Design of welded joint based on transient thermal condition

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Abstract
This paper presents the design of welded joint based on transient thermal condition. Resistance spot welding is a fast, easily automated and easily maintained process with high productivity. This paper was performed to investigate the design parameters of sheet metal welded joint based on transient thermal condition. The transient thermal condition of the sheet metal was analyzed and the factor of safety was proposed at the end of the project. The design parameters included were the number of spot welding, dimension, material and thickness of sheet metal. aluminum 5182-H19 was used as a base material to study the mechanical properties and thermal behavior. The transient thermal analysis was conducted on aluminum alloy 5182-H19 sheet metal with dimension 120mm x 60mm, thickness 1mm to 6mm and number of spot weld two to five. Suitable combination of thickness of sheet metal with number of spot weld is proposed after the simulation and analysis. The CAD model and analysis of sheet metal was performed by using ANSYS software. The results of both the thermal analysis were heat flux, reaction probe and factor of safety. Scoring concept was provided to determine the number of spot weld for each thickness of the sheet metal. It is found that two number of spot weld was suitable for thickness of 1mm, 2mm, 4mm, and 6mm. As a result, sheet metal with thickness 3mm and 5mm, five and two spot weld was suitable respectively.

Key words: Design, Sheet metal, Welded joint, Aluminum alloy, Transient, Thermal

1. Introduction

Sheet metal workings are normally undergone in cold condition compared to form under hot condition. This is because sheet metal has a lower resistance to deformation when heated (Boljanovic, 2004). The sheet metal forming processes included roll forming, stretch forming, drawing, stamping, rubble-pad forming, spinning, superplastic forming, poem forming, explosive forming and magnetic-pulse forming (Kalpakjian and Schmid, 2009).

Many methods have been used in joining materials together which are adhesive bonding, mechanical joining, fusion welding, and solid state bonding welding, friction welding, electromagnetic welding, brazing and roll bonding (Imaizumi, 1996). Resistance spot welding is one of the welding processes that have been used broadly in sheet metal joining (Cho and Cho, 1989). It is also the most commonly method that used in joining car body steel component (Kowieskiet al., 2012). Some of the advantages of this welding process are high speed, suitability for automation industry and high productive assembly lines (Cho and Cho, 1989).

Resistance spot welding process is fast, easily automated and easily maintained compared to other welding processes (Pingili, 2012). In resistance welding process, when sufficient energy is generated at the interface of the workpiece, the forming of a welding nugget is started. The factors that affect the size of nugget formed is the resistance offered, the flow of current and the time of current flow (Li, et al., 2013). When a structure or part is produced by welding process, a non-uniform temperature distribution is created in the structure or part. A rapid thermal expansion and contraction in weld and the surrounding areas during welding process results in this temperature distribution. Thus, inhomogeneous plastic deformation and residual stresses in the weldment is formed when the structure is cold
(Armentani et. al., 2006). Resistance spot welding process includes the combination of thermal, electrical, mechanical and metallurgical phenomena. It is a complicated welding process (Nied, 1983). The complexity of this welding process had led to some difficulties in understanding the thermal behavior in the weldment (Cho and Cho, 1989). The most common approach in resistance spot welding was studied on the nugget size that influenced by the weld current (Asadi, et. al., 2012) and (Zhao, et. al., 2013).

After resistance spot welding process, the residual stress and strain will remain in the weldment due to the deformation during the welding process. Upon electrode force and heating, stress and strain will be created and changed. A numbers of researches of the mechanical features for resistance spot welding process are being done. As a conclusion from the researches, the factors that might lead to the failure of resistance spot welding are residual stress, welding schedule, nugget size, welding parameters, thickness, material properties and gap (Wang et al., 2009).

Due to the complexity of resistance spot welding, the actual setting of resistance spot welding such as current and welding time is determined by trial and error most of the time (Saleem, et al., 2012). At the same time, the number of spot welds needed for a particular dimension is also a factor that leads to failure (Ertas and Sonmez, 2008). During resistance spot welding, sheet metal experienced change of temperature. Different amount of spot weld generated produced different amount of heat energy. It cannot be denied that thermal condition is one of the factors that need to be considered in resistance spot welding. Thus, there is a need to analyze a sheet metal welded joint within the factor of safety based on transient thermal condition where the number of spot welds need to be determined.

2. Materials and Methods

Data was obtained from the output of literature review. The data that obtained for this project included the thickness of sheet metal, material of the sheet metal, and parameters that need to be used in the analysis. The data that were used in the analysis was summarized in Table 1. The measurement of temperature in the spot welding zone was captured as a result in transient analysis simulation using ANSYS Software. Based on the simulation result, the geometry that experienced this temperature with magnitude 600°C is in the center of spot welds. The setting of convection constraints in this transient thermal analysis was performed in the ANSYS software. The geometry selected is all the surface of the 3D model because it will undergo natural convection during the heat releasing. The ambient temperature is set to 22°C and the heat transfer coefficient is 14.24 W/m².°C. However, the convection coefficient was calculated manually which showed in Table 1.

| Thickness of Sheet Metal | 1mm, 2mm, 3mm, 4mm, 5mm, 6mm |
|--------------------------|--------------------------------|
| Number of Spot Weld      | 2, 3, 4, 5                     |
| 3D Modelling Software    | Ansys Design Modeler           |
| 3D Model                 | As Shown in Figure 1 and 2     |
| Material                 | Aluminium Alloy 5182-H19       |
| Types of Welding         | Resistance Spot Welding        |
| Temperature in Spot Weld | 600°C                          |
| Ambient Temperature      | 22°C                           |
| Convection Coefficient, $h$ | 14.24 W/m².°C                 |
| Analysis Software        | ANSYS Workbench                |
| Type of Analysis         | Steady State Thermal Analysis  |
|                          | Transient Thermal Analysis    |

Calculations of convection coefficient, $h$ of sheet metal were based on the formulas in Cengel and Ghajar (2011). The sheet metal 3D model is assumed to be rectangular with dimension 210mm x 60mm.

The convection coefficient, $h = \frac{N_u k}{L_c}$ where $N_u = \text{Nusselt Number} = 0.54 \left(\frac{Pr}{k}\right)^{1/4}$, $k = \text{Thermal Conductivity}$, and $L_c = \text{Characteristic Length}$.
\[ L_c = \frac{A_s}{p} \]  

in which \( A_s \) is the surface area and \( p \) is the perimeter;

\[ R_{nl} = \frac{g \beta (T_s - T_{\infty}) L_c^3}{v^2} P_r \]  \hspace{1cm} (1)

Where \( R_{nl} \) = Rayleigh Number; \( g \) = gravitational acceleration, 9.81 m/s\(^2\); \( v \) = kinematic viscosity of fluid, m\(^2\)/s, and \( P_r \) = Prandtl number

\[ \beta = \frac{1}{T_f} \]  \hspace{1cm} (2)

\[ T_f = \frac{T_s - T_{\infty}}{2} = \frac{(600 - 22)\,^\circ C}{2} = 311 \, ^\circ C = 584K \]

Where \( T_f \) is the film temperature; \( T_s \) is surface temperature; and \( T_{\infty} \) is ambient temperature. Since the sheet metal is very thin, the heat lost during conduction from spot weld to surface of sheet metal is neglected. Thus, the surface temperature was 600\(^\circ\)C.

\[ L_c = \frac{A_s}{p} = \frac{0.06 \times 0.21}{2(0.06 + 0.21)} = 0.0233 \]

From the data obtained from Table A-15 in Cengel and Ghajar (2011), \( k = 0.04487 \, \text{W/m.K} \), \( v = 4.921 \times 10^{-5} \, \text{m}^2/\text{s} \), and \( P_r = 0.69354 \)

\[ R_{nl} = \frac{(9.81 \, \frac{\text{m}}{\text{s}^2})}{549K} \frac{1}{(4.921 \times 10^{-5})^2} \frac{(600 - 22)\,^\circ C \times (0.0233)^3}{0.69354} = 3.5174 \times 10^4 \]

\[ N_u = 0.54 \, R_{nl}^{1/4} = 0.54 \times (3.5174 \times 10^4)^{1/4} = 7.3952 \]

\[ h = \frac{N_u k}{L_c} = \frac{7.3952 \times 0.04487}{0.0233} = 14.24 \, \text{W/m}^2/\text{C} \]

In this phase, 3D modeling and simulation is carried out. There are total of 24 sets of sheet metal simulated by using ANSYS software. The analysis is done by using ANSYS Workbench. The solution of each of the thermal analysis is transferred to static structural analysis to obtain the factor of safety. Next, 3D modeling is created by using ANSYS Design Modeler. The two sheet metals with thickness from 1mm to 6mm are created in this software. Since this is just a simple 3D model, only rectangular features, extrude and dimension function is used to produce this model. Next, the spot welding is generated for each thickness. The number of spot welding is range from two spot welds to five spot welds. Figure 1 shows the sheet metal with thickness 4mm and 3 spot welds that being used for analysis. The dimensions of these two sheet metals are the same which is 60mm×120mm with different thickness. The resistance spot welding is generated in the middle of the overlapping of the two sheet metals. Figure 2 shows the meshing of 3D model generated by the software. The mesh size of 3D model is performed by ANSYS Software. The value of mesh size is 4329 nodes and 2168 elements.

Fig. 1  Sheet metal with thickness 4mm and 3 spot welds

Fig. 2  Meshing of 3D model.
3. Results and Discussions

Figure 3 shows the average total heat flux for transient thermal analysis. The average total heat flux decreased as the thickness of the sheet metal decreased. At the same time, the average total heat flux decreased as the number of spot welds increased except for 6mm thick sheet metal. The average total heat flux for 6mm thick sheet metal with four numbers of spot welds was higher than three spot welds.

In transient thermal analysis, the heat flux increased as thickness of sheet metal increased. At the same time, the reaction probe increased as the thickness of sheet metal increased. The increment in reaction probe is significant and therefore the heat flux tends to vary with the reaction probe in state of the thickness of the sheet metal. In order to choose the suitable number of spot welds required for each thickness, the results from transient thermal analysis were used. The criteria are total heat flux (W/m²), reaction probe or rate of heat transfer (W) and factor of safety. It is performed that the transient conditions suit the thermal behavior of sheet metal depends of the thickness. Furthermore, this study agreed with (Cho and Cho, 1989), that the complexity of welding process had led to some complications in understanding the thermal behavior. Therefore, this study proposes that the total heat flux in transient condition has been contributed in designing of welded joint based for Aluminum 5182-H19.

Figure 4a and 4b show the average reaction probe for steady state and transient thermal analysis, respectively. The average reaction probe increased as thickness and numbers of spot welds increased. In steady state condition, it is found that the reaction probe or heat flow increasing as the thickness of the sheet metal increasing. Also, the reaction probe increased as the number of spot welds increasing. There were no significant increments of the reaction probe in steady state thermal analysis.
As compared to the reaction probe in steady state thermal analysis, the reaction probe increased significantly in transient thermal analysis as the numbers of spot welds increased. Resistance spot welding for aluminum is a very fast welding process. According to Rashid et al., (2011) the whole process takes around 42 cycle times which is around 7s where 1 cycle time is equal to 16.67ms. However, the nugget or spot weld being generated in current stage and the cooling time is at the hold stage which only consists of 12 cycle times which is around 2s. Thus, the spot weld need to be cooled down in a very fast rate. As a result, a smaller amount of heat flux and reaction probe is preferable in determining the numbers of spot weld needed for each of the thickness.

This results made agreement with Li et al., (2013) that spot weld formed and influenced the flow of current and the time of current flow. This practice can be applicable to study the thermal behavior of welded joint based in sheet metal working. In addition, the spot weld in transient condition led the sheet metal thermal behavior to represent the characteristic of welded joint based in sheet metal working.

Figure 5 shows the factor of safety for transient thermal analysis. The highest factor of safety with 1mm, 4mm and 6mm thick sheet metal was with two numbers of spot welds. Sheet metal with thickness 2mm and 3mm had the highest factor of safety when there are five numbers of spot welds. As for 5mm thick sheet metal, the highest factor of safety present when the number of spot welds are three.

![Figure 5](image)

**Fig.5** Average Factor of Safety for Transient Thermal Analysis.

Factor of safety represented the how safe the design of the substances. The higher amount of factor of safety, the better the product is. Thus, the highest amount of factor of safety is more suitable for the selection. Since the data from steady state thermal analysis is more suitable for ideal case, the selection was based on the results from transient thermal analysis. From the graphs obtained, the numbers of spot welds that fulfill the three criteria were transferred into the Table 2. It was found that the there were different number of spot welds which fulfilled the requirement. In order to select the most suitable numbers of spot welds, scoring was done. It is found that factor of safety is important in designing of welded joint based in sheet metal working and needs further study in determining the safety of welded joint. The result has been supporting the findings from Asadi et al., (2012) and Zhao e. al., (2013) that size spot weld contributes in strength of welded joint in sheet metal working. Therefore, it is necessary to determine the number of spot weld for particular sheet metal thickness.
Table 2  Number of Spot Weld That Fulfil the Requirements.

| Thickness, mm | Highest Factor of Safety | Lowest Heat Flux | Lowest Reaction Probe |
|---------------|--------------------------|------------------|-----------------------|
| 1             | Two                      | Five             | Two                   |
| 2             | Five                     | Five             | Two                   |
| 3             | Five                     | Five             | Two                   |
| 4             | Two                      | Five             | Two                   |
| 5             | Three                    | Five             | Two                   |
| 6             | Two                      | Five             | Two                   |

Since factor of safety represented the safe of the sheet metal, the weightage of factor of safety was 50% which is 0.5. The weightage of total heat flux and reaction probe was 0.15 and 0.35 respectively. This is because the reaction probe represented the rate of heat transfer which is important in heat releasing. The highest rating score was 4 and the lowest was 1. Table 3 shows the scoring for sheet metal with thickness 1mm. Two spot welds and five spot welds were being rated. The total scores of two spot welds and five spot welds are 3.55 and 2.45 respectively. Thus, two spot welds were chosen for 1mm thick sheet metal.

Table 3  Scoring for Sheet Metal with Thickness 1mm.

| Criteria               | Weightage | Two Spot Welds | Five Spot Welds | Two Spot Welds | Five Spot Welds | Weighted Score |
|------------------------|-----------|----------------|-----------------|----------------|----------------|----------------|
| Factor of Safety       | 0.50      | 4              | 2.00            | 3              | 1.50           |                |
| Total Heat Flux        | 0.15      | 1              | 0.15            | 4              | 0.60           |                |
| Reaction Probe         | 0.35      | 4              | 1.40            | 1              | 0.35           |                |
| Total Score            |           |                |                 |                |                | 3.55           |

Table 4 shows the scoring for sheet metal with thickness 2mm. Two spot welds and five spot welds were being rated. The total scores of two spot welds and five spot welds are 3.05 and 2.95 respectively. Thus, two spot welds were chosen for 2mm thick sheet metal.

Table 4  Scoring for Sheet Metal with Thickness 2mm.

| Criteria               | Weightage | Two Spot Welds | Five Spot Welds | Two Spot Welds | Five Spot Welds | Weighted Score |
|------------------------|-----------|----------------|-----------------|----------------|----------------|----------------|
| Factor of Safety       | 0.50      | 3              | 1.50            | 4              | 2.00           |                |
| Total Heat Flux        | 0.15      | 1              | 0.15            | 4              | 0.60           |                |
| Reaction Probe         | 0.35      | 4              | 1.40            | 1              | 0.35           |                |
| Total Score            |           |                |                 |                |                | 3.05           |

Table 5 shows the scoring for sheet metal with thickness 3mm. Two spot welds and five spot welds were being rated. The total scores of two spot welds and five spot welds are 2.55 and 2.95 respectively. Thus, five spot welds were chosen for 3mm thick sheet metal.

Table 5  Scoring for Sheet Metal with Thickness 3mm.

| Criteria               | Weightage | Two Spot Welds | Five Spot Welds | Two Spot Welds | Five Spot Welds | Weighted Score |
|------------------------|-----------|----------------|-----------------|----------------|----------------|----------------|
| Factor of Safety       | 0.50      | 2              | 1.00            | 4              | 2.00           |                |
| Total Heat Flux        | 0.15      | 1              | 0.15            | 4              | 0.60           |                |
| Reaction Probe         | 0.35      | 4              | 1.40            | 1              | 0.35           |                |
| Total Score            |           |                |                 |                |                | 2.55           |
Table 6 shows the scoring for sheet metal with thickness 4mm. Two spot welds and five spot welds were being rated. The total scores of two spot welds and five spot welds are 3.55 and 2.45 respectively. Thus, two spot welds were chosen for 4mm thick sheet metal.

| Criteria         | Weightage | Two Spot Welds | Five Spot Welds |
|------------------|-----------|----------------|-----------------|
|                  | Rating    | Weighted Score | Rating          | Weighted Score |
| Factor of Safety | 0.50      | 4              | 2.00            | 3              | 1.50           |
| Total Heat Flux  | 0.15      | 1              | 0.15            | 4              | 0.60           |
| Reaction Probe   | 0.35      | 4              | 1.40            | 1              | 0.35           |
| Total Score      |           | 3.55           |                 | 2.45           |

Table 7 shows the scoring for sheet metal with thickness 5mm. Two spot welds, three spot welds and five spot welds were being rated. The total scores of two spot welds, three spot welds and five spot welds are 3.05, 3.35 and 1.95 respectively. Thus, three spot welds were chosen for 5mm thick sheet metal.

| Criteria         | Weightage | Two Spot Welds | Three Spot Welds | Five Spot Welds |
|------------------|-----------|----------------|------------------|-----------------|
|                  | Rating    | Weighted Score | Rating           | Weighted Score  |
| Factor of Safety | 0.50      | 3              | 1.50             | 4              | 2.00           | 2              | 1.00           |
| Total Heat Flux  | 0.15      | 1              | 0.15             | 2              | 0.30           | 4              | 0.60           |
| Reaction Probe   | 0.35      | 4              | 1.40             | 3              | 1.05           | 1              | 0.35           |
| Total Score      |           | 3.05           |                  | 3.35           |                 | 1.95           |

Table 8 shows the scoring for sheet metal with thickness 6mm. Two spot welds and five spot welds were being rated. The total scores of two spot welds and five spot welds are 3.55 and 2.45 respectively. Thus, two spot welds were chosen for 6mm thick sheet metal.

| Criteria         | Weightage | Two Spot Welds | Five Spot Welds |
|------------------|-----------|----------------|-----------------|
|                  | Rating    | Weighted Score | Rating          | Weighted Score |
| Factor of Safety | 0.50      | 4              | 2.00            | 3              | 1.50           |
| Total Heat Flux  | 0.15      | 1              | 0.15            | 4              | 0.60           |
| Reaction Probe   | 0.35      | 4              | 1.40            | 1              | 0.35           |
| Total Score      |           | 3.55           |                 | 2.45           |

As a result, the numbers of spot welds recommended for each thickness of sheet metal were shown in Table 8. Two spot welds were suitable for 1mm, 2mm, 4mm, and 6mm thick sheet metal with dimension 120mm x 60mm. As for 3mm and 5mm thick sheet metal with the same dimension, five and three spot welds were suitable respectively.

Table 9 Number of Spot Welds Recommended for Each Thickness of Sheet Metal.

| Thickness, mm | Number of Spot Weld | Factor of Safety |
|---------------|---------------------|------------------|
| 1             | Two                 | 7.59544          |
| 2             | Two                 | 7.6031           |
| 3             | Five                | 7.60884          |
| 4             | Two                 | 7.60463          |
| 5             | Three               | 7.619095         |
| 6             | Two                 | 7.62614          |
The uniqueness of this approach is to present the thermal behavior of welded joint sheet metal. This study was focused on the simulation in transient condition. This approach is one of the solutions for sheet metal working industries as reference with different perspective in low cost at the design stage. The thermal behaviors of total heat flux, reaction probe and factor of safety have been contributed to the welded joint. Furthermore, the comprehensive of thickness and number of spot weld of Aluminum 5182-H19 was proposed for sheet metal working industries.

4. Conclusion

The thermal condition of sheet metal after spot weld was analyzed by using ANSYS software. There are two thermal analysis were done in this project to study the thermal condition which are steady state and transient thermal condition. There were two analyses being done in this project which were steady state thermal analysis and transient thermal analysis. The transient thermal analysis gives the results of total heat flux, reaction probe and factor of safety.

The results that obtained from the analyses were tabulated in table form and then convert into graphs for further discussion. The results were used to determine the number of spot welds that suitable for each thickness. The results of the two analyses are total heat flux, reaction probe and factor of safety. From the results obtained, the number of spot welds that is suitable for each thickness is determined. As a result, a comprehensive number of spot welds recommended for 1mm to 6mm thickness of sheet metal.

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