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Fatigue Life Prediction of Spot-Welded Structures: A Finite Element Analysis Approach

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Abstract

This paper presents the technique of the fatigue analysis of spot-weld joints to predict the lifetime and location of the weakest spot-welds due to the imposed loading conditions. A simple model was used to illustrate the technique of spot-weld fatigue analysis. Finite element model and analysis were carried out utilizing the finite element analysis commercial codes. Linear elastic finite element analysis was carried out to predict the stress state along the weld direction. It can be seen from the results that the predicted life greatly influence the sheet thickness, spot diameter and loading conditions of the model. Acquired results were shown the predicted life for the nugget and the two sheets around the circumference of the spot-weld at which angle the worst damage occurs. It is also observed that the sheet-2 appeared the maximum stress range among the model. The spot-welding fatigue analysis techniques are awfully essential for automotive structure design.

Keywords: Sot-weld structure, finite element analysis, spot diameter, sheet thickness, variable amplitude loading.

1. Introduction

Spot welding is one of the primary methods to join sheet metals for automotive components. A typical car or truck may have more than 2000 spot welds. Since spot welds in automotive components are subjected to complex service loading conditions, various specimens have been used to analysis fatigue lives of spot welds [Sheppard and Pan (2001); Zhang (2001)]. The static strengths of spot welds have also been investigated. Ewing et al. (1982) investigated the strength of spot welds in terms of the specimen geometry, welding parameter, welding schedule, base metal strength, testing speed and testing configuration. Zhang and Taylor (2000) reported the thickness effect of spot welded structure on fatigue life. Pan and Sheppard (2003) calculated stress intensity factors for crack propagation through the thickness of plate by numerically utilizing finite element analysis. Lee et al. (1998) adopted a fracture mechanics approach using the stress intensity factor to model their experimental results on the strength of spot welds in U-tension specimens under combined tension and shear loading conditions. Wung (2001) and Wung et al. (2001) obtained and analyzed test results from lap-shear, in-plane rotation, coach-peel, normal separation, and in-plane shear tests and proposed a failure criterion based on the experimental data of spot welds in various specimens.

It is important for the automotive design engineers to understand the mechanical behaviors of different joints and furthermore, to incorporate the static, impact, and fatigue strength of these joints in the early design stage using computer aided engineering and design tools. Although more and more joints are being used in vehicle assemblies, very limited performance data on joints have been reported in the open literature. This is particularly true for spot welded joints of dissimilar metals combinations. For example, literature search on the topic of spot welded joints on fatigue yielded only a handful of publications, and majority of them focus on joints made between aluminum sheets of the same gages [Porcaro et al. (2004); Li and Fatemi (2006); Iyer et al. (2005)]. Moreover, almost all of these studies use only one coupon configuration, i.e., lap-shear or coach peel. The objective of this paper is to study the fatigue life behavior and characteristics of spot welded high strength steel joints.

2. Structural Stress Parameter

Welded joints experience highly localized heating and cooling from welding processes. As a result, the material properties around the welding joints can be significant variations after welding. The local geometry of the welded joints may have variations due to the amount of heat inputs and welding skills. These variations present significant difficulties for reliable fatigue prediction of welded joints.

Dong (2001a, 2001b) proposed a structural stress parameter for welded joins based on local stresses at weld toe. A typical through-thickness stress distribution at a fatigue critical location and the corresponding structural stress definition for through-thickness fatigue crack at the edge of a spot weld are shown in Fig. 1 and Fig. 2. Stress distribution at the edge of the spot weld nugget is assumed as shown in Fig. 1. In Fig. 1, t represents the thickness of the sheet steel, σ_x and τ are the normal and transverse shear stress under axial force P respectively. The corresponding structural stress distribution is shown in Fig. 2. The structural stress (σ) is expressed in Eq. 1.

$$\sigma = \sigma_m + \sigma_b \tag{1}$$

where σ_m is the membrane stress component and σ_b is the bending stress component due to the axial force P in the x direction. The transverse shear stress can be calculated based on local structural shear stress distribution, however, the effect of transverse shear stress neglected since the spot weld does not experience significant transverse shear loads in general [Dong (2001a)].

Figure 1: Local normal and shear stress in thickness direction at the edge of a spot weld

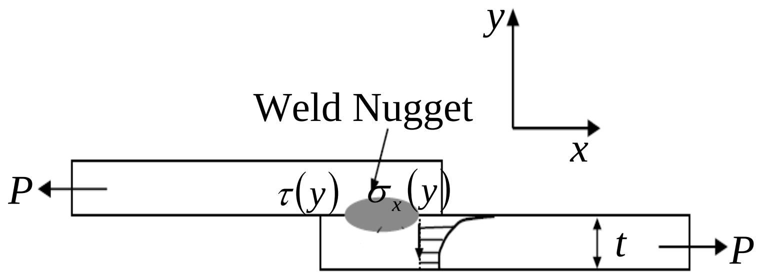


Figure 2: Structural stress definition at the edge of spot weld nugget

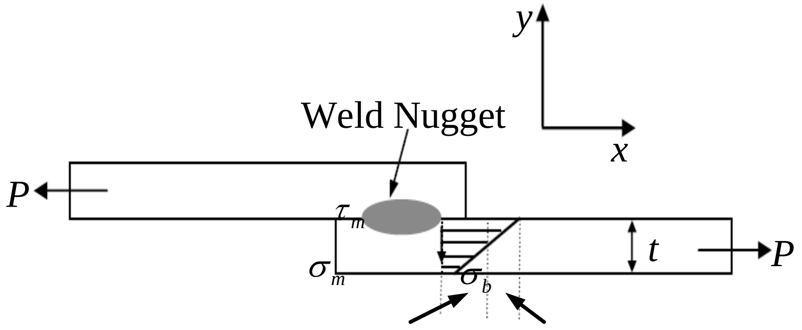
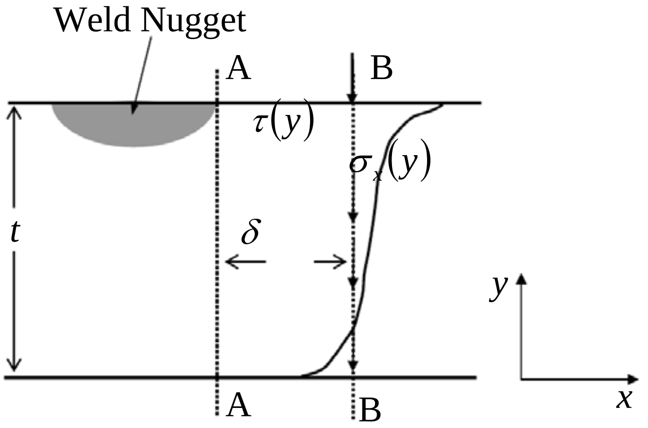


Figure 3: Structural stress calculation procedure for fatigue crack in thickness direction at the edge of the weld nugget.



The structural stress is defined at a location of interest such as plane A-A in Fig. 3 and the second reference plane can be defined along plane B-B. Both local normal and shear stress along plane B-B can be obtained from the finite element analysis. The distance in local *x*-direction between plane A-A and B-B is defined as δ. The structural membrane stress and bending stress must satisfy Eq. (2) and Eq. (3) for equilibrium conditions between plane A-A and B-B. Eq. (2) represents the force balances in *x*-direction, evaluated along the plane B-B. On the other hand, Eq. (3) represents moment balances with respect to plane A-A at $y = 0$. When δ between plane A-A and B-B becomes smaller then transverse stress τ in Eq. (3) is negligible. Therefore, Eq. (2) and Eq. (3) can be evaluated at Plane A-A in Fig. 3.

$$\sigma_m = \frac{1}{t}\int_0^1 \sigma_x(y)dy \tag{2}$$

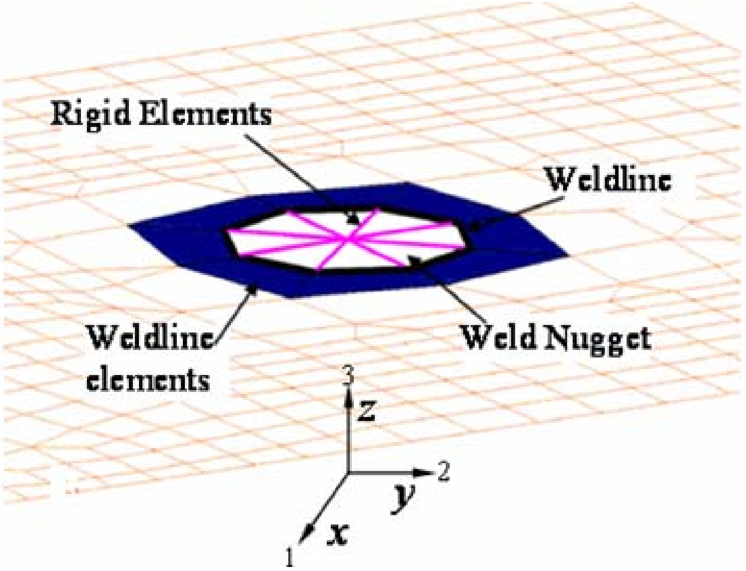
$$\sigma_m\left(\frac{t^2}{2}\right) + \sigma_b\left(\frac{t^2}{2}\right) = \int_0^t y\sigma_x(y)dy + \delta\int_0^t \tau(y)dy \tag{3}$$

3. Development of FEM

Traditionally, a very detailed finite element model of a spot welded joint is required to calculate the stress states near the joint [Wang and Pan (2005); Lee and Choi (2005); Lin et al. (2006)]. This model produces reasonable results but it requires a good amount of effort for modeling and computational time. Therefore, the very detailed finite element modeling of spot welds is not feasible for 3000- 5000 spot welds in a typical automotive body structure [Rupp et al. (1995)]. Instead of the detailed modeling of the spot welds, a simple beam element represents a spot weld for fatigue calculation of the spot welds in a vehicle structure [Rupp et al. (1995); Kang (2005)].

For the mesh insensitive structural stress calculation, the specimen for a spot welded joint is modeled with shell/plate, beam and rigid elements. The circular weld mark in each plate is modeled by triangular shell elements and rigid beams forming a spoke pattern as shown in Fig. 4. The rigid beam elements are connected from the center node to the peripheral nodal points of the circular weld marks in the both plates. Then the center nodes of the circular weld marks in both plates are connected with a beam element. Fig. 4 shows a finite element mesh around a circular weld mark. The geometry of the circular weld mark is required in the finite element model since the structural stress is calculated along the periphery of the weld. The normal direction of the shell elements (weldline elements) along the outside of the weldline is important for the calculation of the structural stress. Here, the weldline is defined as the periphery of the weld mark as shown in Fig. 4. A beam element represents the weld nugget to connect the top and bottom sheet steels. The length of the beam element is determined to be equal to one half of the total thickness for two sheets.

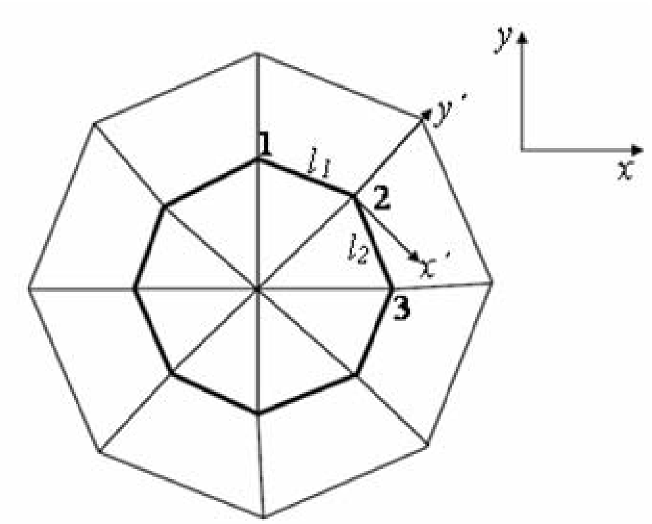
Figure 4: FEM around spot weld nugget



4. Finite Element Analysis

The nodal forces and moments in a global coordinate system at each mesh corner along the weld line (nugget periphery) with respect to the shaded elements in Fig. 4 are directly obtained from a linear elastic finite element analysis. The forces and moments in the global coordinate system are then transferred into the local coordinate systems since the structural stresses are defined as those components normal to the weld line of the spot weld. Fig. 5 shows a local coordinate system at a node used to convert the global forces and moments to local forces and moments on the weldline.

Figure 5: Local coordinate system at a grid point

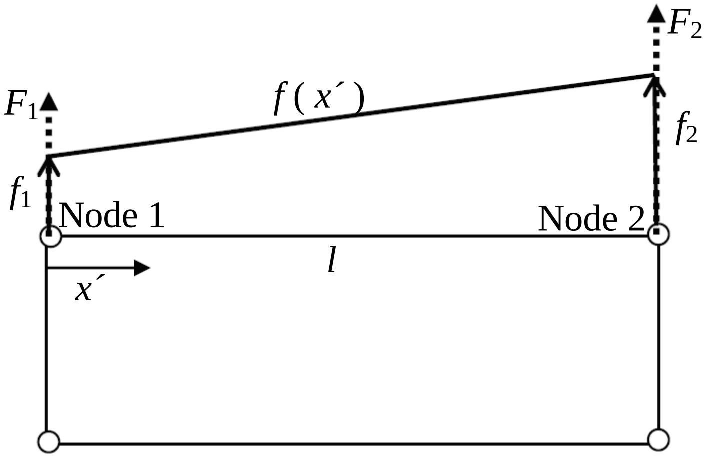


The nodal forces and moments in the local coordinate system are then converted to the distributed forces in terms of line forces and moments using the assumption that the work done by the nodal forces is equal to the work done by the distributed forces. The transfer equations for the line forces and moments are derived along the welding between to nodes on the weld periphery. The simultaneous equations for converting local forces to line forces are shown in Eq. (4).

$$\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ \bullet \\ \bullet \\ F_{n-1} \end{Bmatrix} = \begin{bmatrix} \frac{l_1+l_{n-1}}{3} & \frac{l_1}{6} & 0 & 0 & \bullet\bullet & \frac{l_{n-1}}{6} \\ \frac{l_1}{6} & \frac{l_1+l_2}{3} & \frac{l_2}{6} & 0 & \bullet\bullet & \bullet\bullet \\ 0 & \frac{l_2}{6} & \frac{l_2+l_3}{3} & \frac{l_3}{6} & \bullet\bullet & \bullet\bullet \\ \bullet\bullet & \bullet\bullet & \bullet\bullet & \bullet\bullet & \bullet\bullet & \bullet\bullet \\ \bullet\bullet & \bullet\bullet & \bullet\bullet & \bullet\bullet & \bullet\bullet & \bullet\bullet \\ \frac{l_{n-1}}{6} & 0 & 0 & 0 & \frac{l_{n-2}}{6} & \frac{l_{n-2}+l_{n-1}}{3} \end{bmatrix} \times \begin{Bmatrix} f_1 \\ f_3 \\ f_3 \\ \bullet \\ \bullet \\ f_{n-1} \end{Bmatrix} \tag{4}$$

where f_1, f_2, f_3, … f_{n-1} are the line forces at nodal point 1,2, 3, …, n-1 and F_1, F_2, F_3, …, $Fn\text{-}1$ are the nodal forces in local coordinate systems at the nodal point 1, 2, 3, …, n-1. The line forces at nodal point n is the same as the line force at nodal point 1 since the weldline along the nugget periphery is closed. The line forces and nodal forces are presented for a single element case in Fig. 6. The line moments at the nodal points can be obtained from the nodal moments in the local coordinate systems suing simultaneous equations similar to Eq. (4).

Figure 6: Definition of the line forces at the nodal element



Linear static stress is calculated suing the line forces and moments at each nodal point on the periphery of the nugget. The structural stress consists of a membrane stress component (σ_m) and a bending stress component (σ_b) at each nodal points as expressed in Eq. (5) [Dong (2001a, 2001b)].

$$\sigma = \sigma_m + \sigma_b = \frac{f_{y'}}{t} + \frac{6m_{x'}}{t^2} \tag{5}$$

where t represents sheet thickness, $f_{y'}$ is the line force in the direction of y' and $m_{x'}$ is the line moment about x' axis in a local coordinate system as shown in Fig. 5. The structural stress (σ) was shown to be constant even though the size of the finite element mesh was changed [Dong (2001a, 2001b); Dong and Hong (2002)].

The specimen geometry and dimensions with the finite element meshes are shown in Fig. 7. Eight nodal points are located along the weldline of the spot weld in the finite element models for tensile shear and coach peel specimens. The sheet thickness of the specimens was 1.5 mm and the diameter of the spot weld was considered 7.0 mm in the finite element models. One side of the specimen was constrained in all directions and the other side of the specimen was constrained in all directions except the direction of the loading that was applied at the center of the grip with RBE3 elements [MSC (2005)]. The RBE3 stands for rigid body element type 3. This element distributes the loads on the reference node to a set of nodes connected to the RBE3 element without adding extra stiffness in the model [MSC (2005)]. The sheet-2 is loaded with 25 N loads in the X, Y and Z directions while the legs of the sheet-1 are clamped at the edges. The load-time histories are shown in Fig. 8.

Figure 7: Dimensions and FEM for tensile shear and coach peel specimens

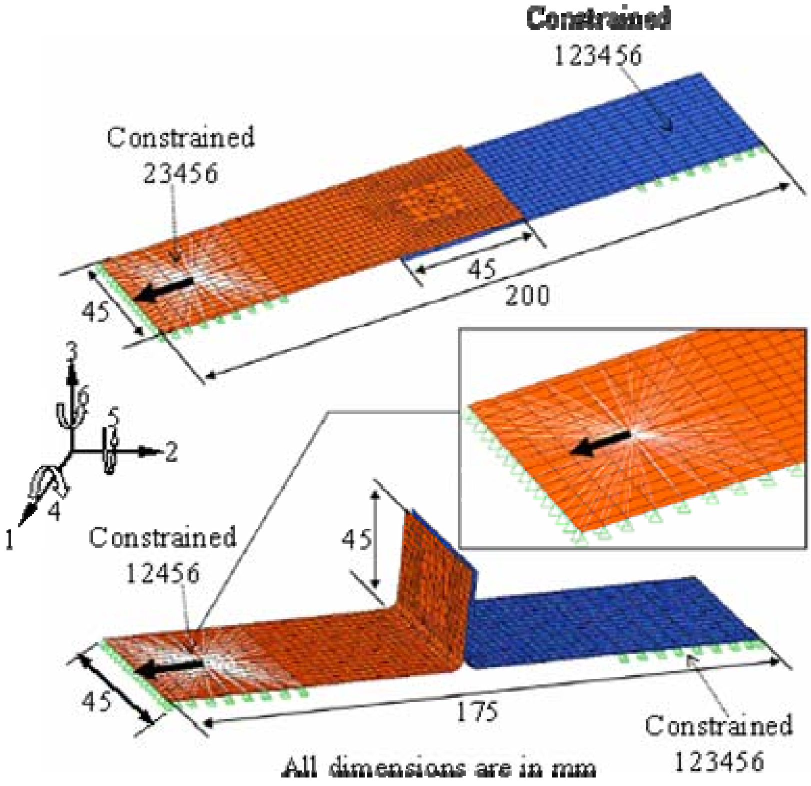
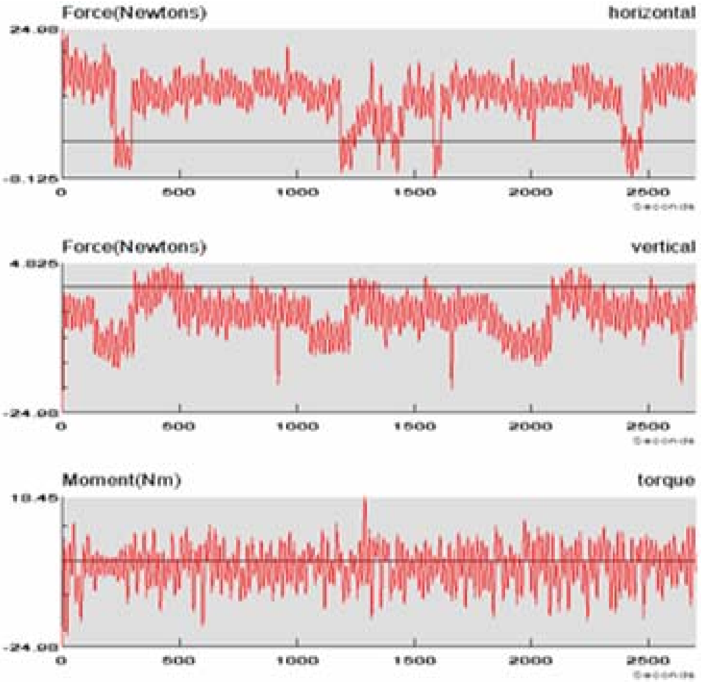


Figure 8: Load-time histories



5. Materials properties

The data on material properties required for the numerical calculations were collected after extensive search through information of literatures and handbooks. Table 1 shows the mechanical and fatigue properties of the sheets and nugget in which the young's modulus, poison's ratio and density and so on.

Table 1: Mechanical and fatigue properties of the sheets and nugget

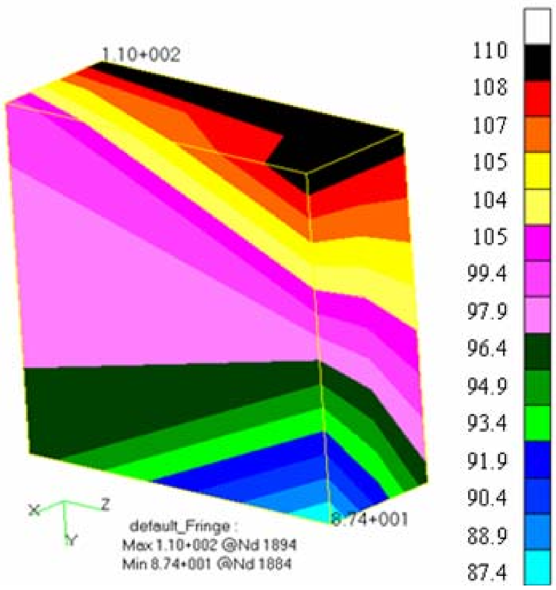
Name of Properties	Sheet-1	Sheet-2	Nugget	Unit
Modulus of elasticity	205900	205900	205900	MPa
Ultimate tensile strength	500	500	500	MPa
Poison's ratio	0.3	0.3	0.3	
Density	7850	7850	7850	Kg/m^3
Stress range intercept (SRI1)	2100	2100	2900	MPa
First fatigue strength exponent (b_1)	-0.1667	-0.1667	-0.1667	
Fatigue transition point	1×10^{-6}	1×10^{-6}	1×10^{-6}	Cycles
Second fatigue strength exponent (b_2)	-0.0909	-0.0909	-0.0909	
Mean stress sensitivity	0.1	0.1	0.1	
Standard error of Log (N)	0.334	0.334	0.330	

6. Results and Discussion

The mechanical features are important aspects of resistance spot welding process since they have great influences on the properties of the welded joint and the quality of the welded structure such as the failure strength, fatigue life and so on. In this paper, a finite element analysis was conducted to simulate the mechanical behavior of the spot weld process. A FEM was developed using the commercial software. The stress and strain distributions in the weldment and their changes during the spot weld process were determined.

The linear static analysis was performed using MSC.NASTRAN finite element software to determine the stress and strain results from the finite element model. The results of the maximum principal stresses and strains are used for the subsequent fatigue life analysis and comparisons. The maximum principal stresses distributions of the nugget are presented in Fig. 9. From the acquired results, the maximum principal stresses of 110 MPa occurring at node 1894 were obtained.

Figure 9: Maximum principal stresses distribution of the nugget



The aim of this paper was to illuminate the effect of sheet thickness on the fatigue behavior of spot welds and in particular to investigate the use of fatigue life prediction approach. In this respect, the problem was a special one due to the geometry of the spot weld contains a stress singularity. The model clearly needs to be tested against more experimental data in a variety of situations, an exercise which is beyond the scope of this paper.

Figures 10 and 11 show the effect of the sheet thickness and spot diameter on the fatigue life of the spot weld structure. Spot weld diameter of 2.5 mm to 8.5 mm and sheet thickness for 1 and 2 of 0.2 mm to 1.2 mm are considered in this study. It can be seen that from Figures 10 and 11, the spot weld diameter and the thickness of the sheet metals are influences the fatigue life of the structure. It is observed that the fatigue life of the structure increases with the increases of the spot weld diameter and thickness of the sheet.

Figure 10: Effect of spot diameter and sheet-1 thickness on the fatigue life

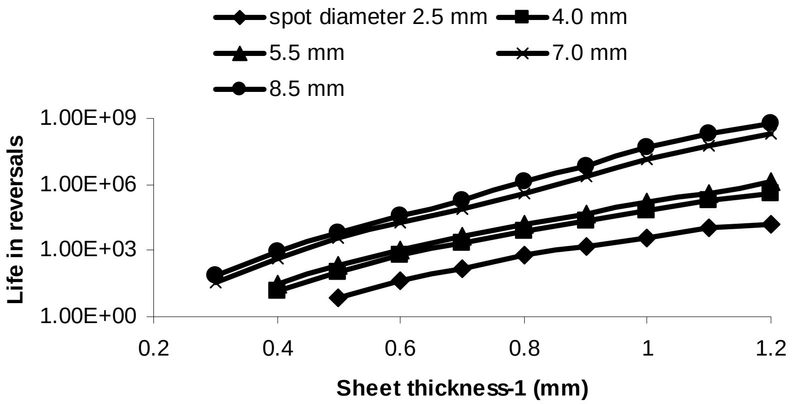
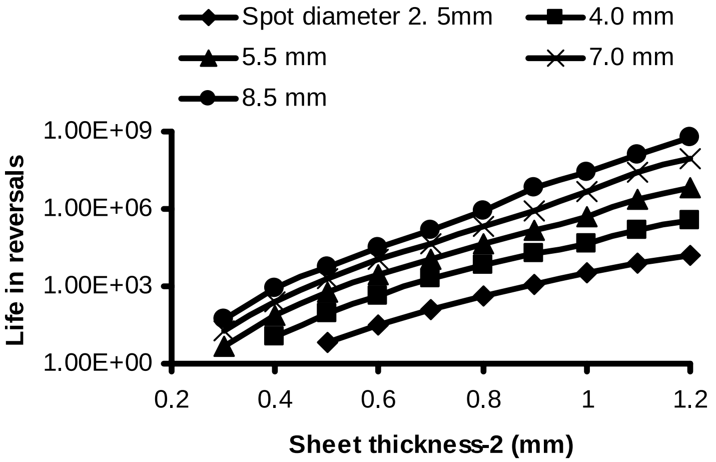


Figure 11: Effect of spot diameter and sheet-2 thickness on the fatigue life



Figures 12 and 13 show the effects of the loads and confidence of survival on the fatigue life on the spot weld structure. From the obtained results, it can be seen from Fig. 12 that the fatigue life decreases linearly with the increases of loads, however, the increases of fatigue life with increases of spot weld diameter. The obtained results from Fig. 13, it is clearly seen that the fatigue life influences on the confidence of survival parameter which is based on the standard error of the *S*-*N* curves. The prediction of the fatigue life distribution with the range of probabilities of 50 to 97.5 % is shown in Fig. 13.

Figure 12: Effects of the loads on the spot fatigue life

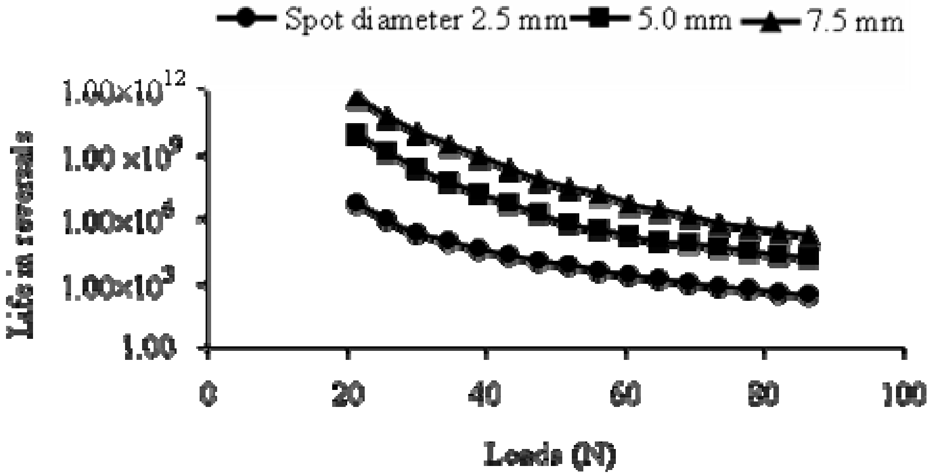
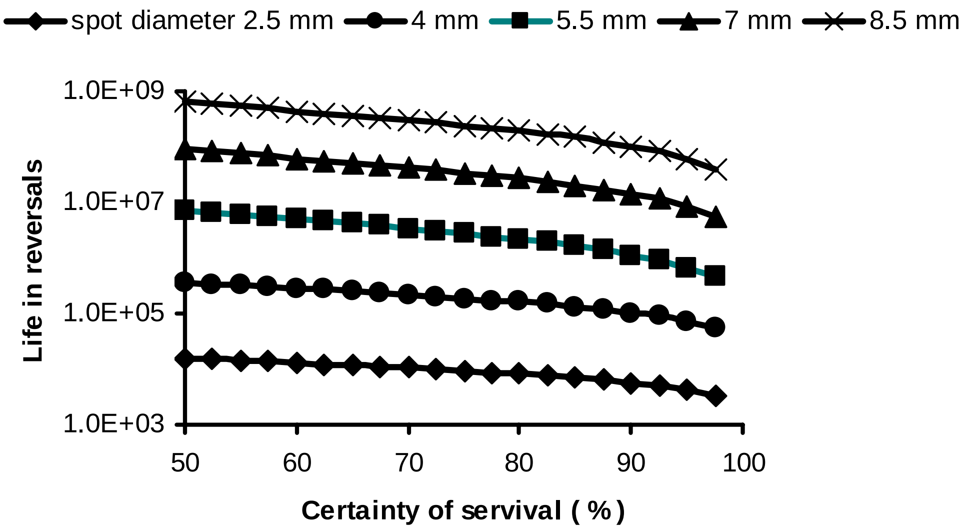


Figure 13: Effect of the confidence of survival on the fatigue life



Polar display of spot weld damage shows in Figure 14. Fig. 14 shows the damage for the nugget and the two sheets around the circumference of the spot weld showing at which angle the worst damage occurs. It is very much like a critical plane analysis display. Fig. 15 also shows the life of the spot weld at the most critical element.

Figure14: Polar display of spot weld damage at critical location (element 1884)

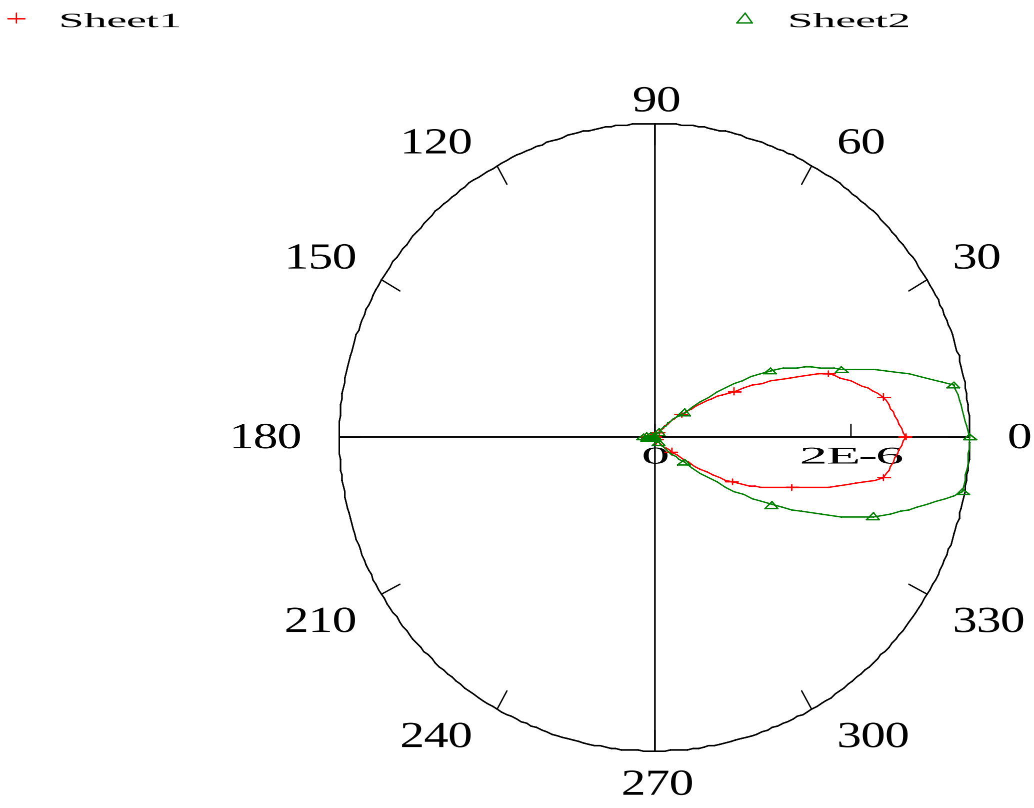


Figure 15: Polar display of spot weld life at critical location (element 1884)

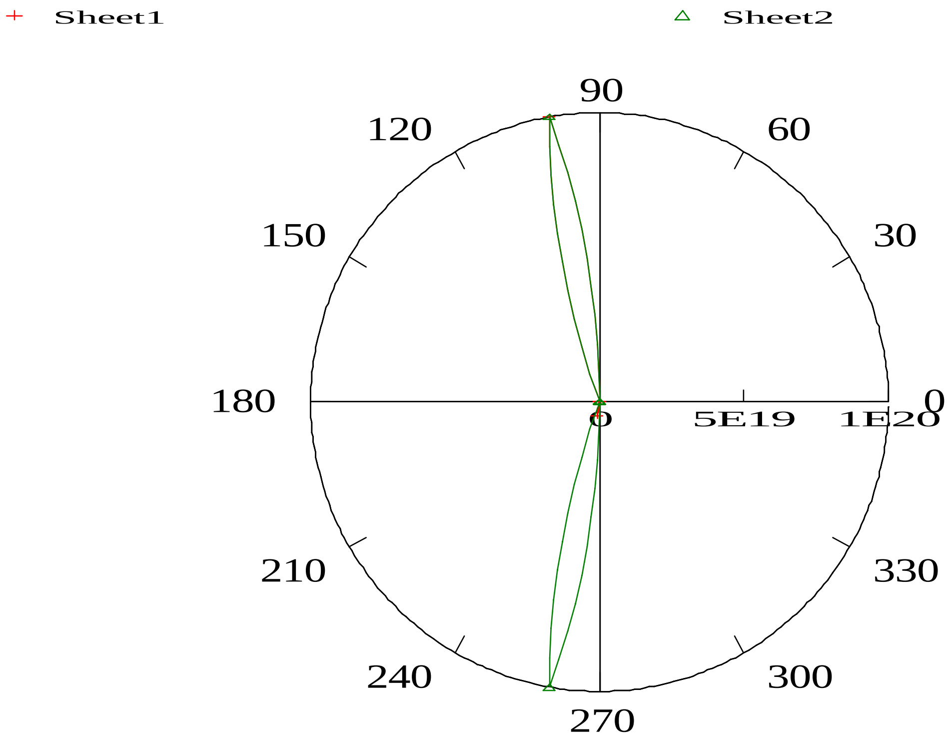
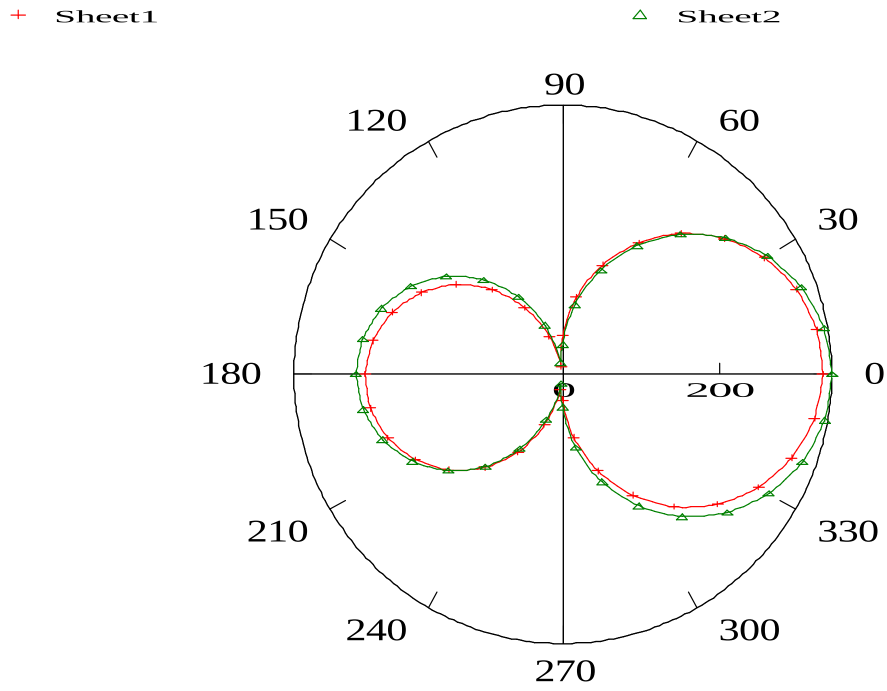


Fig. 16 shows the maximum stress ranges for the two sheets. Fig. 16 show that the sheet 2 the most stress range and thus the reason for damage appearing from the sheet-2. The stress range in the sheet-1 also contribute the less damage compare to the sheet-2 however the nugget do not cause much damage.

Figure 16: Polar display of maximum stress range at critical location (element 1884)



5. Conclusions

A numerical technique developed and has been applied to predict the fatigue life of spot welded structures. In this paper, the fatigue behavior of spot welded sheets under variable amplitude loading is presented and the prediction of the fatigue lifetime and identified the critical locations. The technique works reasonably well in predicting the fatigue life when some readily identifiable independent variables of spot welded are taken into account. The behavior of diameter of spot weld and sheet thicknesses are very important parameters in stress distribution near spot welds. It can be seen that the spot diameter and thickness of the sheets are greatly influence the fatigue life of the spot welded structures. Finally, this method could be incorporated into automated durability and strength analyses of spot welded structures subsequent to a finite element analysis. This application and related experiments will be the subject of further investigations.

Acknowledgement

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