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# An Investigation of Aluminum Spot Weld Joint Quality through Process Simulation and Real Experimental

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## دراسة جودة وصلة اللحام النقطي للألومنيوم من خلال محاكاة العملية والتجارب الحقيقية

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**Abstract:**
In many industries, the resistance spot welding process (RSW) has shown great promise, particularly for large-scale manufacturing. Typically, this procedure is used in the furniture, automotive, and other sheet metal sectors. Recently, the industrial sector has expressed interest in joining aluminum alloys utilizing resistance spot welding. The following work is based on the spot welding of successive joint of aluminum – magnesium alloy ( A-5454) with thickness of 1 mm and carried out in two phases, the first study aims to achieve the optimum process parameters by conducting real welding experimental using different welding parameters and inspect the welded joints. In the second phase of the work, SIMUFACT WELDNG software was used to simulate the spot welding process of aluminum to predict the joint characteristics (nugget diameter, strength and distortion) and compare the results with experimental output. Obtained result showed that, Relative percentage errors for the nugget diameter derived from the models and the actual experimental data can reach 9.8%, and 9.28% for shear strength, for distortion the relative percentage error is4.8%. These discrepancies are minor and to be expected given the model's assumptions about heat transport and the precision of the measurement instruments, leading to the conclusion that Simulufact welding software is a suitable method for simulating the model.

**Keywords**: Resistance Spot Welding Process, Aluminum Alloys, SIMUFACT Welding Software.

**الملخص**
يستخدم اللحام النقطي بالمقاومة الكهربائية بشكل واسع في مختلف التطبيقات الصناعية مثل صناعة السيارات والاثاث وغيرها نظراً لإنتاجيته العالية ومرونته وقلة تكلفته نسبة لبعض طرق اللحام الأخرى وخصوصاً عند استخدامه في الإنتاج الكمي. في الآونة الأخيرة، زاد الاهتمام باستخدام اللحام النقطي بالمقاومة الكهربائية لوصل صفائح الألومنيوم لدخولها في العديد من الصناعات. في هذا البحث، تم استخدام برنامج SIMUFACT WELDNG لمحاكاة عملية اللحام بالنقطة لصفائح من سبائك الألومنيوم - مغنيسيوم (A-5454) بسمك 1 مم للتنبؤ بخصائص وصلة اللحام (قطر درزة اللحام, قوة القص والتشوه) ومقارنة النتائج بالناتج التجريبي. أظهرت النتيجة التي تم الحصول عليها أنه عند مقارنة قطر درزة اللحام الذي تم الحصول عليه من عمليات المحاكاة بنتائج التجارب الفعلية؛ تصل نسبة الأخطاء إلى 9.8٪، و9.28٪

لقوة القص، وأخيرًا 4.8٪ للتشوه. بالنظر إلى ظروف نقل الحرارة في النموذج، والنظر في دقة أدوات القياس، فإن هذه الاختلافات صغيرة ومتوقعة بحيث نستنتج أن نتائج المحاكاة باستخدام Simufact مقبولة.

**الكلمات المفتاحية:** اللحام النقطي بالمقاومة الكهربائية، سبائك الألومنيوم، برنامج سيميوفاكت لمحاكاة عمليات اللحام

## Introduction

The manufacturing business is extremely competitive, and organizations must constantly work on product development in order to maintain a competitive advantage. Meanwhile, enterprises should keep up with changes in manufacturing technology. This is because there is a synergy between technology and product development, and it is only by concurrently improving both that successful products can be achieved with optimal lead time. [1]. Welding techniques are critical to the development of almost every industrial product. However, these processes frequently appear to consume larger fractions of the product cost and produce more manufacturing issues than could be predicted. [2].

Welding is the process of uniting two components through the coalescence of surfaces in contact with one another. This coalescence can be accomplished by melting the two pieces together (fusion welding) or by bringing the two parts together under pressure, sometimes with the addition of heat, to form a metallic bond across the contact surfaces (pressure welding) [2]. Pressure welding can be performed using a variety of welding techniques, all of which include pressing the joint's surfaces together [3, 4].

Among various pressure welding processes, spot welding is the most known of the numerous resistance welding techniques. It is frequently used in a variety of sectors to joint thin sheet materials (up to 3 mm) using overlap joints. The high current, along with a short heating time, means that the thermal energy input is used efficiently, giving spot welding significant advantages over other sheet metal welding procedures [3, 4].

In many different industries, the resistance spot welding process (RSW) has shown great promise, particularly for large-scale manufacturing. This procedure is typically used in the furniture, automotive, and other sheet metal sectors. Recently, the industrial world has expressed interest in joining aluminum alloys utilizing resistance spot welding. However, welding aluminum alloys using this method has certain joint strength issues, in contrast to RSW for steels. Due to their sensitivity to environmental factors and much higher electrical and thermal conductivities than steel, aluminum alloys necessitate a high welding current. It’s important to control the quality of weldments by control the welding variables those have a direct influence on the joint volume, strength and distortion [5,6,7].

Choosing the ideal welding parameters to achieve excellent quality at low cost is one of the difficulties engineers and technicians encounter while using the resistance spot welding technique (RSW). These significant problems can be solved by strategic planning of experiments design to set process parameters at optimum values to achieve high joint quality.

Few studies have investigated the simulation of thin aluminium sheets welded by resistance spot welling. Anil Kumar Deepati et al. studied the mechanical properties of A5083 aluminum alloy with 2.5mm thickness welded using resistance spot welding and found that the dimensions of the weld nugget were augmented by increasing the current, duration, and pressure of the electrode and the maximum nugget size and strength achieved were 7.94 mm and 231 kN, respectively [6]. Ambroziak et al. Investigated the efficacy of resistance spot welding for the assembly of aluminum components in the automotive industry, noting that the industry tends to utilize light alloys such as aluminum and magnesium which able to join by resistance spot welding [7].

De et al. studied the electrode/sheet interface using numerical simulation and proves that the numerical simulation is an efficient tool to predetermine the process parameters and predict the possible nature of electrode wear [8]. L. DORN et al. developed an effective numerical model used Fortran- 90 for resistance spot welding of aluminium alloys with a typical curved face electrode and found that the formation of the fusion zone is significantly influenced by the contact resistance along the sheet / sheet and the electrode / sheet interface [9].

Radu Stefanel Florea simulated spot welded joints of A 6061 aluminum alloy using ABAQUS software and showed that the shape and formation of the nugget align well with the experimental results presented in the macrographs and microscopy analysis [10]. In this work, numerical simulation will be used to imitate the spot welding process and estimate the joint characteristics (nugget diameter, strength and distortion) and compare the results with experimental output. Experimental and numerical simulation works have been carried out at the (Advanced Occupational Center for Welding Technologies) in Tajura, Tripoli, Libya.

## Experiment Studies
### Materials

Aluminum – magnesium alloy (A-5454) with thickness of 1 mm and (100 *25) mm dimension were used. The chemical composition and mechanical properties of the material are given in Table 1 and Table 2, respectively.

**Table (1):** Chemical composition of (A-5454) aluminum alloy [11].

| Alloy /Wt.% | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
|---|---|---|---|---|---|---|---|---|
| A-5454 | 0.25 | 0.4 | 0.1 | 0.5 - 1 | 2.4 - 3 | 0.05 - 0.2 | 0.25 | 0.2 |

**Table (2):** Mechanical properties of (A-5454) alloy [11].

| Alloy | Tensile strength ( Mpa ) | Yield strength ( Mpa ) | E% | HB |
|---|---|---|---|---|
| A-5454 | 215 - 285 | 115 | 22 | 62 |

### Experiments

The experiment was conducted at advanced occupational center for welding technologies in Tajura, Tripoli, Libya. The welding machine which is used to conduct the welding process is ESAB resistance welding machine model 4623N that is illustrated in Figure 1. The main parameters of resistance spot welding are defined in Table 3.


**Figure (1):** Spot welding machine.

**Table (3):** Description of welding parameters.

| Parameter | Unit | Symbol | Description |
|---|---|---|---|
| Squeeze Time | Cycle | ST | ▪ The time between beginning the movement of electrodes and the beginning of the welding cycle. |
| Welding Time | Cycle | T | ▪ Indicates the current flow duration |
| Welding Current | Ka | A | ▪ Indicates the welding operating power |
| Electrode Force | N | F | ▪ Enough force to produce contact between the sheets |
| Hold Time | Cycle | HT | ▪ The time between the end of the process and the opening of the electrodes |

### Resistance Spot Welding Procedure

In the present work, the specimens for experimentation on resistance spot welding were cut to the size of 100*25*1 mm, as highlighted in Figure 2. Before welding, the abrasive paper and acetone were used to clean samples and remove the contaminants.

In this direction, the first welding parameters were chosen based on previous studies that covered resistance spot welding of aluminum. Several trails were carried out and visually inspected then the maximum and minimum values of welding variables are chosen as outlined in Table 4 [6].

**Figure (2):** Welding samples preparation.

**Table (4):** Welding parameters.

| Parameters | Lower | Upper |
|---|---|---|
| Welding Current A (KA) | 15 | 16 |
| Welding Time T (cycle) | 25 | 30 |
| Electrode Force F (N) | 1600 | 1600 |
| Squeezing Time ST (cycle) | 40 | 40 |
| Holding Time HT (cycle) | 40 | 40 |

It worthy to mention that, four experimental runs (S1 to S4) were carried out by change one parameter and keeping the other constant as given in Table 5. Each experimental repeated four times, one for peel test and three for average of shear test. Figure 3 displays the actual sample that was jointed for investigation.

**Table (5):** Experimental runs.

| Experiment No | Squeeze Time (ST) (cycle) | Welding Time (T) (cycle) | Welding Current (A) (KA) | Electrode Force (F) (N) | Hold Time (HT) (cycle) | No. of Replication |
|---|---|---|---|---|---|---|
| S1 | 40 | 25 | 15 | 1600 | 40 | 4 |
| S2 | 40 | 30 | 16 | 1600 | 40 | 4 |
| S3 | 40 | 25 | 16 | 1600 | 40 | 4 |
| S4 | 40 | 30 | 15 | 1600 | 40 | 4 |

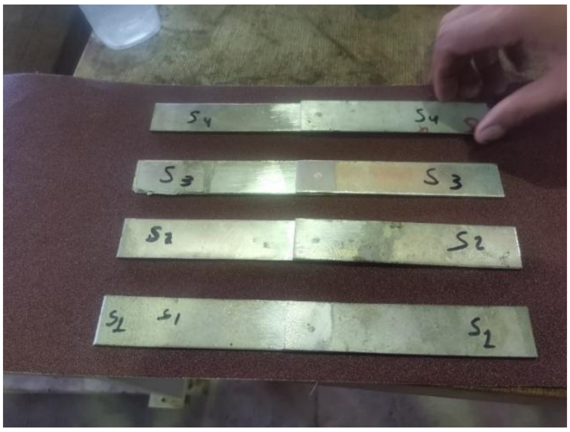



**Figure (3):** Real welded samples.

**Mechanical Characterization**

**Peel Test**

In order to perform this test, the sheets are gradually peeled apart until every weld that is being examined is completely fractured. The most common way to do this test is to use pliers or a roller tool to separate the sheets after locking one of them in a vise. A calliper is used to measure the maximum and minimum diameters, and non-circular welds and imperfections are taken into consideration by using the average diameter [12, 13]. A schematic image of the peel test is shown in in Figure 4.

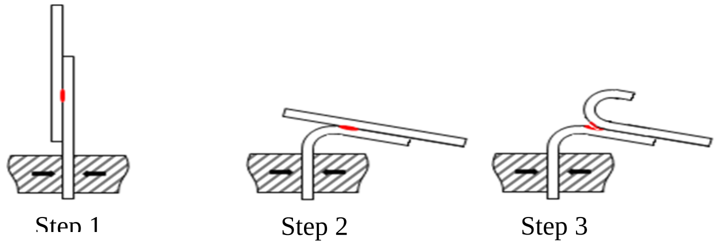
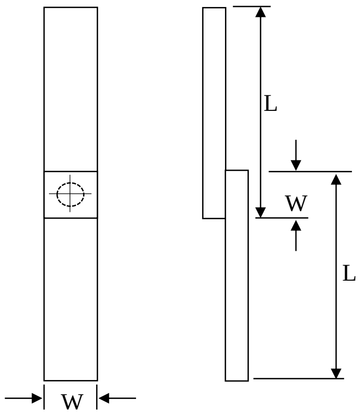



**Figure (4):** Step 1: Grip in vise. Step 2: Bend specimen. Step 3: Peel pieces apart with pincers [13].

### Tension – Shear Test

A test specimen made by lapping two strips of metal and connecting them with a single weld is placed on a traditional testing machine and dragged under tension until it breaks. Figure 5. displays the dimensions of the test specimen. Both the specimen's ultimate strength and the weld's diameter whether caused by the parent metal tearing or the weld metal shearing should be recorded [13,14].




| Nominal Thickness of Thinner Sheet (mm) | W (mm) Min |
|---|---|
| 0.20 to 0.80 | 17 |
| 0.80 to 2.50 | 25 |
| 2.50 to 3 | 30 |
| over 3 | 38 |

**Figure (5):** Dimensions of tension test specimen [13].

### Metallographic Characterization

A metallographic examination can be carried out to investigate the existence of voids and cracks in the heat-affected zone and the weld. To accomplish this, the nugget's center is sliced through, and the surface is then polished and etched using (15 g NaOH + 100 mL distilled H2O) solution [12].

### Experimental Results

The experimental runs were carried out using parameters as given in Table 5. Figure 3 displays the actual sample that was jointed for investigation.

### Mechanical Characterization

### Peel Test Results

The peel test was carried out on four samples welded by different parameters as represented in Figure 6. The vertical (D1) and horizontal (D2) diameters are measured by caliper, and recorded in Table 6. Figure 7 shows fractured samples after peel tests.

**Figure (6):** The peel test.

**Table (6):** Nugget diameter according to peel test.

| No | D1 mm | D2 mm |
|---|---|---|
| S1 | 4.6 | 5.2 |
| S2 | 5 | 6 |
| S3 | 4.3 | 4.6 |
| S4 | 3 | 4 |


**Figure (7):** Fractured samples after peel test.

The test gives good results and according to standard for thickness 1mm the minimum nugget diameter is 4 mm [15]. As recorded in Table 6, the best results are obtained from experimental S1 and S3 with diameter of (4.6 mm). This value will be used to validate the results of simulation work.

**Tension – Shear Test Results**

Three lap welded samples were tested according to ASME IX, the maximum and minimum diameters are measured by caliper and the area of nugget was calculated using minimum diameter for each experimental. Then, the shear strength is calculated based on Equation 1. All results are recorded in Table 7 [13]. Figure 8 shows fractured samples after tension–shear tests.

$$\text{Shear stress (Mpa)} = \text{Force} / \text{area of nugget} \qquad (1)$$

**Table (7):** The Shear strength values.

| No | Maximum diameter mm | Minimum diameter mm | A\|(area) mm2 | Force N | Shear stress N/mm$^2$ | Average Shear stress |
|---|---|---|---|---|---|---|
| S1 – Sh1 | 4 | 3.5 | 9.62 | 788 | 81.95 | 68.03 |
| S1 – Sh2 | 4.5 | 4 | 12.57 | 835 | 66.48 | |
| S1 – Sh3 | 5 | 4.5 | 15.90 | 885 | 55.67 | |
| S2 – Sh1 | 6.5 | 5.5 | 23.76 | 935 | 39.36 | 38.95 |
| S2 – Sh2 | 8 | 6.5 | 33.18 | 1157 | 34.87 | |
| S2 – Sh3 | 6 | 5 | 19.63 | 837 | 42.63 | |
| S3 – Sh1 | 7 | 6.5 | 33.18 | 791 | 23.84 | 23.84 |
| S3 – Sh2 | 4.5 | 2 | 3.14 | 581 | 184.94 | |
| S3 – Sh3 | 3 | 2.5 | 4.91 | 921 | 187.626 | |
| S4 – Sh1 | 5 | 5 | 19.63 | 304 | 15.48 | 49.55 |
| S4 – Sh2 | 4 | 3 | 7.07 | 591 | 83.61 | |
| S4 – Sh3 | 2.5 | 1.5 | 1.76 | 631 | 357.1 | |

The average of shear strength for each set of experimental was calculated and the shear strength of samples S3-Sh2, S3-Sh3 and S4-Sh3 were rejected and cancelled because of diameters are very small. Consider that the best average shear strength is (68.03 N/mm2) obtained from exp. S1, this value will be used to validate the results of simulation work.

**Macroscopic Examination Results**

A sample from the centre of the weld nugget was taken for macroscopic examination. The sample was cold-mounted in epoxy and grinded with different grades of SiC papers to measure the nugget dimensions and boundary of HAZ, see Figure 9, and making sure whether internal defects are present or not. The samples were etched using (15 g NaOH + 100 mL distilled H2O) solution [12].

**Figure (8):** Fractured samples after tension–shear tests.

The macro-image of the sample as seen in Figure 9 shows the nugget dimensions and distortion, the nugget diameter was 4.4 mm and distortion was 0.231 mm. Given the possibility of fracture in the base material, the nugget size determined by peel testing is probably greater than the weld size determined by metallographic testing.

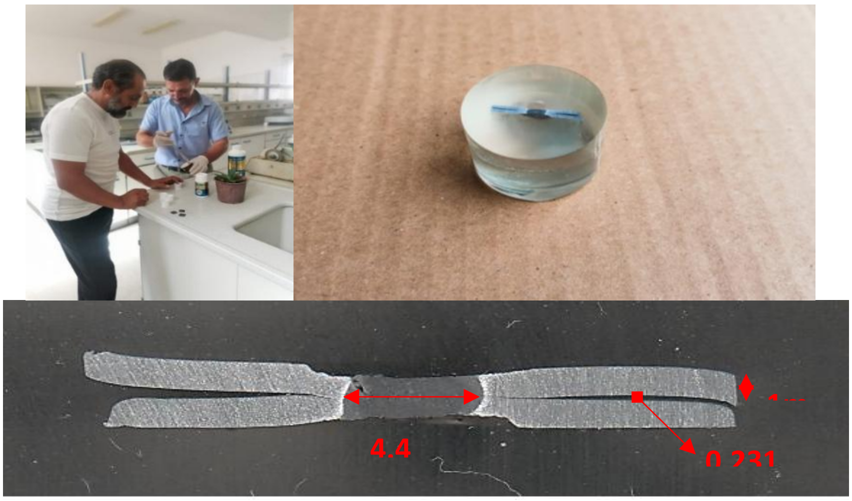



**Figure (9):** Macroscopic examination and nugget dimensions.

**Numerical Work (Simulation)**

Experimental work can be aided by numerical simulations, which offer a thorough understanding of the process and serve as a framework for experimenting with various parameters, geometries, and setups. Today's investigations were mostly conducted using commercial software that was already in use [16].

**Simufact Welding**

Simufact welding is a high-performance software program that uses finite elements to simulate spot welding and resistance projection. This software's fundamental concept is to provide an intuitive simulation tool to assist industrial users in the creation of new products and process optimization. To ensure that welding engineers and technicians can use the software directly, the process parameters are chosen to be similar to those of actual machines.

Because of its design, the user interface is thought to be simple to use and understand. The software pre-defines the electrode geometries and there is a material library that contains a variety of pre-defined, frequently used materials that are categorized. Additionally, it is possible to make new materials, alter, and duplicate the ones that already exist. The software effectively predicts the distortions and residual stresses that happen during welding and after unclamping, taking phase transformations into account and managing them in the component. This is one of the most crucial tasks [17].

**Modelling and Simulation of Spot Welding Process**

In particular, in this study, the optimum welding variables were selected based on the values of shear strength and nugget dimeter in experimental work. The process simulation are designed in the form of single nugget using Simufact welding software [18]. The material properties are given in Table 8.

**Table (8):** Aluminum properties [18].

| Property | Value | Unit |
|---|---|---|
| Thermal conductivity | 235 | W/(m.K) |
| Heat capacity at constant pressure | 890 | J/(kg.K) |
| Poisson's ratio | 0.32 | -- |
| Young's modulus | $67\times10^{3}$ | MPa |
| Density | 2.70 | $g/m^3$ |
| Coefficient of thermal expansion | $24\times10^{-6}$ | 1/K |

**Computational Domain Description**

The geometrical size and schematic diagram of the computational domain are displayed Figure 10. The model dimension is similar to real sample which used in experimental work also the same welding parameters of experimental S1 was chosen to implement numerical simulation of spot welding.

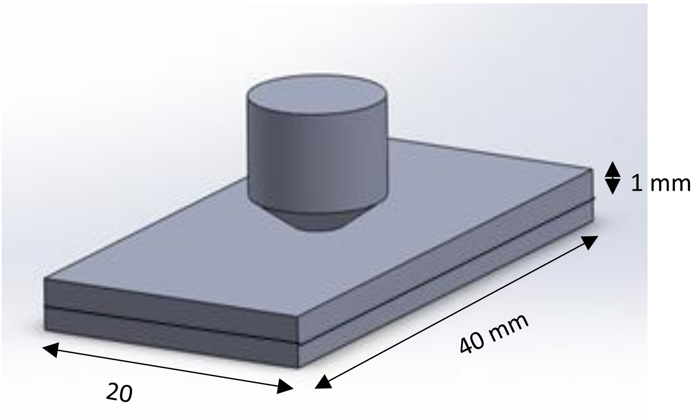



**Figure (10):** Schematic diagram of domain.

**Assumptions of Simulation**

- Heat is calculated at the interface of the components.
- In the established model, the simple transfer of heat is taken into account, but the flow of the molten pool is ignored.

**Modeling of Heat Source**

The accuracy of simulation work is mainly dependent on the proper modeling of the heat source, which determines the heat generated by the welding process. The heat source energy of spot welding can be expressed as follows [18]:

$$Q = RI^2 \quad (2)$$

Where:

- Q = Heat generated, joules (J).
- I = Welding current, amperes (A).
- R = Resistance at interface, ohms (Ω).

The boundary conditions of convection and radiation cooling between the workpiece and the environment were determined using equations 3 and 4 respectively [19].

$$q_{con} = h \times (T - T_0) \quad (3)$$
$$q_{rad} = \varepsilon \times \sigma \times (T^4 - T_0^4) \quad (4)$$

where ε = 0.05 is the emissivity of Aluminum and h (10 $W/m^2.K$) is the natural convective heat transfer coefficient [20].

## Model Validation

The actual and simulated nugget diameters of RSW are compared in order to give an experimental validation of the numerical model's effectiveness. The model was validated based on experimental work results.

## Simufact Welding Interface and Build-up the Model

The user interface of Simufact welding program is designed to be simple to use and understand. The first step after select the welding process is build-up the model and select the material of the parts to be welded as seen in Figure 11. Thereafter, as shown in Figure 12 and Figure 13, welding parameters (current, time and electrode force) can be added through different interfaces. Figure 14 shows the final model include the material and electrodes.

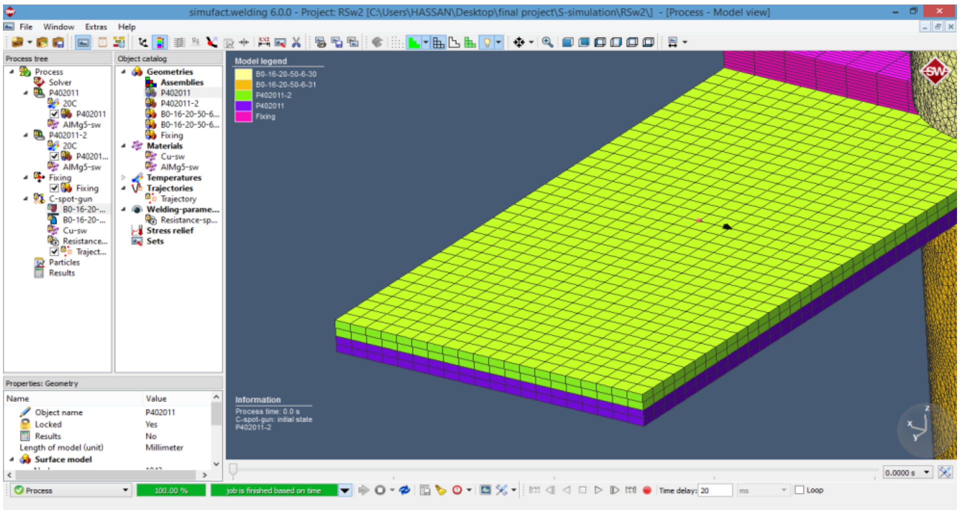
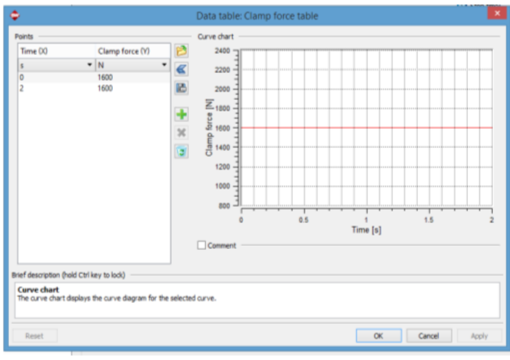


**Figure (11):** Building of model.



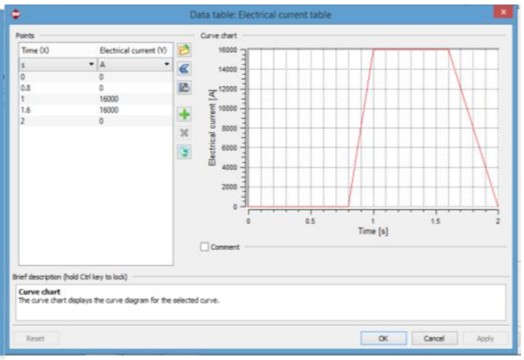




**Figure (12):** Current and time selecting. **Figure (13):** Electrode force selecting.

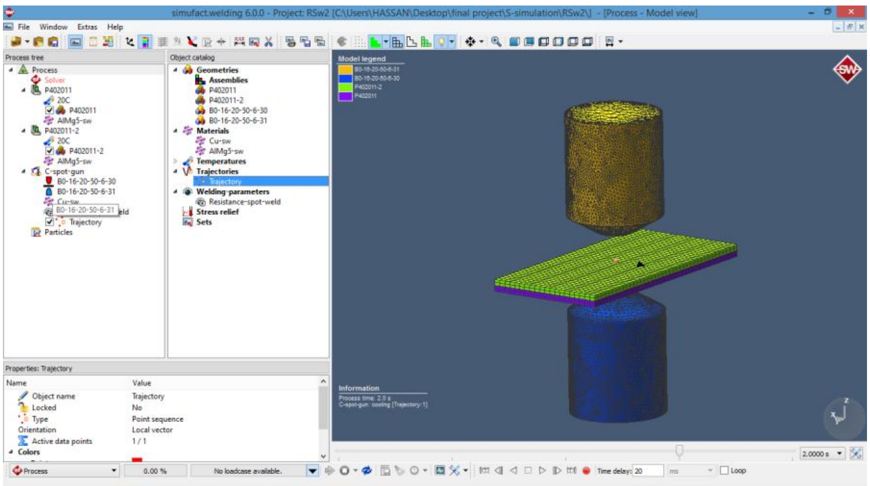


**Figure (14):** Final model.

### Simulation Results

The results of simulation work were recorded in Table 9 and documents in figures from Figure 15 to Figure 17.

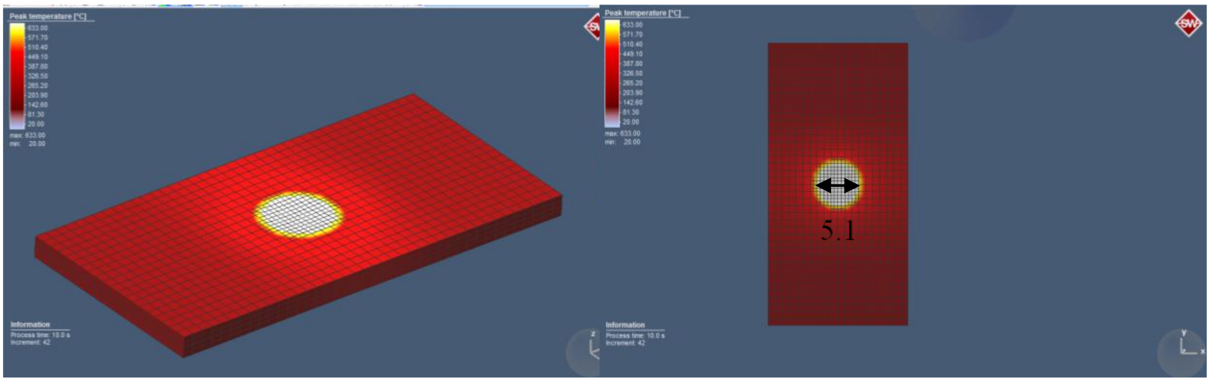



**Figure (15):** Peak temperature displayed by simulations.

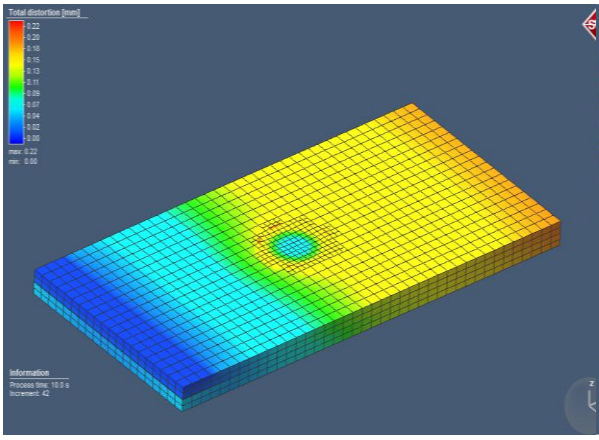


**Figure (16):** Shear strength from simulation.

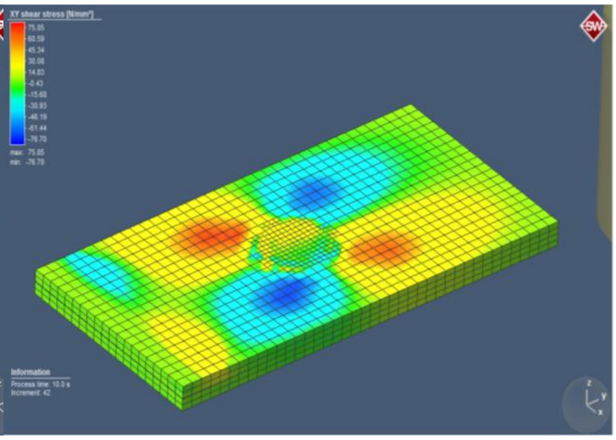


**Figure (17):** Total distortion from simulation.

### Model Validation

A comparison between the simulated and real results of an RSM is used to give an experimental validation of the numerical model's effectiveness. The model's validity was confirmed by means of experimental data. The simulation findings were documented and compared with the experimental data, as indicated in Table 9.

**Table 9.** Experimental and simulation results.

| Result | Experiment | Simulation | Error |
|---|---|---|---|
| Nugget diameter (mm) | 4.6 | 5.1 | 9.8 % |
| Shear strength (N/mm2) | 68.03 | 75.85 | 9.28 % |
| Distortion (mm) | 0.231 | 0.22 | 4.8 % |

Relative percentage errors for the nugget diameter derived from the models and the actual experimental data can reach 9.8%, and 9.28% for shear strength, for distortion the relative percentage error is4.8%. These discrepancies are minor and to be expected given the model's assumptions about heat transport and the precision of the measurement instruments, leading to the conclusion that Simulufact welding software is a suitable method for simulating the model

### Conclusions

The main conclusions that can be drawn from this study are as follows:

1. Specific to the RSW of Aluminums in this study, the desirable nugget diameter and Shear strength have been found to be 4.6 mm and 68.03 N/mm2 in accordance with the input process variables of 15 kA of welding current, 25 cycle of welding time and 1600 N of electrode force.
2. The nugget diameter derived from the simulations had a relative percentage error of 9.8% and was equivalent to the actual experimental results.
3. With a relative percentage error of 9.28 %., the shear strength derived from the simulations was equivalent to the actual experimental data.

4. The distortion derived from the simulations had a relative percentage error of 4.8% and was equivalent to the actual experimental results.
5. Simufact welding software was successfully used to simulate resistance spot welding.

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