# Optimization of the Aluminum Riveting Process Using an Experimental Design Technique

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## Abstract

The purpose of this research is to determine the optimal factors existing in the aluminum riveting process. First, a $2^5$ full-factorial design was used to screen five factors and two levels by selecting a lapping-joint method using only one rivet which exhibited significant riveting shear. The five riveting parameters used were press force 5,000 and 8,000 newtons, a thickness of material of 2.5 and 4mm, a size of hole of 4.7 and 5.2 mm, over long rivets of 4.7 and 5.2 mm and press times of 5 and 15 seconds. There were three parameter levels: thickness of the metal (2.5, 3.2 and 4.0 mm), size of the hole (2.5, 3.2 and 4.0 mm) and size of the over-long rivet (4.5, 5.6 and 6.7mm), then a Box-Behnken design was used in order to analyze the data and find the optimization point. The experiment found that a standard rivet has a shear strength resistance of 1,113.30 newtons. The study methodology was to prepare the riveting specimens use by selecting a lapping joint per one rivet to test the mechanical quality and shear. The results of the experiment show that the optimal conditions (to a statistically significant degree) were to use a 5.2 mm hole, a 2.8 mm level of thickness and a 6.3 mm over-long rivet. The optimal point for the shear test was 1,417.55 newtons, and an over-shear strength of 303 newtons could be increased by 27.32 percent.

**Key words**: Optimization, Aluminum Riveting, Experiment

## 1. Introduction

Joining workpieces together so as to increase length or to create another form can be carried out in two ways; using melted materials and non-melted materials, depending upon the purpose. Welding is a process that joins materials through melting the same type of metal. The principle is to melt the workpieces where heat will cause a change in their internal structure. However, some metals cannot be used in the welding process, and as a result, riveting plays an important role as a substitute for welding, whilst maintaining the required strength of the metal. Riveting can be done in two ways, using heated rivets, such as in the fabrication of a large structure, or cooled rivets, such as in the fabrication of non-steel metal structures and spacecraft structures, so as to create flexibility in the structure and to maintain the internal structure in its original form.

The riveting process can be used for different types of metals, for example aluminum and copper sheeting. The construction of some workpieces requires riveting, in order to maintain the mechanical properties and the form, under a design principle. Each type of metal rivet has different mechanical properties. If using the same size of drilled holes and with the rivet size remaining the same, the rivet's tensile strength, the pressing time on the length of the rivet body and the different size and type of materials will vary the strength of the work. The results of the research provide a relationship between variables and an appropriate set of conditions that influence the maximum shear resistance of aluminum rivets.

## 2. Research Methodology

1. The material used in the experiment was St 37 hot-rolled carbon steel, including:
Flat steel bar 2.5x25x80 millimeters
Flat steel bar 4.0x25x80 millimeters
Flat steel bar 2.5x25x80 millimeters
Flat Steel bar 4.0x25x80 millimeters
With a chemical composition as follows:

| C | Mn | P | S |
|---|---|---|---|
| 0.17 | - | 0.040 | 0.040 |

**Table 1:** Chemical Composition of Carbon Steel

2. The rivets used in the tension test were aluminum rivets with a size of Ø4.5 mm. as shown in the picture.

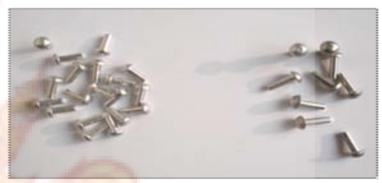

Fig. 1 Aluminum Rivets

3. The drilling sets for the punching work were as follows:
- Drilling set size Ø4.7 mm.
- Drilling set size Ø5.2 mm.

Fig. 2 Drilling Sets

### 2.1 Steps in Workpiece Preparation

1) Cut St 37 carbon steel with a 2.5 and 4 mm. thickness into pieces 80 mm. in length and 25 mm. wide

2) Drill the workpieces to Ø4.7 and Ø5.2 mm.

3) Fasten the workpieces by riveting.

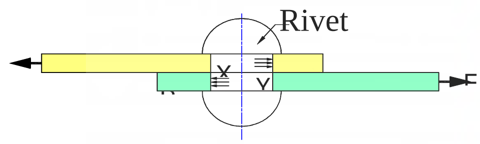


Fig. 3 Riveting the Test Workpieces

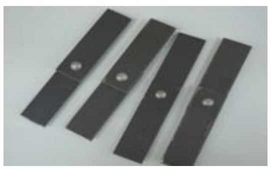

Fig. 4 Tested Workpieces

### 2.2 Shear Resistance Test

1) Hold the riveted workpieces at both ends using a tension testing tool

2) Pull the tested workpieces from both ends until the parts detach

3) Record the shear resistance.

## 3. Experiment Results

### 3.1 Screening Experiment

As there were five main parameters used in the preliminary study, a screening experiment was required. The obtained factors were then used for further in-depth study, using the $2^5$ factorial design methods (Full Factorial Design). Each factor was comprised of two levels and two replicates, and was conducted across 160 experiments. The experiment design and the results are shown in Table 3. The experiments were organized in an orderly pattern so as to minimize the possible errors caused by uncontrolled factors.

**Table 2:** Factors, Parameter Levels, and Symbols used in the Study

| Factor/Unit | Level | | Symbols |
|---|---|---|---|
| | Low( -1 ) | High( +1 ) | |
| 1. Press Force (Newton ) | 5000 | 8000 | A |
| 2. Size of Hole (m.m.) | 4.7 | 5.2 | B |
| 3. Thickness (m.m.) | 2.5 | 4.0 | C |
| 4. Rivet Long (m.m.) | 4.5 | 6.7 | D |
| 5. Press Time (sec.) | 5.0 | 15.0 | E |

**Table 3:** Experiment Patterns and Results

| Std Order | A | B | C | D | E | Shear Strength ( N/mm$^2$ ) | | | | | Apo |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 | 2 | 3 | 4 | 5 | |
| 1 | 5000 | 4.7 | 2.5 | 4.5 | 5 | 1160 | 1110 | 1210 | 1200 | 1120 | 1160 |
| 2 | 8000 | 4.7 | 2.5 | 4.5 | 5 | 1120 | 1220 | 1120 | 1210 | 1130 | 1281 |
| 3 | 5000 | 5.2 | 2.5 | 4.5 | 5 | 1400 | 1390 | 1360 | 1420 | 1440 | 1407 |
| 4 | 8000 | 5.2 | 2.5 | 4.5 | 5 | 1370 | 1410 | 1430 | 1390 | 1460 | 1318 |
| 5 | 5000 | 4.7 | 4 | 4.5 | 5 | 1250 | 1170 | 1230 | 1180 | 1290 | 1225 |
| 6 | 8000 | 4.7 | 4 | 4.5 | 5 | 1270 | 1200 | 1240 | 1190 | 1230 | 1291 |
| 7 | 5000 | 5.2 | 4 | 4.5 | 5 | 1410 | 1320 | 1380 | 1310 | 1360 | 1356 |
| 8 | 8000 | 5.2 | 4 | 4.5 | 5 | 1390 | 1380 | 1320 | 1300 | 1390 | 1267 |
| 9 | 5000 | 4.7 | 2.5 | 6.75 | 5 | 1200 | 1170 | 1130 | 1200 | 1190 | 1164 |
| 10 | 8000 | 4.7 | 2.5 | 6.75 | 5 | 1130 | 1150 | 1210 | 1140 | 1120 | 1267 |
| 11 | 5000 | 5.2 | 2.5 | 6.75 | 5 | 1400 | 1420 | 1370 | 1350 | 1380 | 1391 |
| 12 | 8000 | 5.2 | 2.5 | 6.75 | 5 | 1390 | 1360 | 1410 | 1450 | 1380 | 1300 |
| 13 | 5000 | 4.7 | 4 | 6.75 | 5 | 1210 | 1220 | 1210 | 1190 | 1180 | 1203 |
| 14 | 8000 | 4.7 | 4 | 6.75 | 5 | 1230 | 1220 | 1190 | 1220 | 1160 | 1288 |
| 15 | 5000 | 5.2 | 4 | 6.75 | 5 | 1390 | 1400 | 1370 | 1340 | 1360 | 1377 |
| 16 | 8000 | 5.2 | 4 | 6.75 | 5 | 1360 | 1340 | 1370 | 1390 | 1450 | 1271 |
| 17 | 5000 | 4.7 | 2.5 | 4.5 | 15 | 1200 | 1140 | 1120 | 1190 | 1150 | 1157 |
| 18 | 8000 | 4.7 | 2.5 | 4.5 | 15 | 1190 | 1190 | 1130 | 1160 | 1100 | 1271 |
| 19 | 5000 | 5.2 | 2.5 | 4.5 | 15 | 1380 | 1380 | 1420 | 1410 | 1350 | 1382 |
| 20 | 8000 | 5.2 | 2.5 | 4.5 | 15 | 1380 | 1430 | 1350 | 1330 | 1390 | 1289 |
| 21 | 5000 | 4.7 | 4 | 4.5 | 15 | 1240 | 1210 | 1200 | 1170 | 1190 | 1203 |
| 22 | 8000 | 4.7 | 4 | 4.5 | 15 | 1210 | 1220 | 1220 | 1190 | 1180 | 1290 |
| 23 | 5000 | 5.2 | 4 | 4.5 | 15 | 1410 | 1370 | 1390 | 1370 | 1340 | 1374 |
| 24 | 8000 | 5.2 | 4 | 4.5 | 15 | 1390 | 1330 | 1330 | 1430 | 1380 | 1278 |
| 25 | 5000 | 4.7 | 2.5 | 6.75 | 15 | 1160 | 1190 | 1180 | 1160 | 1230 | 1175 |
| 26 | 8000 | 4.7 | 2.5 | 6.75 | 15 | 1190 | 1210 | 1130 | 1130 | 1170 | 1276 |
| 27 | 5000 | 5.2 | 2.5 | 6.75 | 15 | 1390 | 1420 | 1410 | 1330 | 1380 | 1386 |
| 28 | 8000 | 5.2 | 2.5 | 6.75 | 15 | 1360 | 1430 | 1390 | 1410 | 1340 | 1292 |
| 29 | 5000 | 4.7 | 4 | 6.75 | 15 | 1240 | 1190 | 1150 | 1210 | 1200 | 1199 |

**Table 3:** Experiment Patterns and Results (continued)

| ลำดับ | A | B | C | D | E | Shear Strength ( N/mm$^2$ ) | | | | | Apo |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 | 2 | 3 | 4 | 5 | |
| **30** | 8000 | 4.7 | 4 | 6.75 | 15 | 1160 | 1210 | 1190 | 1240 | 1200 | **1290** |
| **31** | 5000 | 5.2 | 4 | 6.75 | 15 | 1390 | 1360 | 1370 | 1420 | 1360 | **1381** |
| **32** | 8000 | 5.2 | 4 | 6.75 | 15 | 1410 | 1360 | 1420 | 1330 | 1390 | **1382** |

**Table 4:** Results of the Coefficient Analysis

| Term | Effect | Coef | SE Coef | T | P |
|---|---|---|---|---|---|
| Constant | | 1283.75 | 2.735 | 469.31 | 0.000 |
| A | -1.5 | 0.75 | 2.735 | -0.27 | 0.784 |
| B | 196.00 | 98.0 | 2.735 | 35.83 | ***0.000*** |
| C | 12.00 | 6.00 | 2.735 | 2.19 | ***0.030*** |
| D | 1.50 | 0.75 | 2.735 | 0.27 | 0.784 |
| E | -3.25 | -1.62 | 2.735 | -0.59 | 0.554 |
| AB | 4.0 | 2.00 | 2.735 | 0.73 | 0.466 |
| AC | 3.50 | 1.75 | 2.735 | 0.64 | 0.523 |
| AD | -0.50 | -0.25 | 2.735 | -0.09 | 0.927 |
| AE | -2.75 | -1.38 | 2.735 | -0.50 | 0.616 |
| BC | -31.5 | -15.75 | 2.735 | -5.67 | ***0.000*** |
| BD | 2.5 | 1.25 | 2.735 | 0.46 | 0.648 |
| BE | 1.25 | 0.63 | 2.735 | 0.23 | 0.820 |
| CD | -1.0 | -0.50 | 2.735 | -0.18 | 0.855 |
| CE | 2.25 | 1.12 | 2.735 | 0.41 | 0.682 |
| DE | 4.75 | 2.38 | 2.735 | 0.87 | 0.387 |
| ABC | -4.00 | -2.00 | 2.735 | 0.73 | 0.466 |
| ABD | 4.50 | 2.25 | 2.735 | 0.82 | 0.412 |
| ABE | -3.25 | -1.63 | 2.735 | -0.59 | 0.544 |
| ACD | 2.50 | 1.25 | 2.735 | 0.46 | 0.648 |
| ACE | 1.25 | 0.63 | 2.735 | 0.23 | 0.820 |
| ADE | 1.25 | 0.63 | 2.735 | 0.23 | 0.8200 |
| BCD | 11.00 | 5.50 | 2.735 | 2.01 | 0.046 |
| BCE | 10.75 | 5.37 | 2.735 | 1.96 | 0.052 |
| BDE | -3.25 | -1.63 | 2.735 | -0.59 | 0.544 |
| CDE | -3.75 | -1.88 | 2.735 | -0.69 | 0.494 |
| ABCD | -2.50 | -1.25 | 2.735 | 0.46 | 0.648 |
| ABCE | 1.75 | 0.88 | 2.735 | 0.32 | 0.750 |
| ABDE | -0.75 | -0.37 | 2.735 | -0.14 | 0.891 |
| ACDE | -1.75 | -0.88 | 2.735 | -0.32 | 0.750 |
| BCDE | -4.75 | -2.37 | 2.735 | -0.87 | 0.387 |
| ABCDE | 0.25 | 0.12 | 2.735 | 0.05 | 0.964 |

From Table 4: The P-value was compared with Alpha, by which the P-value of each factor had to be less than 0.05, then they would be the main factors that affected the shear resistance of the rivets to a significant degree. These factors were: the sizes of the holes (B), the thickness of the workpieces, (C), the correction among the sizes of the holes (B), the thickness of the workpieces (C), the co-reaction among the sizes of the holes (B), the thickness of the workpieces (C) and the length of the rivets (D).

### 3.2 Analysis of the Most Appropriate Values of the Factors

After the screening, an experiment was carried out to screen and determine those factors affecting the number of metal beads and the shear resistance of the welding line obtained. The experiment was designed by using Response Surface Methodology based on a Box-Behnken Design, in order to determine the best result, as shown in Table

**Table 5:** Factors and Symbols used in the Box- Behnken Design

| Factor/Unit | levels | | | Symbols |
|---|---|---|---|---|
| | low | medium | high | |
| 1 Thickness (m.m.) | 2.50 | 3.20 | 4.00 | C |
| 2. Size of Hole (m.m.) | 4.70 | 4.90 | 5.20 | B |
| 3. Rivet Long (m.m.) | 4.50 | 5.60 | 6.70 | D |

From Table 5. After welding the 30 tested workpieces based on the Box-Behnken design with two replications, the workpieces were then tested using the pulling method, in n order to determine the shear resistance of the rivets. The results are shown in Table 6. The obtained data was used for a response surface analysis.

**Table 6:** Experimental Pattern

| Std Order | Run Order | C | B | D | Shear |
|---|---|---|---|---|---|
| 1 | 12/20 | 2.50 | 4.70 | 5.60 | 1180 |
| 2 | 30/22 | 4.00 | 4.70 | 5.60 | 1290 |
| 3 | 15/16 | 2.50 | 5.20 | 5.60 | 1380 |
| 4 | 11/25 | 4.00 | 5.20 | 5.60 | 1390 |
| 5 | 28/26 | 2.50 | 4.90 | 4.50 | 1210 |
| 6 | 13/29 | 4.00 | 4.90 | 4.50 | 1240 |
| 7 | 7/17 | 2.50 | 4.90 | 6.70 | 1340 |
| 8 | 10/3 | 4.00 | 4.90 | 6.70 | 1320 |
| 9 | 18/4 | 3.20 | 4.70 | 4.50 | 1190 |

**Table 6:** Experimental Pattern (continued)

| Std Order | Run Order | C | B | D | Shear |
|---|---|---|---|---|---|
| 10 | 21/1 | 3.20 | 5.20 | 4.50 | 1400 |
| 11 | 9/5 | 3.20 | 4.70 | 6.70 | 1210 |
| 12 | 19/6 | 3.20 | 5.20 | 6.70 | 1390 |
| 13 | 8/24 | 3.20 | 4.90 | 5.60 | 1310 |
| 14 | 27/2 | 3.20 | 4.90 | 5.60 | 1320 |
| 15 | 23/14 | 3.20 | 4.90 | 5.60 | 1320 |
| 16 | 12/20 | 2.50 | 4.70 | 5.60 | 1170 |
| 17 | 30/22 | 4.00 | 4.70 | 5.60 | 1280 |
| 18 | 15/16 | 2.50 | 5.20 | 5.60 | 1370 |
| 19 | 11/25 | 4.00 | 5.20 | 5.60 | 1380 |
| 20 | 28/26 | 2.50 | 4.90 | 4.50 | 1200 |
| 21 | 13/29 | 4.00 | 4.90 | 4.50 | 1230 |
| 22 | 7/17 | 2.50 | 4.90 | 6.70 | 1350 |
| 23 | 10/3 | 4.00 | 4.90 | 6.70 | 1320 |
| 24 | 18/4 | 3.20 | 4.70 | 4.50 | 1190 |
| 25 | 21/1 | 3.20 | 5.20 | 4.50 | 1400 |
| 26 | 9/5 | 3.20 | 4.70 | 6.70 | 1200 |
| 27 | 19/6 | 3.20 | 5.20 | 6.70 | 1390 |
| 28 | 8/24 | 3.20 | 4.90 | 5.60 | 1320 |
| 29 | 27/2 | 3.20 | 4.90 | 5.60 | 1320 |
| 30 | 23/14 | 3.20 | 4.90 | 5.60 | 1320 |

**Table 7:** Shear Resistance of Aluminum Rivets using Response Surface Analysis

| Term | Coef | Se Coef | T | P |
|---|---|---|---|---|
| Constant | 1318.33 | 12.29 | 107.208 | 0.000 |
| C | 15.62 | 7.530 | 2.075 | 0.051 |
| B | 86.88 | 7.530 | 11.537 | 0.000 |
| D | 28.75 | 7.530 | 3.818 | 0.001 |
| CC | -16.67 | 11.084 | -1.504 | 0.148 |
| BB | 3.33 | 11.084 | 0.301 | 0.767 |
| DD | -25.42 | 11.084 | -2.293 | 0.033 |
| CB | -25.00 | 10.649 | -2.348 | 0.029 |
| CD | -13.75 | 10.649 | -1.291 | 0.211 |
| BD | -6.25 | 10.649 | -0.587 | 0.564 |

S = 30.1213 R-Sq = 89.30% R-Sq(adj) = 84.48%

A shear resistance projection equation was then carried out by using the coefficients of the variables in order to determine the most appropriate value of each variable. The equation used was as follows:

$$\text{Maximize} = 1318.33+15.62(C)+86.88+(B)+28.75(D -16.67(C)^{2}+3.33(B)^{2} -25.42(D)^{2}- 25.0(CB)-13.75(CD)-6.25(BD)$$

### 3.3 Determination of the Most Appropriate Value of the Variables Affecting the Shear Resistance of the Rivets

The analysis of the data using the Response Optimizer Function resulted in the most appropriate values for the factors affecting shear resistance, as shown in Table 8.

**Table 8:** The Most Appropriate Values of the Factors

**Response Optimization**

Parameters

| Goal | Lower | Target | Upper | Weight | Import |
|---|---|---|---|---|---|
| Maximum | 1170N | 1400N | 1400N | 1 | 1 |

Global Solution

C = 2.8485

B = 5.2

D = 6.255

Predicted Responses

Shear = 1417.55, desirability = 1.0000

Composite Desirability = 1.0000

### 3.4 Experiment using the Most Appropriate Values of the Factors; To Confirm the Results

An experiment to confirm the results was conducted on the most appropriate values of the factors that affect the shear resistance of the rivets, performing five replications so as to enhance confidence. The results are shown in Table 9.

**Table 9:** The Results of the Responses

| Std Order | Response (y) | | | |
|---|---|---|---|---|
| | B | D | E | Shear |
| 1 | 2.8 | 5.2 | 6.3 | 1400 |
| 2 | 2.8 | 5.2 | 6.3 | 1420 |
| 3 | 2.8 | 5.2 | 6.3 | 1420 |
| 4 | 2.8 | 5.2 | 6.3 | 1410 |
| 5 | 2.8 | 5.2 | 6.3 | 1430 |

## 4. Conclusion

The experiment to confirm the results found that the adjustment level of the factors obtained form the workpiece pulling experiment showed that the shear resistance was at an average of 1,416 Newton. a comparison of the experiment results with the actual values showed similar values. It can thus be concluded that the results obtained from the experiment are actually the most appropriate values for setting the variables used in the riveting process. In addition, this experiment was carried out in line with the objectives, in that an aluminum rivet of Ø4.7 mm. was found to have a shear resistance at 1,113 Newton. When fastened with a hole of Ø5.2 mm. and pressed with 5,000 Newton tension, its body increased to Ø5.2 mm. which was bigger than the original size by 0.7 mm. yet the structure remained unchanged. Moreover, the body of the rivet was also strengthened and was able to resist a shear of 1,416 Newton, an increase of 303 Newton, thus enhancing its shear resistance.

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