Kumar et al. 2018. *Int. J. Vehicle Structures & Systems*, 10(4), 287-290
ISSN: 0975-3060 (Print), 0975-3540 (Online)
doi: 10.4273/ijvss.10.4.12

International Journal of
Vehicle Structures & Systems
Available online at www.maftree.org/eja

Numerical Study on Stress Distribution in Ultrasonically Welded Electrical Contacts used in Automotives

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ABSTRACT:

Numerical stress analysis while joining an electrical contact comprising of copper wire and copper sheet using ultrasonic metal welding process is vital in many of the automotive applications. During ultrasonic metal welding, shear and normal force act at the interface between the welded specimens. These forces are the result of ultrasonic vibrations transmitted by Sonotrode onto the welded specimens. In this work, the distribution of the stress developed at the interface and the correlation of the developed stress with strength of joint are studied. The theoretical stress values are determined using various levels of ultrasonic metal welding process parameters such as clamping force, vibration amplitude and weld time to validate the results of stress obtained from finite element analysis. The results of stress from numerical analysis are found to be in good agreement with that of results obtained from the theoretical calculations.

KEYWORDS:

Ultrasonic metal welding; Finite element method; Stress distribution; Vibration; Plastic deformation

CITATION:

J.P. Kumar, M.S.A. Kumar, N.G. Devi, M.N. Kumar and S.M.P. Raja. 2018. Numerical Study on Stress Distribution in Ultrasonically Welded Electrical Contacts used in Automotive, *Int. J. Vehicle Structures & Systems*, 10(4), 287-290. doi:10.4273/ijvss.10.4.12.

1. Introduction

Ultrasonic metal welding is a solid state joining process in which the electrical energy is converted into heat energy by using a piezoelectric transducer which produces high frequency ultrasonic vibrations. In this process, the high frequency vibration is combined with pressure to join two similar or dissimilar materials. Elangovan et al [1] developed a finite element model for ultrasonic metal welding of copper sheets and observed that the temperature increases with weld time and decreases with the increase in thickness of sheet and clamping force. Ding et al [2] focused on the effects of bonding parameters on temperature rise by varying bond pad sizes and bond forces. Yong Ding et al [3] discussed on importance of wire bonding parameters such as bond force and power and presented the effects of these parameters on contact pressure along the wire bond pad interface. Elangovan et al [4] identified the statistically significant process parameters affecting the welding strength using analysis of variance and optimized the process parameters using Taguchi's design of experiments. Edgar de Vries [5] developed an analytical model for characterizing the temperature generation during welding and its effects on strength of the joint. The model is also used to calculate interface forces during welding.

Soundararajan et al [6] developed a finite thermo-mechanical model to predict the stress developed at the interface of the specimens in friction stir welding. The stress developed at the interface of the specimen is determined by considering uniform contact conductance. Zheng et al [7] developed 3D modelling and simulation using finite element method to simulate welding process and also developed numerical modelling of ultrasonic impact treatment to determine the weld residual stress distribution of butt and T-weld joint. It is found that the predicted residual stress using finite element model is in good agreement with that of the experimental residual stress. From the literature survey, it is evident that the major problem in ultrasonic metal welding process is to control the strength of the joint and part sticking with the tip of the Sonotrode. The process parameters such as clamping force, vibration amplitude and weld time affects the strength of the joint. During welding, the various levels of these parameters develop stress at the interface which directly affects the quality and strength of the joint. Hence, the prediction of stress value before welding process at the interface is essential. Therefore, an attempt is made determine the correlation of stress developed at the interface developed due to the combined effect of these combinations and process parameters on the strength of the joint.

2. Experimental details

The experiments are carried out using a conventional ultrasonic metal welding machine (2.5 kW, 20 kHz) as shown in Fig.1. In this study, the portion of weld specimens held between the anvil and the tip of the Sonotrode are considered for development of finite element model. The CAD model depicting the joint is shown in Fig. 2. The dimensions of copper sheet, copper wire, anvil and tip used in this work are given in Table 1. The ultrasonic metal welding experiments are conducted with various levels of parameters (lower, medium and higher) such as clamping force, vibration amplitude and weld time to weld an electrical contact comprising of copper wire and copper sheet as shown in Table 2. The output response quality characteristics considered in this study are stress developed at the interface and strength of the joint in tension.

Fig. 1: Ultrasonic metal welding machine

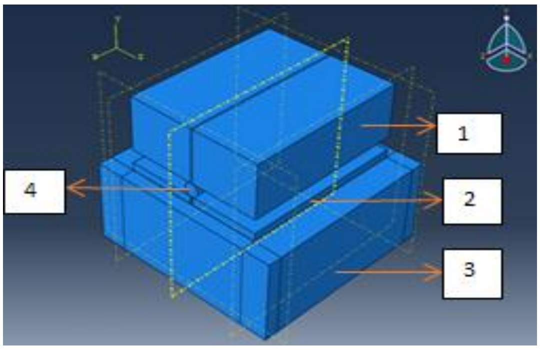

Fig. 2: CAD model; 1. Tip of Sonotrode, 2. Copper sheet, 3. Anvil, 4. Copper wire

Table 1: Dimensions of parts

Part name	Length (mm)	Width (mm)	Thickness (mm)	Diameter (mm)	Material
Wire	6	-	-	0.9	Copper
Sheet	6	5	0.03	-	Copper
Anvil	7	7	3	-	Steel
Tip	6	5	2	-	Steel

Table 2: Combination of process parameters

Process parameter	Level		
	Low	Medium	High
Clamping force (N)	795	995	1195
Vibration amplitude (µm)	30	42.5	57
Weld time (sec)	2	2.5	3

3. Materials and methods

The properties of copper wire & sheet and steel anvil & tip considered in this study are given in Table 4. During ultrasonic metal welding, the stress is developed at the interface due to the clamping force and vibration provided by the tip of the Sonotrode. These stresses are calculated theoretically by using,

$$b=K_b\sqrt{F} \quad (1)$$

$$K_b=\sqrt{\left(\frac{2}{\pi\times l}\right)\left(\frac{\frac{(1-\gamma_1)2}{E_1}+\left(\frac{(1-\gamma_2)2}{E_2}\right)}{(1/d_1)+(1/d_2)}\right)} \quad (2)$$

$$P_{max}=\left(\frac{2}{\pi}\right)\left(\frac{F}{b\times L}\right) \quad (3)$$

Where b is the half width, K_b is the constant, F is the normal force applied, γ_1 and γ_2 are the Poisson's ratio of the materials, E_1 and E_2 are the Young's modulus of the materials, d_1 and d_2 are the diameter of the component to be welded and P_{max} is the maximum contact pressure. For a sheet, the diameter is considered to be infinity and L is the length to be welded. The calculation of stress for the lower level combination of process parameters (clamping force of 795N, vibration amplitude of 30µm and weld time 2 seconds) is shown below.

$$b=\sqrt{\left(\frac{2}{\pi\times 6}\right)\left(\frac{\frac{(1\text{-}0.3)2}{117000}+\left(\frac{(1\text{-}0.3)2}{11700}\right)}{(1/0.45)+(0)}\right)}\times\sqrt{795}=0.033mm$$

$$P_{max}=\left(\frac{2}{\pi}\right)\left(\frac{795}{0.033\times 6}\right)=2556.12\text{MPa}$$

Similarly, the stresses for medium and higher levels of process parameter combination are calculated as 2853.31MPa and 3092.5MPa respectively.

Table 4: Material properties of copper and steel

Material	Young's modulus (MPa)	Poisson ratio	Density (kg/mm^3)
Steel	200000	0.3	7950e-9
Copper	117000	0.3	8900e-9

4. Finite element analysis

The stress developed at the interface is determined using ABAQUS 6.12 finite element analysis (FEA) software. The finite element model developed in this study is shown in the Fig. 3. The element used for meshing the model is C3D8R (Eight-node brick element with reduced integration). The number of elements used for meshing the model is shown in the Table 3. The number of elements is selected based on the sensitivity analysis so that it eliminates the uncertainty in the results.

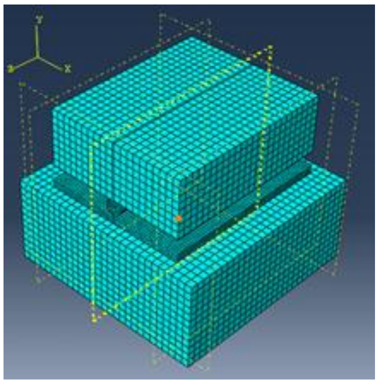

Fig. 3: FEM model

Table 3: Details of elements count

Instance name	Element count	Element type
Sheet	48550	C3D8R
Wire	51960	C3D8R

The following are the assumptions made to simulate the distribution of stress at the interface using FEA:

- The upper portion of the wire is made flat to a width which is equal to hertz contact half width.

- There is no air gap between the wire and the sheet during welding.
- The deformation on the tip is negligible.

5. Results and discussions

The simulations are carried out using lower, medium and higher levels of combination of process parameters to estimate the stress developed at the interface. The results for this combination of process parameters are shown in the Figs. 4-6 respectively. Based on the FEA, it is observed that the strength of the joint significantly depends on stress developed at the interface. During welding, the upper part of the specimen (wire) is pressed and rubbed against the lower specimen (sheet). The simultaneous pressing and rubbing of the specimens due to clamping force and vibration amplitude for a particular amount of weld time initiate the welding action, resulting in formation of micro welds at the interface. These micro welds further propagate due to temperature developed at the interface and plastic deformation of the weld specimens. Owing to these facts, the stress developed at the interface can be used as an indicator for evaluation of formation of joint and prediction of strength of the joint in tension.

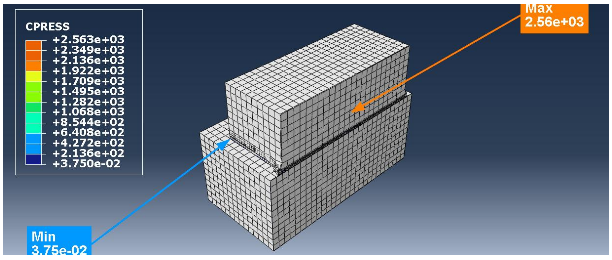

Fig. 4: FEA result for lower level combination of parameters

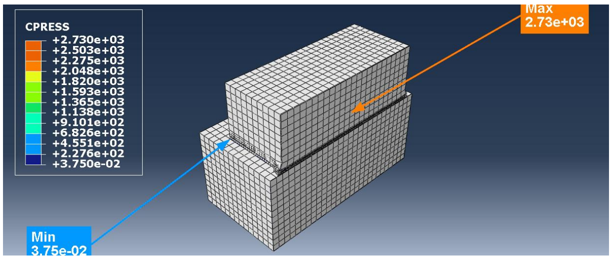

Fig. 5: FEA result for medium level combination of parameters

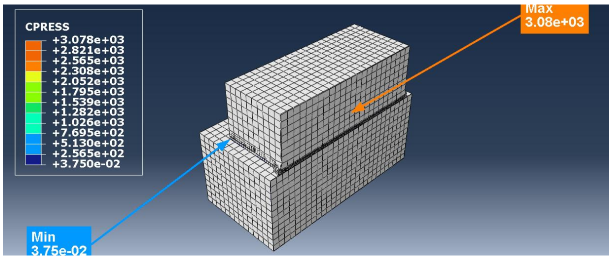

Fig. 6: FEA result for higher level combination of parameters

The results obtained from simulation and theoretical calculation is compared in Table 5. The stress increases with increase in levels of process parameters. When the lower level of parameters is used the stress and strength of the joint is found to be minimum when compared with medium and higher level process parameters. There is no phenomenal increase in strength of the joint obtained using higher level parameters when compared with strength obtained using medium level of parameters. On the contrary, the stress developed at the interface using higher level of process parameters is larger than the stress developed at the interface using medium level parameters. Even though the stress is higher, the increase in joint strength is of a lesser extent. The strength of the joint reduces due to the severe deformation of wire and penetration of the wire into the sheet. Identification and usage of optimum combination of process parameters is crucial for achieving significant strength of the joint. The medium level of process parameters (995N, 42.5µm and 2.5 seconds) can be used to achieve required strength of the joint without severe deformation of the welded specimens.

Table 5: Stress results - FEA vs. Theoretical calculations

Parameter	Level		
	Low	Medium	High
Stress from simulation (MPa)	2563	2730	3078
Stress from theoretical calculation (MPa)	2556.12	2853.31	3092.5
Strength of the joint (N)	192.62	229.31	233.87

6. Conclusions

In this work, the distribution of the stress developed at the ultrasonic weld interface of copper wire and copper sheet and the correlation of the developed stress with strength of joint are studied using FEA. The stress values are observed to increase with increase in various levels of process parameters such as the clamping force, vibration amplitude and weld time. The stress values obtained from simulation are in close agreement with the stress values obtained using theoretical calculation. Therefore, the developed finite element model is capable to predict the stress developed at the interface while joining an electrical contact comprising of copper wire and copper sheet using ultrasonic metal welding.

There is no phenomenal increase in strength of the joint at higher levels of process parameters due to severe plastic deformation of the wire. Though the strength of the joint obtained using higher level of process parameters (1195N, 57µm and 3 seconds) is more than the strength obtained using lower level and medium level, the welded specimens are subjected to severe deformation which can result in inefficient performance of the electrical contact over a period of time. The strength of the joint obtained using medium level of process parameters (995N, 42.5µm, and 2.5 seconds) is found to be meet out the industrial requirements (greater than 200N) and the quality of the joint (without part deformation) is found to be superior than the joint obtained using other levels of process parameters.

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