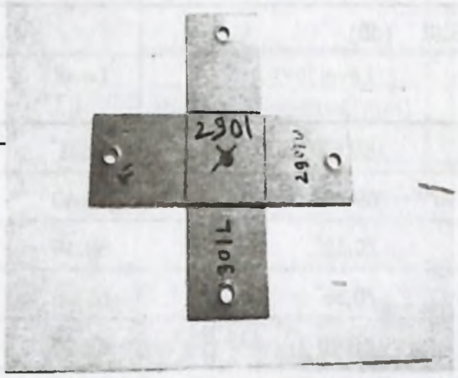


Figure 1: Test Sample

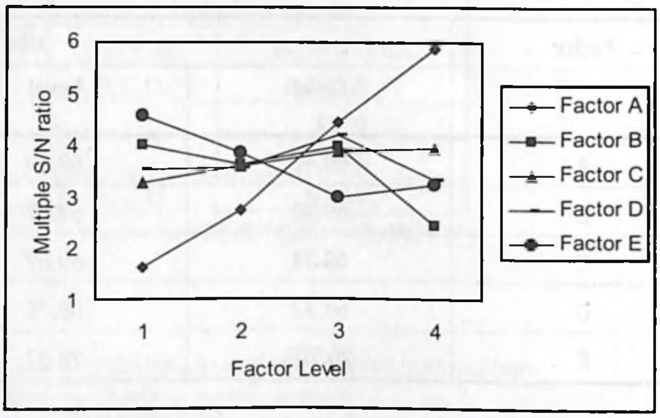


Fig 2: Response plot for MSNR

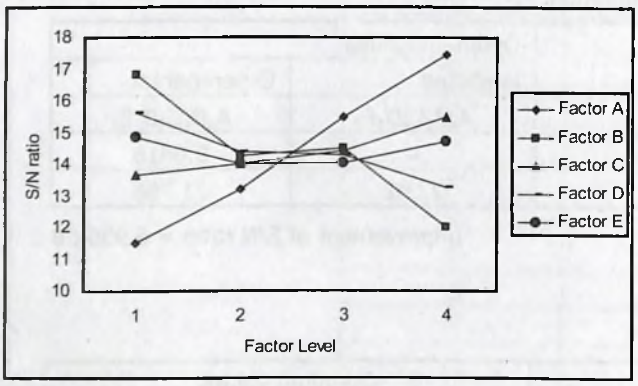


Fig. 3: Response plot for Weld Indentation

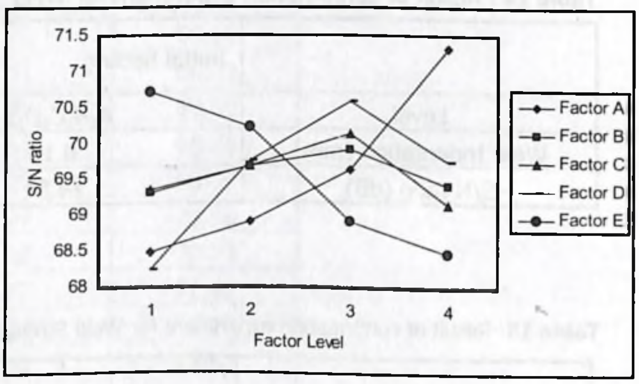


Fig. 4: Response plot for Weld Strength

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