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Numerical Study on Fatigue Life of Spot Welding using FEA

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Abstract: Spot welding is one of the primary methods to join sheet metals for automotive components. 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.

The aim of the work is to predict the life of nugget when subjected to fatigue loading. The parameters mainly considered for carrying out the analysis are sheet thickness, spot diameter and loading conditions. A simple model is used to illustrate the technique of spot-weld fatigue analysis. Finite element model and analysis are carried out utilizing the finite element analysis commercial codes. The commercial software Ansys workbench is used for performing the fatigue analysis. It can be seen from the results that spot diameter and sheet thickness greatly influence the fatigue life of the spot welded joint. Acquired results also show that the specimen fails at stress value far below the yield stress limit of the material which clearly shows the characteristic of fatigue failure. Further in this work, an economical design method is proposed to predict the fatigue life of spot welded specimen of different dimensions by defining a maximum stress equation using artificial neural networks.

Keywords : Spot welding, fatigue strength and Finite Element Analysis (FEA).

1. Introduction

Fatigue damage has long been an important aspect of designing an automotive component to perform a specific function, and it has been extensively studied. Design engineers have to accurately predict the service performance of their components. Among others, fatigue life is one of the most important properties when designing such components. The majority of structural components under actual conditions, in the customer's environment, are subjected to random amplitude service loading, during their lives. 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. The static strengths of spot welds have also been investigated. The strength of spot welds in terms of the specimen geometry, welding parameter, welding schedule, base metal strength, testing speed and testing configuration. Stress intensity factors for crack propagation through the thickness of plate are calculated numerically by utilizing finite element analysis.

A. Fatigue

Mechanical failure of structures and components is a serious concern in all types of industries. It has been estimated that between 50 to 90 % of these failures are due to fatigue. Fatigue is defined as "The process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations". Fatigue of materials involves a very complex interaction of different metallurgical, mechanical and technological factors and is still only partly understood.

The three major fatigue life methods used in design and analysis are the stress-life method, the strain-life method, and the linear-elastic fracture mechanics (LEFM) method. The numerical techniques based on the linear-elastic fracture mechanics with input data from laboratory tests is often used to establish fatigue failure criteria. In general, the fatigue process is characterized by three distinct regions. Region I is associated with the growth of cracks at low stress intensity factor ranges and is commonly believed to account for a significant proportion of the fatigue life of a component. Region II is the stable crack growth region and has been extensively studied for its technological importance. Rapid crack growth occurs in region III and this region is typically thought to account for a small fraction of the total life.

B. Fatigue analysis

Characterizing the capability of a material to survive the many cycles a component may experience during its lifetime is the aim of fatigue analysis. In a general sense, Fatigue Analysis has three main methods, Strain Life, Stress Life, and Fracture Mechanics; the first two being available within the ANSYS Fatigue Module. The Strain Life approach is widely used at present. Strain can be directly measured and has been shown to be an excellent quantity for characterizing low-cycle fatigue. Strain Life is typically concerned with crack initiation, whereas Stress Life is concerned with total life and does not distinguish between initiation and propagation. Fracture Mechanics starts with an assumed flaw of known size and determines the crack's growth as is therefore sometimes referred to as "Crack Life". Fracture Mechanics is widely used to determine inspection intervals.

1) Analysis decisions

The fatigue decisions are grouped into the types listed below:

- Fatigue Analysis Type
- Loading Type
- Mean Stress Effects
- Multiaxial Stress Correction
- Fatigue Modification Factor

Within the ANSYS fatigue module, the first decision that needs to be made in performing a fatigue analysis is which type of fatigue analysis to perform – Stress Life or Strain Life. Stress Life is based on empirical S-N curves and then modified by a variety of factors. Strain Life is based upon the Strain Life Relation Equation where the Strain Life Parameters are values for a particular material that best fit the equation to measured results. The Strain Life Relation requires a total of 6 parameters to define the strain-life material properties; four strain-life parameter properties and the two cyclic stress-strain parameters. Thus by simultaneously solving Neuber's equation along with cyclic strain equation, we can thus calculate the local stress/strains (including plastic response) given only elastic input.

Common decisions to both types of fatigue analysis

Once the decision on which type of fatigue analysis to perform, Stress Life or Strain Life, there are 4 other topics upon which your fatigue results are dependent upon. Input decisions that are common to both types of fatigue analyses are listed below:

- Loading Type
- Mean Stress Effects
- Multiaxial Stress Correction
- Fatigue Modification Factor

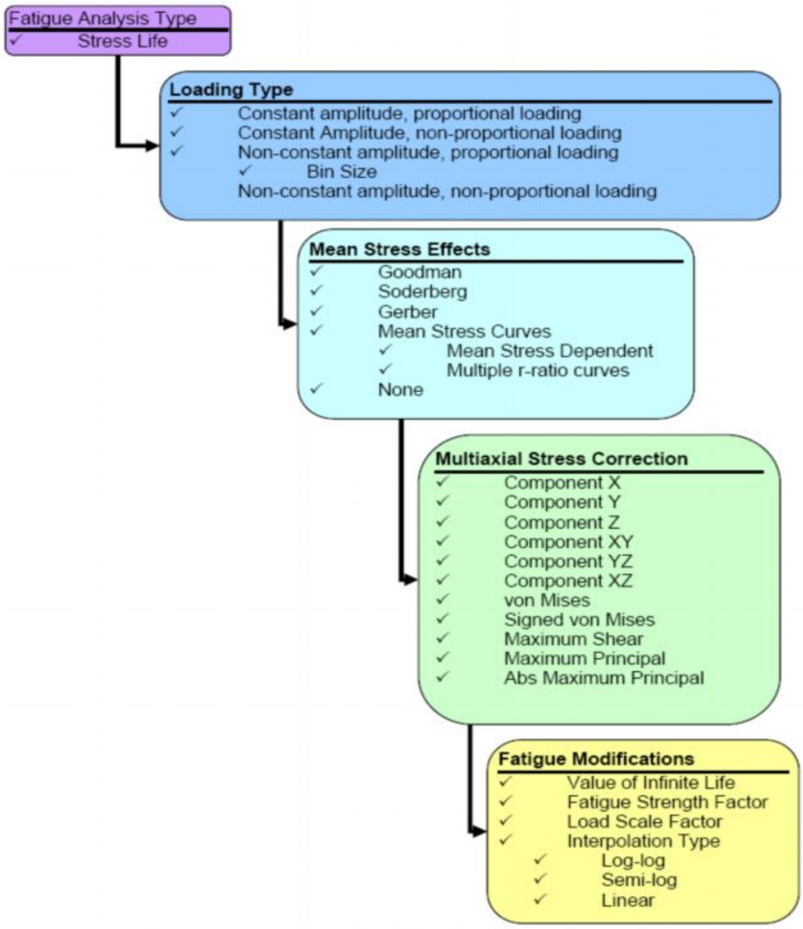


Fig 1 Fatigue Analysis Chart

2) Types of cyclic loading

Unlike static stress, which is analyzed with calculations for a single stress state, fatigue damage occurs when stress at a point changes over time. There are essentially four classes of fatigue loading, with the ANSYS Fatigue Module currently supporting the first three:

- Constant amplitude, proportional loading
- Constant amplitude, non-proportional loading
- Non-constant amplitude, proportional loading
- Non-constant amplitude, non-proportional loading

In the above descriptions, the amplitude identifier is readily understood. Is the loading a variant of a sine wave with a single load ratio or does the loading vary perhaps erratically, with the load ratio changing with time? The second identifier, proportionality, describes whether the changing load causes the principal stress axes to change. If the principal stress axes do not change, then it is proportional loading. If the principal stress axes do change, then the cycles cannot be counted simply and it is non-proportional loading.

C. Spot welding process

Spot welding is one of the primary methods to join sheet metals for automotive components. The resistance spot welding (RSW) is the most important joining method for joining sheets of metal. According to studies, about 90 % of the welds used in an automotive body assembly are RSWs. A typical vehicle contains more than 3000 spot welds. This number may reach 5000 and sometimes 8000 in couch and bus bodies. The advantages of using spot welding are that it is a quicker joining technique, no filter material is required, and that the low heat input implies less risk for altered dimensions during welding.

D. Artificial neural network

Neural computing requires a number of elementary processing units called neurons, to be connected together into a neural network. In most common networks neurons are arranged in layers with the input data fed to the network at the input layer. The data then passes through the network to the output layer to provide the solution.

2.Literature Survey

Alenius[2] have investigated Spot weldability of dissimilar metal joints between stainless steels and nonstainless steels The aim was to determine the spot welding parameters for the dissimilar metal joints and to characterize the mechanical properties of the joints. Bin Zhou[4] has presented a methodology for determining the cohesive facture parameters associated with pull-out of spot welds. Since failure of a spot weld by pull-out occurs by mixed-mode fracture of the base metal, the cohesive parameters for ductile fracture of an aluminum alloy were determined and then used to predict the failure of two very different spot-welded geometries.

Helmut Dannbauer[5] modeled has given an overview of some common methods and standards for the assessment of welding seams and spot joints including spot welds and self piercing rivets. It has been shown, how the influence of the mesh quality and the element size can be minimized. For spot welds force based concepts and stress based concepts have been presented. It has been shown, that stress based concepts usually deliver better results and can be applied for self piercing rivets too, but the effort for the local mesh refinement is very high and error prone.

Jeremy L. Lucas[6] have designed tests with the intention of addressing the highway sign problem and determining a solution as quickly as possible with the limited amount of material available for testing. It must be noted that these results are based on testing sample connections from one new sign panel. There are many variables (including weld quality and pre-torque) involved in manufacturing and erection that add to uncertainties in the quality of the signs in service and the test sign. Unfortunately, the testing procedures described did not adequately model the loading conditions found in the field because the load ranges that found “infinite fatigue” life cycles are still higher than the fatigue loads due to wind gusts in the field.

Palma E.S.[10] presented a method for design durability qualification of a vehicle body shell. Field test data were used to produce an accelerated durability test that retains the entire damaging real time load histories present in the original test cycle. Fatigue analysis methods are used to access and compare the fatigue damage imposed during durability test and laboratory (torsion) experiments.

The literature review carried out on various areas of the project in fatigue analysis and spot welded joints suggests that various tests have been carried out for lap-shear, inplane rotation; coach-peel, normal separation, and in-plane shear tests. But very limited performance data on fatigue life of spot welded joints have been reported in the open literature.

3. Methodology

A. Objective of the work

- To predict the fatigue life of spot-weld joint under imposed loading conditions.
- To examine the influence of spot welded diameter and sheet thickness on fatigue life of the spot welded joint.

B. Formulation

The following are the variables that have been varied accordingly for the analysis considered.

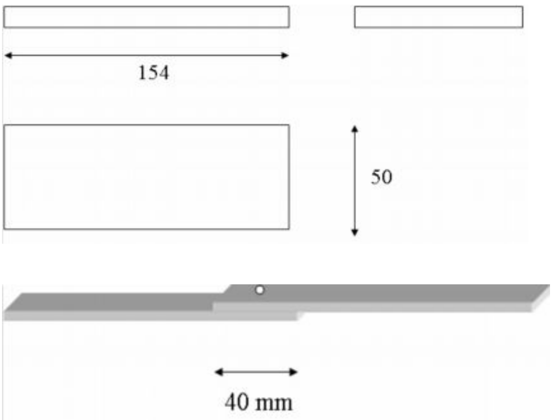
- Spot weld diameter
- Thickness of the plates
- Load values

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. A finite element analysis was conducted to simulate the mechanical behavior of the spot weld process. A detailed finite element model of a spot welded joint is required to calculate the stress states near the joint. Detailed finite element modeling of spot welds is not feasible for 3000- 5000 spot welds in a typical automotive body structure. Instead of the detailed modeling of the spot welds, a simple spot welded specimen is chosen for the fatigue analysis.

Number of spot welds = 1

Material = STEEL 4340

The arrangement of spot welded structure under investigation is shown in the Fig 2. The analysis is carried out by repeatedly loading the geometry to predefined time steps.



All dimensions are in mm

Fig 2 Plate Specification

Table I Material Properties

Property	Value
Young's modulus (E)	2×10^{11} Pa
Density (ρ)	7850 kg/m^3
Poisson's Ratio	0.3
Tensile strength	744.6×10^6 Pa
Yield strength	472.3×10^6 Pa

Table III S-N Table

Cycles	Alternating Stress Pa
1000	5.1×10^8
2000	4.40×10^8
10000	2.68×10^8
20000	2.14×10^8
100000	1.38×10^8
200000	1.14×10^8
1000000	8.62×10^7
2000000	7.892×10^7
10000000	5.22×10^7
20000000	4.92×10^7

4. Analysis

A. Steps in Analysis Procedure

The following are the important steps involved in problem solving, which are as follows:

Step 1: Building the model

Pro-E wildfire platform is utilized to build the model of plate with the following dimensions.

Length of the plate	=	154 mm
Width of the plate	=	50 mm
Lapped length	=	40 mm

Step 2: Assembly

The next step is the assemble of the plates in the assembly module of Pro-E wildfire. The bottom plate is imported in to the assembly window and kept as default reference. Then the top plate is imported at the same compass location and assembled.

Step 3: Creation of spot weld

1. Enter Assembly mode and retrieve the assembly.
2. Click Applications > Welding. The WELDING menu appears.
3. Set up the welding environment.
4. Choose Spot from the WELD ROUTE menu.
5. A dialog box appears, listing elements of the weld feature that need to be defined.

Spot Refs - Specify geometric references for the weld.
Penetration - Specify the penetration depth.
Measurements - Create measurements used to control welding parameters

6. Locate the weld by referencing datum points. Create or select datum points for locating the weld using options in the SELECT POINT menu. Choose Create and create datum points, or Select and pick existing datum points.
7. When finished specifying reference points, choose done from the FEATURE REFS menu.
8. Enter the penetration distance.
9. To conclude feature creation, choose OK from the dialog box.

Step 4 : Meshing the model

In this section we have to tell Ansys, how to divide the model assembly such that it has enough nodes, to make an accurate enough analysis.

Number of elements	=	33500
Number of nodes	=	171801
Element type	=	Solid Element – Mid sized nodes

Step 5: Performing Fatigue analysis

The fatigue analysis procedure is based on stress life method. Stress Life is concerned with total life and does not distinguish between initiation and propagation.

Boundary Condition:

Now we have modeled the plate and in order to define Ansys, how to analyze the plate assembly, we need to apply the appropriate boundary conditions. The model is considered to be one single beam of cantilever type. i.e. At one end all the displacement degrees of freedom are arrested and load is applied at the opposite end in vertical direction. Two load cases are applied to the free end of the specimen:

a) +ve N at each corner. The time at the end of the load step is 10 seconds.

b) –ve N at each corner. The time at the end of the load step is 20 seconds. Loading type is of constant amplitude.

Step 6: Artificial neural network in MATLAB

The initial parameters comprising of input values and target values are to be taught to the artificial neural network in the learning cycles. The network error is reduced by doing further iterations. Then the validation of the values is to be made. Now the input value is to be given to get the required output value. Comparison between the results obtained by both artificial neural network and finite element method is to be carried out to show the integrity of artificial neural network.

5. Result and Discussions

The finite element analysis is conducted to simulate the life of spot welded joints when subjected to fatigue loading. A finite element model is generated using the commercial software. The stress distributions in the weldment and their changes during the loading condition are determined.

The fatigue analysis is performed using Ansys workbench to determine stress and strain results of the finite element model. The results of the maximum principal stresses are used for subsequent fatigue life analysis. The stress distribution of the spot welded specimen is presented in Fig 3.

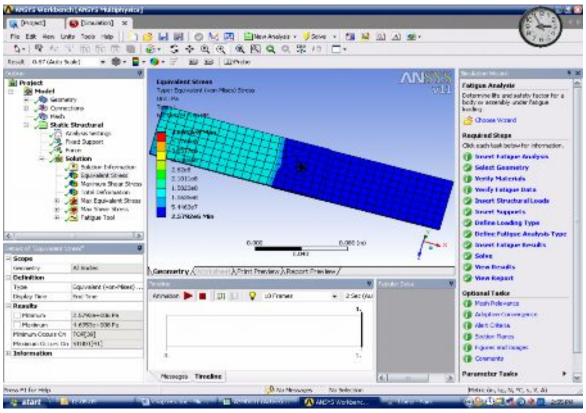


Fig 3. Von-Mises Stress value

In fig 4, the maximum stress around the nugget is 469.53 MPa , which is well below the tensile strength of the material.

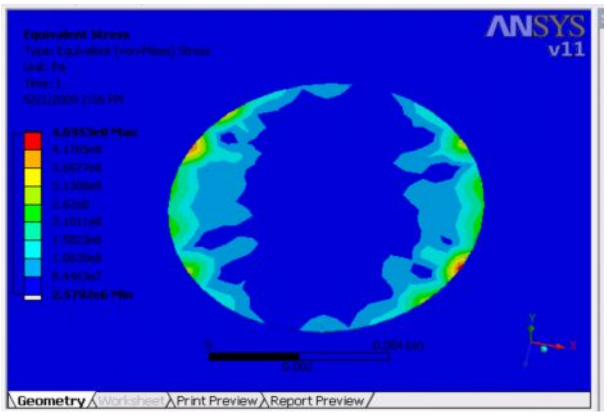


Fig 4. Stress value around the nugget

A. For spot diameter of 2.5 mm with varying sheet thickness

Analysis is carried out on the specimen for a spot diameter of 2.5 mm with varying sheet thickness. Maximum stress and fatigue life values for a spot diameter of 2.5 mm with a sheet thickness of 3 mm are shown in Table III.

Table IIII Case 1 (Sheet Thickness of 3 MM)

Load (N)	Maximum stress (MPa)	No. of cycles to failure
35	86.2	1.00E+06
40	91.8	8.00E+05
50	102.5	2.60E+05
70	110.6	8.10E+04
100	268.2	1.00E+04

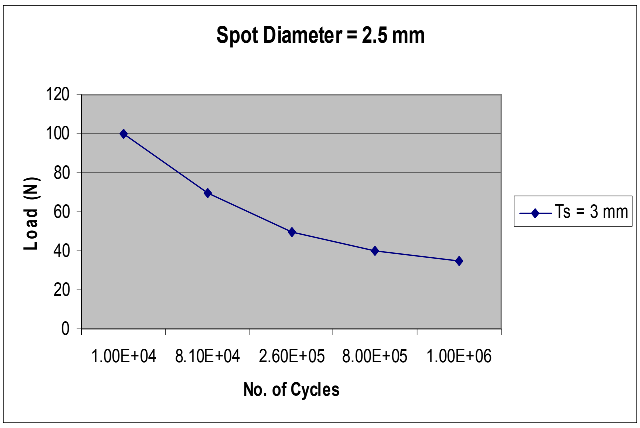


Fig 5. Case 1 (Sheet thickness of 3 mm)

Maximum stress and fatigue life values for a spot diameter of 2.5mm with a sheet thickness of 2mm is shown in Table IV.

Table IVV Case 2 (Sheet Thickness Of 2 MM)

Load (N)	Maximum stress (MPa)	No. of cycles to failure (N_f)
35	95.76	5.00E+05
40	114.5	2.00E+05
50	176.2	8.00E+04
70	241.2	1.50E+04
100	469.53	2.00E+03

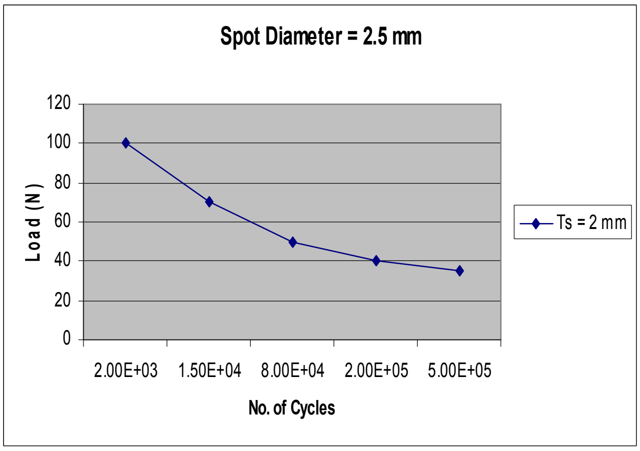


Fig 6. Case 2 (Sheet thickness of 2 mm)

Maximum stress and fatigue life values for a spot diameter of 2.5 mm with a sheet thickness of 1.5 mm is shown in Table V.

Table V Case 1 (Sheet Thickness of 1.5 MM)

Load (N)	Maximum stress(MPa)	No. of cycles to failure
35	138.5	1.00E+05
40	157.1	8.50E+04
50	214.9	2.00E+04
70	311.17	7.50E+03
100	510.4	1.00E+03

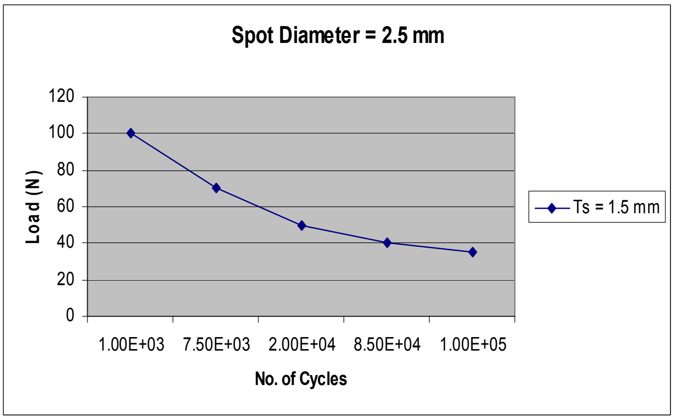


Fig 7. Case 3 (Sheet thickness of 1.5 mm)

B. For spot diameter of 5 mm with varying sheet thickness

Analysis is carried out on the specimen for a spot diameter of 5 mm with varying sheet thickness. Maximum stress and fatigue life values for a spot diameter of 5 mm with a sheet thickness of 3 mm are shown in Table VI.

Table VI Case 1 (Sheet Thickness of 3 MM)

Load (N)	Maximum stress (MPa)	No. of cycles to failure (N_f)
35	58.8	9.00E+06
40	65.56	5.00E+06
50	82.81	1.50E+06
70	99.74	5.00E+05
100	169.5	7.60E+04

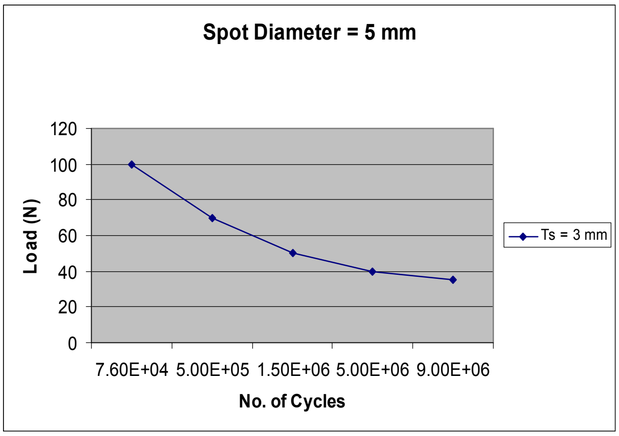


Fig 8. Case 1 (Sheet thickness of 3 mm)

Maximum stress and fatigue life values for a spot diameter of 5mm with a sheet thickness of 2mm is shown in Table VII.

Table VII Case 2 (Sheet Thickness of 2 MM)

Load (N)	Maximum stress (MPa)	No. of cycles to failure (N_f)
35	78.92	2.00E+06
40	97.5	9.00E+05
50	101.2	3.00E+05
70	180.69	8.00E+04
100	241.75	1.50E+04

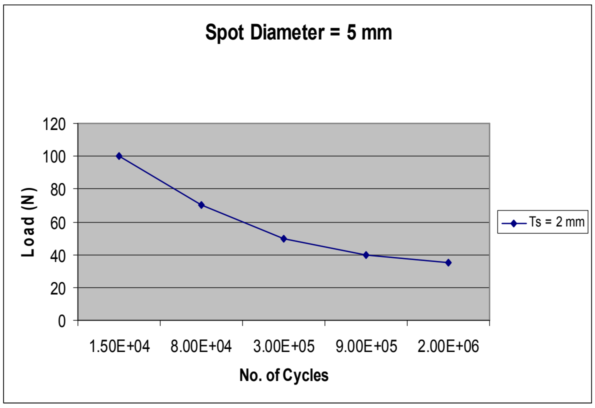


Fig 9. Case 2 (Sheet thickness of 2 mm)

Maximum stress and fatigue life values for a spot diameter of 5mm with a sheet thickness of 1.5mm is shown in Table VIII.

Table VIII Case 2 (Sheet Thickness of 1.5 MM)

Load (N)	Maximum stress(MPa)	No. of cycles to failure(N_f)
35	100.01	7.50E+05
40	101.9	3.00E+05
50	150.2	9.00E+04
70	214.9	2.00E+04
100	380.4	5.00E+03

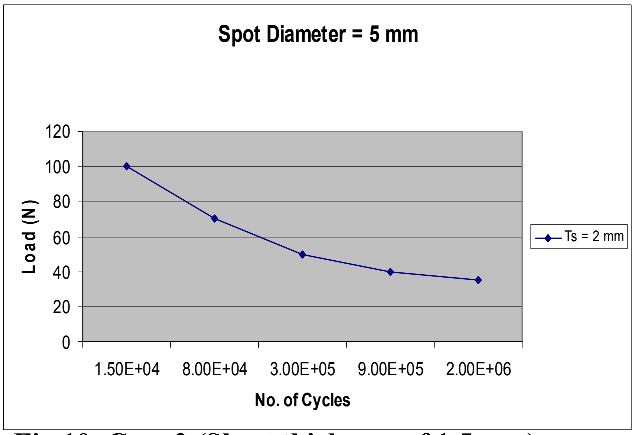


Fig 10. Case 2 (Sheet thickness of 1.5 mm)

C. Effect of sheet thickness

The number of cycles to failure is plotted against sheet thickness for spot diameter values of 2.5 mm and 5 mm.

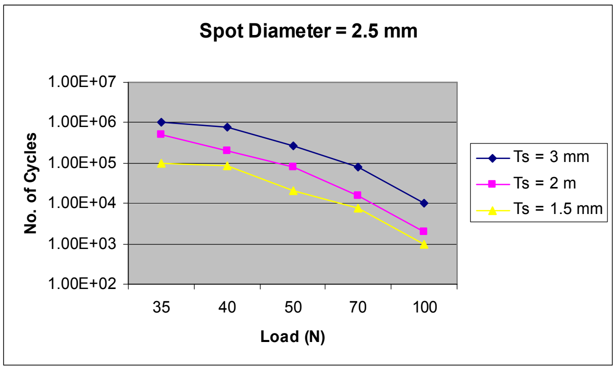


Fig 11. Effect of sheet thickness for spot diameter of 2.5 mm

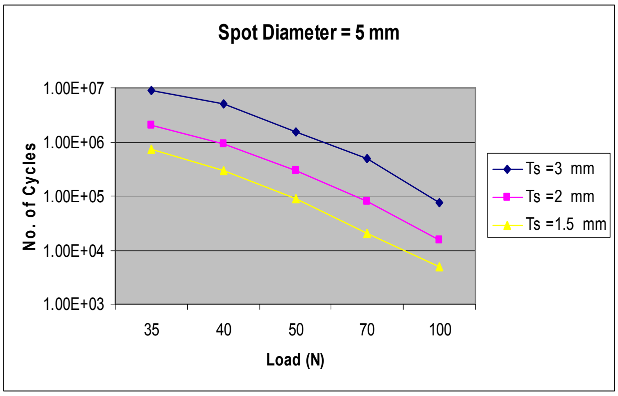


Fig 12. Effect of sheet thickness for spot diameter of 5 mm

210.9854 115.7196 254.135 239.1085 292.6479 254.1564 128.9149
Columns 8 through 14
25.187 105.941 88.4635 141.649 124.187 88.459 141.9864
Columns 15 through 21
124.7080 160.8890 150.7491 364.5842 358.1692 112.9044 175.2982
Column 2264.1378

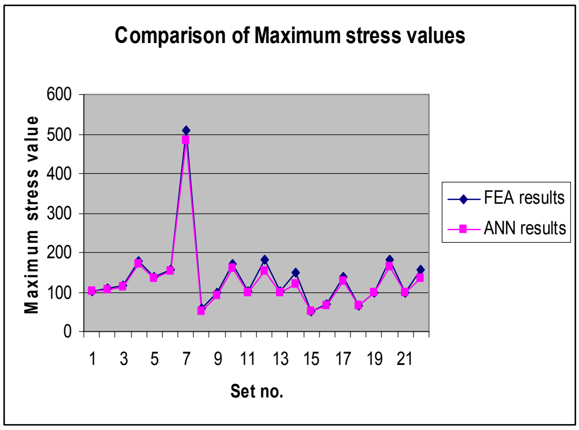


Fig 13. Comparison of Maximum stress values from FEA and ANN results

6. Conclusion

The finite element analysis is conducted to simulate the life of spot welded joints when subjected to fatigue loading. A numerical study to predict the fatigue life of spot-weld joint under imposed loading conditions is presented. The work has been carried out to observe the effect of sheet thickness spot diameter on the fatigue life of spot welded joints and it is seen that fatigue life of the specimen increases with the increase in spot diameter and sheet thickness. But the model clearly needs to be tested against more set of data of different dimensions and more importantly need to be tested experimentally in a variety of situations, so that the ansys results can be validated.

Conclusion can be summarized as follows,

a. By using the maximum stress equation, the fatigue design criteria of spot-welded lap joints of optional dimensions can be predicted without any additional fatigue tests.
b. It is expected that the new fatigue design method proposed in this work can provide design flexibility to the designer as well as a considerable saving of time and money by reducing the additional fatigue tests.

Further the work can be carried out to examine the fatigue life spot welded joint having dissimilar metal sheets and sheets of different thickness.

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