NUMERICAL STUDY OF FATIGUE BEHAVIOR OF SPOT WELDED JOINTS

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ABSTRACT

In this paper, a complete investigation about the fatigue life prediction in spot welded joints has been studied, numerically. To do so, a 2D axi-symmetric finite element model of electrodes and sheets was created in ANSYS FE environment and a coupled thermal-electrical-mechanical analysis was employed to analyze the whole resistance spot welding process schedule and then the residual stresses, nugget dimensions and the amount of gap between sheets were calculated. After that, a 3D finite element model of the spot welded joint was simulated based on the previous transient analysis and finally the strain-based approach was applied to obtain the fatigue life.

The results from the transient analysis show that the relatively high value tensile residual stresses remain in the sheet joint at the areas near the nugget and HAZ. The results also indicate that the welding residual stresses influence on the fatigue life of the joint, therefore, the differences between the fatigue life durations, with and without considering the welding residual stresses, increase with decreasing the applied cyclic load.

Introduction

Resistance spot welding is widely used in industry especially in vehicle manufacturing field and the electronic instruments due to having good rate of welding process, good quality of joints and low cost. Nowadays, the use of aluminum alloys in automotive industry is very common and is used instead of steel alloys because of their advantages like low weight. However, aluminum alloys are usually more difficult to weld. This is because of their narrow plastic range, low bulk resistance and greater thermal conductivity.

To investigate the behavior of the spot welds, two different analyses may be studied: transient and steady-state analysis. The transient analysis is associated with the time dependent welding stages from starting to the end of the process. This analysis in the case of resistance spot welding process includes applying mechanical electrode force or pre squeezing pressure, applying the electrical current, nugget formation, transient heat transfer, electrode removal and finally existing residual stresses. The steady-state analysis is associated with the case in which the nugget has been formed and reached to the stationary state.

The majority of the previous investigations have been focused on one of these two analyses [1-8]. The major objective of this study is to create a connection between these two analyses, transient and steady-state, and to investigate the effects of transient state on the mechanical behavior of the joints and to evaluate their effects on the steady-state parameters.

There are a number of factors that affect the fatigue life of spot welded joints which can be summarized as follows:

1) Residual stress is one of the most important parameters which influence the fatigue life of the spot welds. The electrical force and the rigorous temperature gradient produce the residual stresses during the welding process. In the regions close to the spot welds due to the temperature gradient and relatively high electrode force, the plastic strain components exist, while in the regions far from the nugget, stresses and strains are mainly in elastic range. Therefore, the residual stresses remain on the joint after the electrode removal and reaching the temperature distribution to the steady-state condition. Residual stress is a non-linear and complicated phenomenon that its measurement is very costly.

2) The gap effect between sheets in three dimensional finite element analyses which is very considerable for mono spot-welded tensile-shear [8, 9].

Due to expansion and shrinkage of the aluminum alloy when cooling down to the room temperature, a gap is generated between two sheets. The gap distance between sheets and the residual stresses near the root of nugget have been calculated using an axi-symmetric model of the electrodes and sheets (Fig. 1) and ANSYS Parametric Design Language (APDL).
In the present study, the nugget, heat affected zone and base metal regions have been obtained using the transient thermal analysis and the temperature distribution around the spot weld. Then, the fatigue life of the spot welded joint has been calculated based on the crack initiation conditions. The material used for both transient and fatigue analysis is an aluminum alloy 5182-0 sheet with the thickness of 1.5 mm. Chemical composition of the 5182-0 aluminum alloy has been given in table 1. The electrodes were Cu/Cr/Zr alloy and they were 120-deg truncated cone with 6.5 mm flat tip diameter.

| Table 1. Chemical composition of the 5182-0 aluminum alloy |
|-----------------|---|---|---|---|---|---|
| Si   | Fe  | Cu  | Mn  | Mg  | Cr  |
| 0.01% | 0.31% | 0.025% | 0.34% | 4.32% | 0.025% |

**Transient Analysis**

For the resistance spot welding process, the current, electrode force and welding time are the three major parameters. During the welding schedule, the applied mechanical force reaches its maximum value in the pre-squeezing cycle and remains constant during the welding cycle and applying the electrical current. The electrode force holds for a short time after applying the electrical current and then is removed from the sheets.

In this research, sine ac welding current of 29 kA was applied for 5 cycles (0.1 sec). The holding cycle was 0.25 second and a mechanical electrode force of 5kN was applied at the top of the electrode during the welding and holding stages. The cooling period has been considered about 10 seconds.

Some thermal and mechanical boundary conditions are presented in figure 1. It should be noted that the temperature in the water cooling chamber has been considered constant at 25 °C.

![Figure 1. Axi-symmetric model of the electrodes and sheets with thermal and mechanical boundary conditions](image)

Temperature dependent thermal, mechanical and electrical properties of copper and aluminum alloy 5182-0 collected from the literature were used for the transient analysis [10-12]. Thermal and electrical contact resistances have a major impact in resistance spot welding process. It has been observed that the thermal contact conductance \( h_c \) increases with rising temperature and contact pressure between two sheet metal. The relationship between thermal contact resistance and conductance can be written as follows:
\[ R_c = \frac{1}{h_c A_c} \] (1)

where \( R_c \) is the thermal contact resistance and \( A_c \) is the contact area.

In the present transient analysis, the thermal conductance coefficients have been specified to take into account the conductive heat transfer between electrode/sheet and sheet/sheet interfaces. The electrical contact resistance at the contact interfaces is one of the most important parameters in resistance spot welding. The contact resistance is affected by temperature. Faying resistance decreases with rising temperature and reaches its minimum when a weld nugget forms [13]. The contact resistance at the electrode/sheet interface has less influence on nugget formation because the heat generated on the electrode/sheet interface is removed by water cooling interface. However, the amounts of electrical contact resistances of electrode/sheet and sheet/sheet interfaces are assumed to be similar to the 5754 aluminum alloy [2] and they have been considered in the thermal-electrical analysis.

The monotonic and cyclic stress-strain curve at the room temperature for aluminum alloy 5182-0 has been shown in figure 2. It should be taken into consideration that the monotonic stress-strain curve was used for describing the non-linear behavior of the sheet metal. In this paper, bilinear isotropic hardening has been used to describe the plastic flow.

Figure 2. Monotonic and cyclic stress-strain curve for the aluminum alloy 5182-0 at room temperature [14]

Figure 3 shows the plastic deformations of the aluminum alloy 5182-0 which have been modeled using bilinear isotropic hardening at different temperatures. This is worth noting that, 0.2% proof stress and elongation at fracture was used to determine the slopes of the two lines of each model.

Figure 3. Bilinear isotropic hardening models for the aluminum alloy 5182-0 at different temperatures
Two types of elements have been employed for the transient part of the research: a solid thermal-electric element to model the electrodes and sheets and the contact pair elements to simulate the contact between electrode/sheet interfaces and sheet/sheet interface or faying surface. An incrementally coupled finite element modeling approach was adopted to analyze the electrical, thermal and mechanical behavior of the spot weld.

Results of transient Analysis

The transient thermal fields have been obtained at the end of welding period, holding stage, electrode removal and cooling cycle. Also, the stress distributions for the welding schedule have been obtained and the amounts of residual stresses at the end of cooling cycle have been used in the fatigue analysis. The temperature distribution in the sheet joint has been presented in figure 4. Figure 5 shows the amount of gap between two sheet joint which is measured from the nodal displacement of the end of each sheet. This figure also shows the nugget and HAZ regions based on the melting point of the aluminum alloy 5182-0 (577 ° C) and considering 300 ° C for the HAZ.

![Figure 4. The temperature distribution in the sheet joint after welding cycle](image1)

![Figure 5. Nugget and HAZ regions calculated based on the temperature distribution](image2)

The transient temperature distribution at the end of holding cycle has been presented in figure 6. Figure 7 shows the stress distribution in the x direction of the spot weld after the cooling cycle (10sec). It can be seen from figure 7 that the areas near the nugget and HAZ have the relatively large amount of tensile stresses which can be affected significantly on the fatigue life of the spot welded joints.
Figure 6. Transient temperature distribution at the end of holding cycle

Figure 7. The stress distribution in x direction of the spot weld after the cooling cycle

The welding residual stress profile after the cooling cycle in the x direction of the sheet joint has been shown in figure 8.

Figure 8. The welding tensile residual stress profile after the cooling cycle in x direction of the plate
This figure illustrate that the relatively large amount of tensile residual stresses remain in the sheet joint at the areas close to the nugget and HAZ.

**Fatigue Analysis**

The most commonly referenced spot weld fatigue life prediction method based on structural stresses and strains near the spot welds are: stress based approach, strain based approach, structural stress method and fracture mechanics approach. In this paper the strain-based method has been employed for fatigue analysis. For this reason, the modified Morrow equation has been employed which can be written as follows:

\[
\frac{\Delta \varepsilon}{2} = \frac{\sigma_f - \sigma_m}{2E}(2N_f)^b + \varepsilon_f (2N_f)^c
\]

in which

\[
\sigma_m = \sigma_{m}^* + \sigma_{m}^{res}
\]

Where \( \Delta \varepsilon \) is the total strain amplitude, \( \sigma_f \) is the fatigue strength coefficient, \( \sigma_m \) is the mean stress, \( b \) is the fatigue strength exponent, \( N_f \) is the number of cycles, \( \varepsilon_f \) is the fatigue ductility coefficient, \( c \) is the fatigue ductility exponent and \( E \) is the young modulus. It should be noted that \( \sigma_{m}^* \) is the amount of mean stress which has been obtained from the non-linear 3D analysis, and, \( \sigma_{m}^{res} \) is the corresponding residual value, which has been obtained from transient analysis.

Fatigue parameters for aluminum alloy 5182-0, used in strain-based method are available in table 2.

<table>
<thead>
<tr>
<th>Aluminum Alloy</th>
<th>Production Form</th>
<th>( \sigma_f' ) (MPa)</th>
<th>( \varepsilon_f' )</th>
<th>( b )</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5182-0</td>
<td>Sheet</td>
<td>814</td>
<td>0.293</td>
<td>-0.123</td>
<td>-0.592</td>
</tr>
</tbody>
</table>

To obtain the fatigue life, the problem was physically modeled in ANSYS software using the 3D model and the structural solid-8 node element. Non-linear analysis was performed for the mentioned joint with the gap of 0.09 mm between sheets. Schematic of the sheet joint of the weld and the general boundary condition for 3D model of the spot-welded joint have been presented in figures 9 and 10, respectively.
In the section of fatigue analysis, the cyclic stress-strain curve was used to describe the non-linear behavior of the material (refer to figure 2). Also, the plastic deformation of the material was simulated using the multi-linear kinematic hardening.

**Results of Fatigue Analysis**

Non-linear analysis for different loads from 500 N to 3000 N are applied on the models and load ratio \( R = \frac{F_{\text{min}}}{F_{\text{max}}} \) is assumed to be zero, therefore the amount of mean stress is equal to the half of the longitudinal stress in the sheet joint. The fatigue crack location in the spot weld is very important to take into consideration the effects of residual stresses. It has been observed that the fatigue crack initiation depends on the high cycle fatigue (HCF) or low cycle fatigue (LCF) conditions. In high cycle fatigue condition, the cracks are initiated in the heat affected zone (HAZ), but in the case of low cycle fatigue, the cracks are initiated in the base metal. So, for HCF conditions, the stresses and strains are considered at the root of nugget and for the case of LCF, the stresses and strains are considered at the interface point of heat affected zone and base metal. Figure 11 shows the fatigue life durations versus applied loads with and without consideration of welding residual stresses in the semi-log plot.

![Fatigue life durations versus applied loads](image)

**Figure 11. Fatigue life durations versus applied loads with and without consideration of welding residual stress**

The results from figure 11 illustrate that the welding tensile residual stresses near the spot weld affect on the fatigue life of the joint, significantly. This figure also indicates that the differences between the fatigue life durations with and without considering the welding residual stresses increase with decreasing the applied cyclic load.
Conclusions

In this study, an incrementally thermal-electrical-mechanical analysis was performed to investigate the fatigue behavior of the spot welded lap joint. An axi-symmetric model was developed to determine the transient parameters and a 3D FE model was employed to analyze the fatigue phenomenon in the spot welded joint. Fatigue life duration versus different applied loads were plotted with and without consideration of the residual stress effects.

The results from the transient analysis indicate that the faying surface and the areas near the nugget and HAZ have been surrounded by the relatively high value tensile residual stresses which affect on the fatigue strength of the joint, considerably.

References