Development and Analysis of Ultrasonic Welding Process Using FEM Approach for Aluminum and Copper

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Abstract

Ultrasonic welding is a process that uses mechanical vibrations using ultrasonic frequencies. The vibrations are produced by an ultrasonic sonotrode, which is used for joining two thin materials, especially in electronic industries (for applications in battery-making industries). Typically, ultrasonic welding is based on the parameters (frequency range, input pressure/load of the sonotrode, by varying the coefficient of friction between two metal sheets, the thickness of a sheet) while performing the joining process. In this work, the FEA Model-based study is used for analyzing the ultrasonic welding using "Von-Misses stress theory concepts". The effects of various thickness of the sheet, normal force, coefficient of friction (at different welding conditions) are analyzed while performing the welding process. The temperature variation is studied while using aluminum and copper as thin sheets. This study can be used in the electronic industries for high power ultrasonic welding process, especially using aluminum and copper materials in the form of electrodes, sheets.

Keywords: *Ultrasonic welding, finite element method (FEM), ultrasonic sonotrode, temperature dependent yield strength, Von Mises stress theory.*

Nomenclature

ρ =Density (kg m−3)

c=Specific heat capacity (J/(kg°C))

k=Thermal conductivity (W/(m°C))

Q=Volumetric heat generations rate (Wm−3)

Q_w= Deformation heat flux (W/mm^2)

Q_f= Friction heat flux (W/ mm^2)

T=Temperature (°C)

F_w=Welding force (N)

F_N=Clamping force(N)

A_{dz}=Area of deformation zone (mm^2)

A_w=Area of weld (mm^2)

A_f =Area of friction (mm^2)

A_{TS} =Area of top part sonotrode (mm^2)

P=Power (W)

V_{avg} = Average sonotrode velocity (m/s)

ξ=Amplitude (m)

f=Frequency(Hz)

μ=Coefficient of friction

F_f=Frictional force (N)

τ=Shear stress (N/mm^2)

1. Introduction

Ultrasonic welding is an emerging welding technology in friction-based solid-state welding technology. It's having various advantages over friction steer welding. It has a less heat-affected zone, less welding time, good metallurgical properties and requires less power than other welding techniques. In ultrasonic welding, vibrations are transmitted to the top sheet by the sonotrode. Hence, the top sheet is undergoing plastic deformation. During welding, joining is takes place at the interface between two sheets. Daniels et al. [1] carried out the primary study of ultrasonic welding and they concluded that good weld is depend upon welding parameter, dimension of workpiece, welding time, clamping force and material properties. De Vries [2] described the basic mechanism of ultrasonic welding techniques. He shows that, the mathematical equation of heat generation using maximum shear stress theory.

The same author found that the temperature of welding was varying 40-80% of melting temperature based on welding parameters. Jeng and Horng et al. [3] studied the effect of welding time, applied load, surface roughness, and welding power on the bonding strength of wire and pad welding using ultrasonic bonding machine. They found that the bonding strength is mainly depending on contact temperature in the initial period and surface roughness in the final period of welding. Maximum bond strength is formed in the initial period. Ding et al. [4] had done the stress and deformation analysis of wire and bond pad during ultrasonic wire bonding process by using 3D and 2D FEA model. They were found that the frictional energy is mainly concentrated at the periphery of contact interface, where the weld is made. Hazlett and Ambekar et al. [5] carried out the primary analysis on bonding mechanism and interface temperature in USMW. The welding of different materials e.g., brass, stainless steel, copper, aluminium under various welding parameters were studied.S. Elangovan et al. [6] was performed the analysis of temperature and stresses variation using 2D FEA model in ultrasonic welding by using different parameters. They were used the maximum shear stress theory. Huan Li et. al. [7] studied the ultrasonic softening effect using the 3D FEA model. They define well boundary conditions (heat transfer coefficient). S.Li, J.Yang et .al [8] did the review on aluminium and copper ultrasonic welding. They found that more research is required in high power ultrasonic welding and high thickness welding. Most researchers were reported the analysis of welding process using maximum shear stress theory. Hence, we would like to analysis this welding process by introducing the Von-Mises stress theory instead of maximum shear stress theory. Our main objective is the comparative study between these two theories, while using aluminium-aluminium and aluminium-copper sheet combinations in the welding process.

2. Finite Element Model (FEM)

The thermal 2D model is studied in this work using FEM approach. The governing equation of heat transfer for axisymmetric geometry is considered [9].

$$\rho \times c \times \frac{\partial T}{\partial t} = k \times (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) + Q \qquad (1)$$

Following assumptions are considered in this FEM based study

1) To be considered the perfect contact between the top and bottom sheet without air gap

2) Uniform circular cress section of sonotrode is used

3) The area of weld A_w, the area of sontrode A_s and area of deformation zone A_{dz} are same ($A_w = A_s = A_{dz}$) at the end of welding process.

4) The room temperature is assumed to be 25°C.

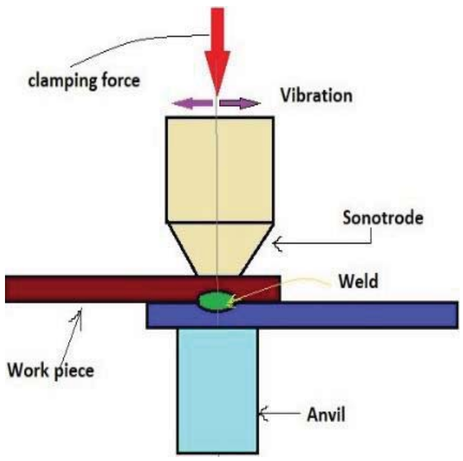


FIG 1. Ultrasonic welding.

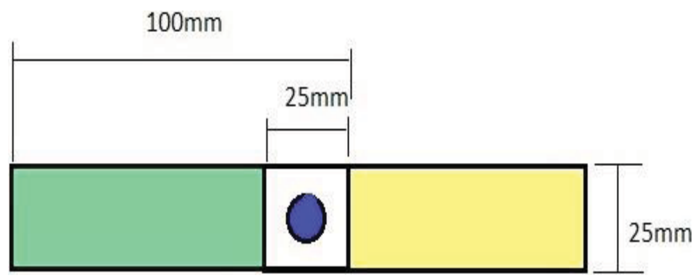


FIG 2. Standard specimen.

The following material properties are considered for studying the welding process.

Table 1. Material properties of anvil, sonotrode, top and bottom sheets [6]

Material	Thermal conductivity W/(m°C)	Specific heat J/(kg°C)	Density (kg/m^3) J/(kg °C)	Youngs modulus (GPa)	Poisson's ratio	Thermal expansion 1/°C
Steel (anvil and sonotrode)	24.3	460	7800	210	0.3	1.51×10^{-5}
Aluminum	183	896	2700	70	0.35	2.43×10^{-5}
Copper	393	385.2	8900	117	0.3	1.66×10^{-5}

2.1 *Heat generation*

The required amount of heat is generated in the welding process, because of material's plastic deformation and the friction effects between the two welding sheets. The sonotrode contact region (along the area of cross section) of sheet (top sheet) undergoes plastic deformation simultaneously bottom sheet bonded/joined with top sheet.

The surrounding region (at the interface between two sheets) of the weld is also subjected in to friction effect due to the ultrasonic vibration. In this FEM studies, our interest is to analysis the temperature variations, clamping force, coefficient of friction and thickness of sheets at the welding region of interest.

The following equation (Eqn.12) is derived for finding the required amount of heat energy due to plastic deformation. The appropriate parameters are taken from early reported papers [2], while deriving this equation. Also, the Eqn. 19 has been used [2,6] for finding heat energy due to friction between two sheets. These energies are given as the input energy in the ultrasonic welding model.

The power dissipate over weld area (deformation) is given by

$$P_d = Q_w \times A_w \quad (2)$$

$$Q_w = \frac{F_w \times V_{avg}}{A_w} \quad (3)$$

The stress equation is considered from De Vries [2]

$$|\sigma_1 - \sigma_2| = 2 \times \sqrt{\left(\frac{F_N}{2 \times A_{dz}}\right)^2 + \tau^2} \quad (4)$$

$$|\sigma_2 - \sigma_3| = \left(\frac{F_N}{2 \times A_{dz}}\right) - \sqrt{\left(\frac{F_N}{2 \times A_{dz}}\right)^2 + \tau^2} \quad (5)$$

$$|\sigma_3 - \sigma_1| = -\left(\frac{F_N}{2 \times A_{dz}}\right) - \sqrt{\left(\frac{F_N}{2 \times A_{dz}}\right)^2 + \tau^2} \quad (6)$$

By Von-Mises stress theory

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2 \times (S_{yt})^2 \quad (7)$$

By deriving the equation, we get

$$\tau = \sqrt{\frac{S_{yt}{}^2 - \left(\frac{F_N}{A_{dz}}\right)^2}{3}} \quad (8)$$

Temperature dependant yield strength $S_{yt} = Y$

Welding force is given by

$$F_w = \sqrt{\frac{Y^2 - \left(\frac{F_N}{A_{dz}}\right)^2}{3}} \times A_{dz} \quad (9)$$

Average sonotrode velocity (V_{avg}) $= 4 \times \xi \times f$ (10)

Deformation heat flux

$$Q_w = \frac{\sqrt{\frac{Y^2 - \left(\frac{F_N}{A_{dz}}\right)^2}{3}} \times A_{dz} \times 4 \times \xi \times f}{A_w} \quad (11)$$

$$\mathrm{Q_w} = \sqrt{\frac{Y^2-\left(\frac{F_N}{\mathrm{A_{dz}}}\right)^2}{3}} \times 4 \times \xi \times f \text{ , where } (\mathrm{A_{dz}} = \mathrm{A_w}) \tag{12}$$

Temperature dependent yield strength is calculated by experimentally by De Vries [2].

Average temperature dependent yield strength

$$\mathrm{Y}=\frac{\int_0^{750}(-0.649T+326.5)\times 10^6 dT}{\Delta T} = 83.125\times 10^6 \text{ N/m}^2 \tag{13}$$

For clamping force 1600 N, area of deformation $\mathrm{A_{dz}} = 20 \times 10^{-6}\mathrm{m}^2$
Frequency f =20× 10^3 Hz
Amplitude ξ =13× 10^{-6} m

$$\mathrm{Q_w} = \sqrt{\frac{(83.125\times 10^6)^2-\left(\frac{1600}{20\times 10^{-6}}\right)^2}{3}} \times 4 \times 13 \times 10^{-6} \times 20 \times 10^3 = 13.5557\times 10^6 \text{ W/m}^2 \tag{14}$$

$$=13.5557 \text{ W/mm}^2$$

Fractional area is twice than radius of deformation zone. Frictional area is given as

$$\mathrm{A_f} = \mathrm{A_{TS}} - \mathrm{A_w} \tag{15}$$

Power dissipates due to friction (P_f)=$\mathrm{Q_f} \times \mathrm{A_f}$ (16)

$$\mathrm{Q_f} = \frac{F_f \times V_{avg}}{\mathrm{A_f}} \tag{17}$$

Frictional force $(F_f) = \mu \times F_N$ (18)

From Equation 10

$$\mathrm{Q_f} = \frac{\mu \times F_N \times 4 \times \xi \times f}{\mathrm{A_f}} \tag{19}$$

$$= \frac{0.3\times 1600\times 4\times 13\times 10^{-6}\times 20\times 10^3}{60\times 10^{-6}} = 8.32\times 10^6 \text{ W/m}^2 = 8.32 \text{ W/mm}^2$$

2.2 Mesh generation

2D axisymmetric model is considered for the analysis as the geometry is symmetric about a vertical axis [6]. 2D 8 Node quadrilateral (plane77) element, 2D 4 node quadrilateral (plane 55) element are chosen for thermal anlysis.2D 3 Node contact (contact 172) element for surface contact and for target segment (target 169) is used. The time step is 0.1 sec and total welding time is 0.5sec.

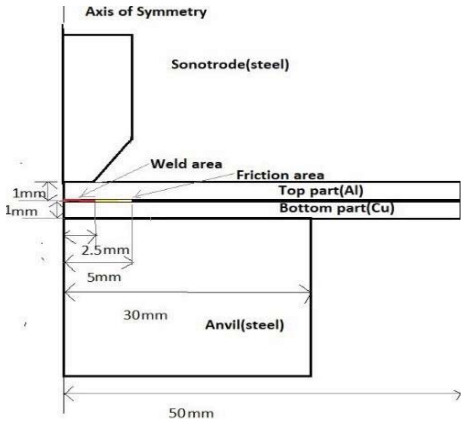


FIG 3. Axisymmetric model.

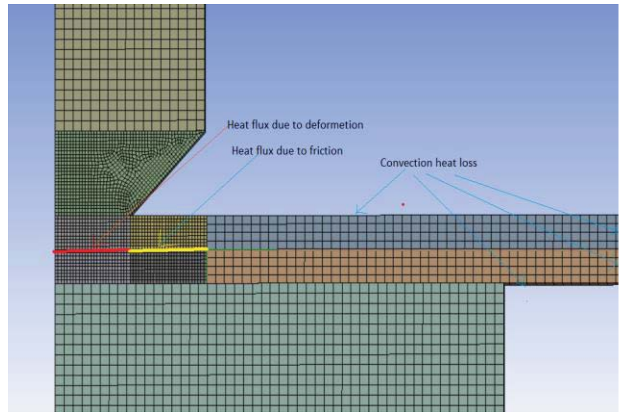


FIG 4. FEA Model.

2.3 *Boundary condition*

The heat transfer coefficient is taken 15w/(m°C) for surfaces expose to air [8]. Deformation heat flux is input to the area under sonotrode at two sheet interface (20 mm^2) and friction heat flux is outer to deformation area (60 mm^2) as shown in the figure 3.

3. Results and discussion

3.1 *Comparative analysis of maximum shear stress theory and Von Mises stress theory*.

3.1.1 *Thickness Analysis*

Thickness analysis is carried out by taking the clamping force 1600 N,the coefficient of friction is 0.3.

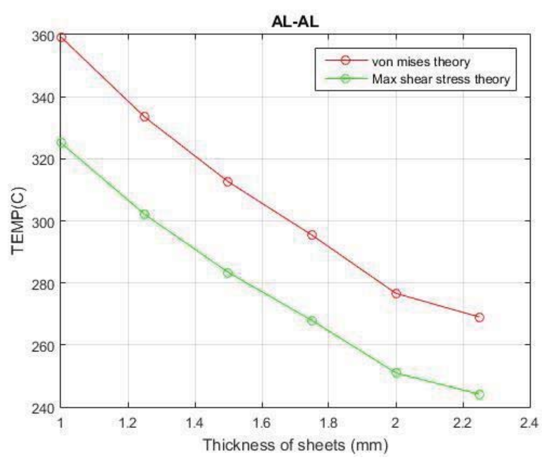


FIG 5. Thickness vs temprature for Al-Al pair.

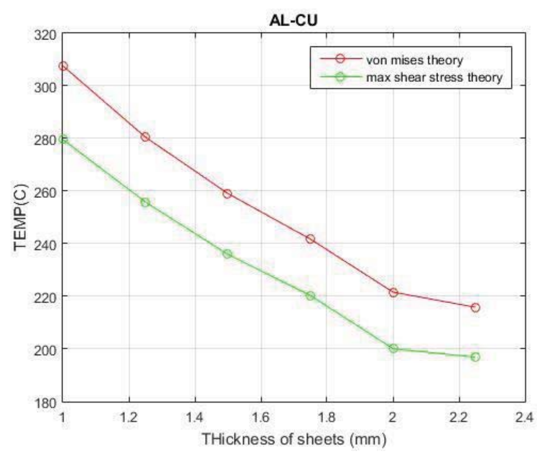


FIG 6 Thickness vs temprature for Al-Cu pair.

Figure 5. shows that the change in temperature at various thicknesses (from 1mm to 2.3 mm) of sheets (with Aluminium-Aluminium pair), while performing the welding process.

The heat energy was evaluated according to Von Mises stress theory, later that was given as input for this welding process. Simillarly, the heat energy was given to the the same idenical model using Maximum Shear Strss theory [6]. Hence, the maximum temperature 359 °C (at 1mm thickness) is generated in the welding region, in which heat energy supplied that was obtained by using Eqn. 12 "Von Mises stress theory". But, wleded portion was reached 325 ^{o}C when the input heat energy was supplied based on maximum shear stress theory concept.

The similar welding process and theories were followed to perform the welding process at aluminium-copper combination of sheets at different thicknesses. Finally, the more amount of heat is generated using Von-Misses theory (307.65^{o}C) based input heat energy as compared to Max-shear stress theory (279.63^{o}C) as shown in Figure 6.

3.1.2 Clamping force

The effect of clamping forces is analysed while considering 1mm thickness of sheets (Al-Al pair and Al-Cu pair) and coefficient of friction is 0.3.

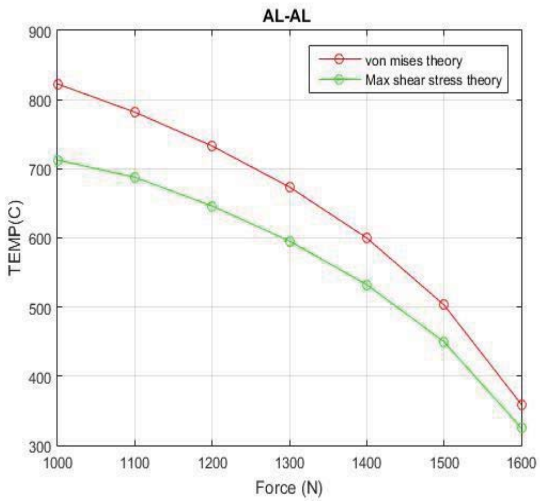


FIG 7. Force vs temprature for Al-Al pair.

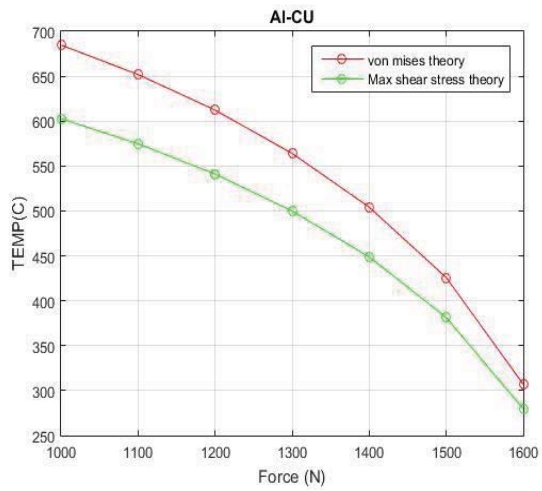


FIG 8. Force vs temprature for Al-Cu pair.

Figure 7 shows the variation of temperature with various clamping forces for Aluminium-Aluminium pair, at 1600 N clamping force maximum temperature is 359 ^{o}C according to Von Mises stress theory.and 325 ^{o}C for maximum shear stress theory. Figure 8 shows for Aluminum-Copper pair, at 1600N clamping force the maximum temperature generates is 307.65 ^{o}C by using Von Mises stress theory and 279 ^{o}C is according to maximum shear stress theory.

As the clamping force is increases than the heat generate due to deformation is reduce and frictional heat is increases, the overall heat is reduced. Increase in the clamping force, welding may be taking place at low heat also, but high clamping force is increasing the yielding and stress in material instead of welding.

3.2 *Aluminum and copper welding*

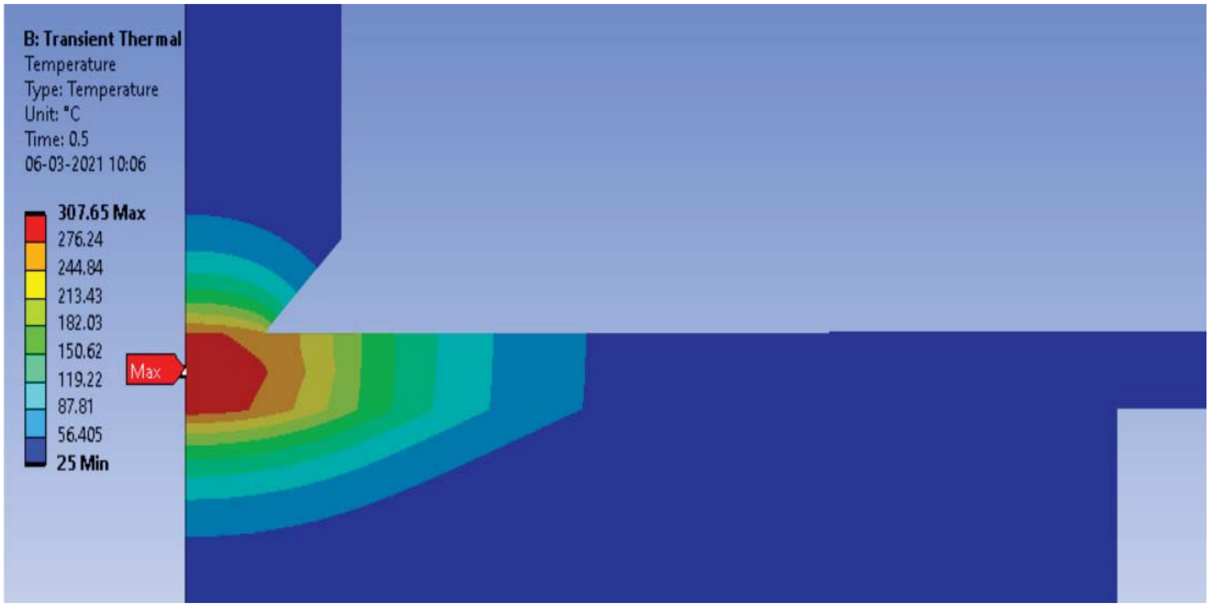


FIG 9. Temperature distribution Al-Cu welding.

Figure 9 shows that the heat affected zone at welding portion. Thermal conductivity of copper material is higher than the aluminum, so the temperature variation in copper sheet is less than aluminum sheet in the welding zone.

3.2.1 *Temperature variation along the interface of sheets*

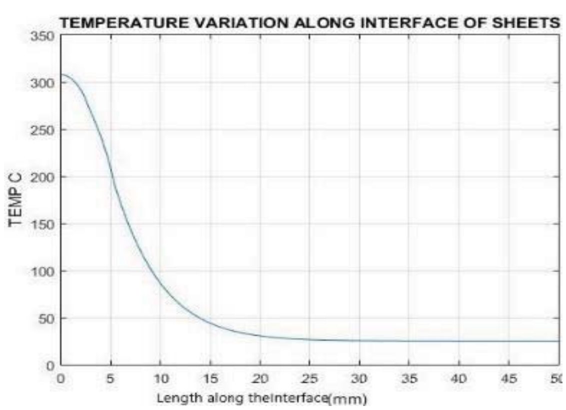
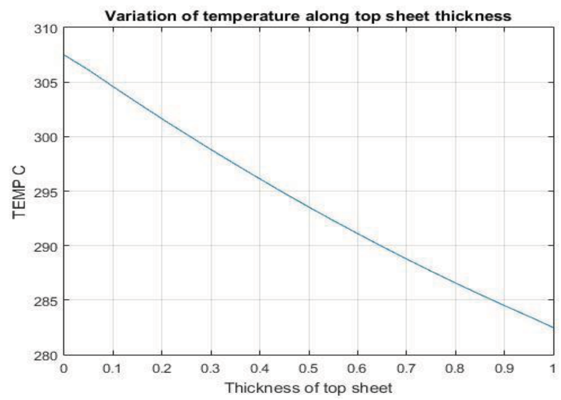


FIG 10. Temperature variation along the interface.

Figure 10 shows the variation of temperature at the interface between two welding sheets in the x-direction. The high heat affected zone was observed up to 15 mm length. After that length (from 15 mm to 30 mm length) the temperature variation of welding sheets is vary less and close to ambient temperature.

3.2.2 Temperature variation along the top sheet thickness and bottom sheet thickness



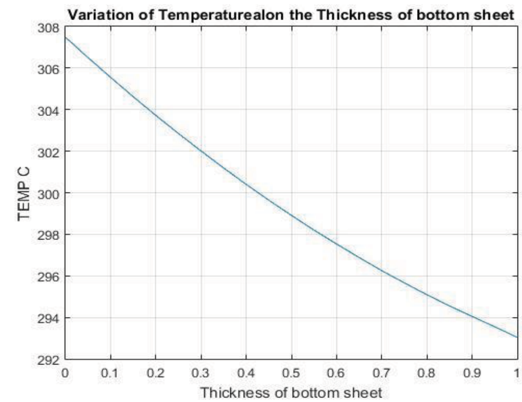


FIG 11. Top sheet thickness vs temperature. **FIG 12**. Bottom sheet thickness vs temperature.

Figures 11 and 12 show that the temperature variations along the thickness of aluminum and thickness of copper sheets respectively, while performing the welding processes at Al-Cu pair. For the top sheet (Aluminum) the maximum temperature is 307.65^{o}C and the minimum temperature is 282.48^{o}C, the difference is 25.17^{o}C. While the bottom sheet (Copper) the maximum temperature is 307.65^{o}C and minimum temperature is 293.03^{o}C, the difference is 14.62^{o}C.

3.2.4 *Maximum temperature with different COF*

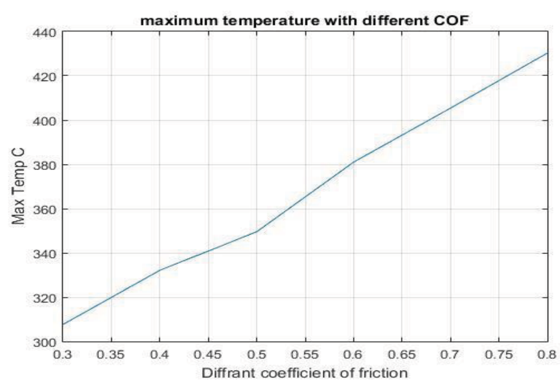


FIG 13. Temperature variation with different coefficient of friction.

Figure 13 shows that maximum temperature is increase with the increase in the coefficient of friction. The coefficient of friction is depending upon the condition of surfaces (roughness, contamination) of frictional surfaces and welding condition.

4. Conclusion

Ultrasonic welding is studied and analyzed with the help of FEA approach using Von-Mises stress theory. The effect of clamping force, thickness of sheets and coefficient of friction are analyzed with respect to welding temperature using Al-Al and Al-Cu pair sheets.

The maximum interface temperatures were observed in both cases for validating this theory. Based on this parameter, the Von-Mises stress theory is predicted more temperature than maximum shear stress theory in the same identical model. It's observed that, thickness variation shows that for welding of high thickness sheet could be required the high power and vibration. The developed concept needs to be verified in practical welding conditions in future.

REFERENCES

[1] Daniels, H.P.C., Ultrasonic welding. J. Ultrason., 190–196 ,(1965)

[2] De Vries, Mechanics and Mechanism of Ultrasonic Metal Welding, Dissertation, The Ohio State University.(2004)

[3] Jeng, Y.R., Horng, J.H, A micro contact approach for ultrasonic wire bonding in microelectronics. Journal *of* Tribology. 123, 725–731.(2001)

[4] Ding, Y., Kim, J., Tong, P., Numerical analysis of ultrasonic wire bonding: effects of bonding parameters on contact pressure and frictional energy. Mechanics of Materials. Elsevier. 38, 11–24.(2006)

[5] Hazlett, T.H., Ambekar, S.M., Additional studies on interface temperatures and bonding mechanisms of ultrasonic welds. Weld. Research. Supplement. 49, 196–200.(1970)

[6] S. Elangovan, S. Semeer, K. Prakasan,' Temperature and stress distribution in ultrasonic metal welding-An FEA-based study, Department of Production Engineering, PSG College of Technology, Coimbatore 641004, India. journal of materials processing technology 2 0 9 (2 0 0 9) 1143–1150.(2009)

[7] Huan Li1 & Biao Cao1 & Jian Liu1 & Jingwei Yang1.Modeling of high-power ultrasonic welding of Cu/Al joint. The International Journal of Advanced Manufacturing Technology.(2018)https://doi.org/10.1007/s00170-018-2002-1

[8] S. Li, J. J. Yang et.al, Ultrasonic spot welding of aluminium to copper: a review. The International Journal of Advanced Manufacturing Technology.(2020) https://doi.org/10.1007/s00170-020-04997-5

[9] Ding Y, Kim J-K. Numerical analysis of ultrasonic wire bonding: part 2. Effects of bonding parameters on temperature rise. Microelectron Reliability. Elsevier 48(1):149–157. (2008) https://doi.org/10.1016/j.microrel.2007.01.083