Thermal-mechanical analysis of ultrasonic spot welding considering acoustic softening effect

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Abstract

A three dimensional coupled thermo-mechanical finite element model was established to simulate the process of ultrasonic spot welding of Cu to Al plates. Heat generation from both friction work of contact surfaces and material plastic deformation was considered in detail. The model did not only incorporate the material thermal softening effect but also acoustic softening effect, which can be deduced from experimental phenomena. The significant influence of acoustic softening effect was demonstrated by two comparison models (considering or not). Obtained results, including structural deformation and heat generation were compared between the two models.

1. Introduction

Ultrasonic spot welding is a rapid joining process during which high frequency ultrasonic energy is used to produce a solid-state bond between two pieces of metal under a clamping pressure. It is generally recognized that ultrasonic spot welding is a solid-state welding process [1]. Extensive plastic deformation is found in the bond zone and makes great contribution to the bond forming [2, 3]. Kong et al. [4] and Janaki et al. [5] both analyzed the cross section of bonded specimens. In their work, the weld density and bond strength was found to be linearly dependent on the plastic deformation area.

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In the process of ultrasonic welding, the specimens are under the effect of ultrasonic energy transferred from sonotrode. Thus acoustic softening of metals is closely related to plastic deformation and plays important role for bond strength. Acoustic (ultrasonic) softening is the reduction in the material plastic (yield) stress under intense ultrasonic energy. Langenecker [6] performed tension tests to study the influence of ultrasonic energy on the mechanical behavior of aluminum and zinc metals. Material yield stress was found to decrease significantly upon the application of ultrasonic energy. The acoustic material softening effect under the ultrasonic vibration of sonotrode will make it easier to get plastic deformation and then help to develop high-strength joint.

The transient nature of ultrasonic spot welding makes it difficult to obtain the real-time data from experimental measurements, so as to find out the effect of acoustic material softening on mechanical behavior and heat generation. The finite element method can overcome these obstacles to some extent and has been employed in recent years. The work by Siddiq and Ghassemieh [7] took the materials’ thermal and acoustic softening effects during ultrasonic welding process into consideration in detail. They adopted the material property of combined isotropic-kinematic hardening model. Zhang and Li [8] constructed a coupled dynamic thermal-mechanical ultrasonic welding finite element model of aluminum foils on aluminum substrate and correlated von Mises plastic strain with the bonded area of ultrasonic joints. Gregory [9] proposed a 2-D FE model to quantify the amount of thermal and acoustic softening by correlating modelling results with experimentally measured temperatures. De Vries [10] and Elangovan et al. [11] analytically computed the heat generated by frictional work and plastic deformation separately. The presented finite element model took the calculated heat as boundary conditions and was capable of predicting the interface temperature and stress distribution.

The acoustic material softening affects both mechanical behavior of metals and heat generation during the ultrasonic welding process. Simulations ignoring the acoustic softening may be inaccurate and result in errors. In order to find out the effect of acoustic softening, especially on the heat generation composition (friction work and material plastic deformation work), two comparison models (considering acoustic softening effect or not) are proposed.

2. Finite element analysis model

2.1. Material model

The Johnson-Cook material model can represents the high strain rate hardening effects and thermal softening effect of metals [12]. The static yield stress, $\sigma^0$, is assumed to be of the following form

$$\sigma^0 = [A + B(\epsilon^p)^n][1 + C\ln(1 + \dot{\epsilon})](1 - \theta^m), \quad (1)$$

where $\epsilon^p$ is the equivalent plastic strain and $A$, $B$, $n$ and $m$ are the material parameters measured at or below the transition temperature, $\theta_{\text{transition}}$. $\dot{\epsilon}$ is the non-dimensional temperature. The Johnson-Cook properties of Al and Cu are found out experimentally by Gupta et al [13] and Johnson [14].

In recent years, the ultrasonic plasticity framework based on the crystal plasticity theory has been developed to describe the acoustic softening effect [15-18]. Acoustic material softening can be incorporated by introducing a phenomenological softening term ($\xi_{\text{ultrasonic}}$) dependent upon the ultrasonic energy density as follows

$$\sigma^0 = \xi_{\text{ultrasonic}}[A + B(\epsilon^p)^n][1 + C\ln(1 + \dot{\epsilon})](1 - \theta^m), \quad (2)$$

in which $\xi_{\text{ultrasonic}} = (1 - d_{\text{ultrasonic}})^e$, $d_{\text{ultrasonic}}$ and $e_{\text{ultrasonic}}$ are acoustic softening parameters that must be defined from experiments. $I_{\text{ultrasonic}}$ is the ultrasonic energy density per unit.

2.2. Finite element model

In order to find out the effect of acoustic softening on the welding process, two separate finite element models have been built up and analysed with different material properties, one incorporating the acoustic softening effect and the other not. The two welding plates (Cu and Al plates) are stacked in sequence with a dimension of 19 mm ×
19 mm by the thickness of 0.2 mm between the sonotrode and anvil. The sonotrode is 7mm×5mm in length and width. The ultrasonic welding process is modelled as a coupled mechanical-thermal case. The mesh is dense at the central contact region of the workpieces to reduce hourglassing effect as depicted in Fig. 1. The boundary condition for anvil is fixed in all six free degrees. The sonotrode gets into contact with the upper plate under applied load in the first step and then vibrates in ultrasonic frequency in the second step. Initial temperature of 20 °C has been prescribed to the entire model. All the surfaces exposed to air have been set under free convection with a convective heat transfer coefficient of 5 W/m²°C and ambient temperature of 20 °C.

3. Analysis of mechanical and thermal results

3.1. Thermal analysis

The heat generation due to friction work at the contact interface and material plastic deformation is plotted in Fig. 2. It can be seen from both models that although the heat generated by plastic deformation is much smaller than that by frictional work (nearly accounting for half of the latter one), it cannot be ignored. The heat generated by friction work in the two models does not show much difference. That is because that the main impact factors for frictional heat generation is interface pressure, coefficient of friction and the relative movements between contact interfaces. Under the same welding parameters, these three impact factors do not differ a lot. The heat generated by material plastic deformation is calculated from Equation 3. At the first half of the welding process (from the start to 0.028s), the heat generation by plastic deformation in the model considering acoustic softening effect is smaller than that not. However, at the second half (from 0.028s to the end), the opposite is true.

![Fig. 1. Fully coupled 3-D FE model: (a) Mesh of the whole model; (b) Mesh of specimen.](image)

![Fig. 2. Evolution of heat generation.](image)
Shown in Fig. 3 is the maximum temperature evolution on the Al plate. At the beginning of the welding process, the temperature in the model ignoring the acoustic softening effect grows more quickly, which agrees with the heat generation tendency revealed in Fig. 2. After a certain time, the temperature growth rates decrease sharply, nearly coming into saturation conditions. The conclusion that the temperature growth rate turns from huge to micro after a certain time agrees well with the work of De Vires [10]. The difference of the maximum temperatures obtained from both models at the end of the welding process seems very slight. This can be drawn from Fig. 2 that the total heat generation in the two models are almost the same. The maximum temperature is nearly 110 °C, well below the welding temperature of Al and Cu, suggesting that the ultrasonic welding is a solid-state welding process.

3.2. Mechanical analysis

As the welding proceeds, the sonotrode has a motion of downwards, the vertical displacement of which is plotted in Fig. 4. At the initial phase of the welding process, there is not much difference between the two conditions. After nearly 0.01s, the difference starts to become apparent. The vertical displacement of sonotrode in the model considering acoustic material softening effect is larger than that not. At the end of the welding process, the difference reaches nearly 27.7%. The reason for that kind of difference is that, by considering the acoustic softening effect, the yield stress of specimens decrease. At the beginning of the welding process, the plastic deformation area is relatively small and the sonotrode displacement is mainly caused by the specimens’ elastic deformation. As the process continues, the specimen deformation becomes large enough for more and more areas to become the plastic deformation zone. Then the difference between the two models becomes obvious: it’s easier for the material to get plastic deformation in the model considering acoustic softening effect, which will lead to larger sonotrode vertical displacement as a result.
The deformed shape of the specimens at the end of welding process is transversely sectioned, parallel to the direction of vibration. The simulated results are shown in Fig. 5. Fig. 5(a) shows the deformed structure from the model without considering the acoustic softening effect and Fig. 5(b) the opposite one. There are certain differences between the two figures because of the distinct material properties. In the model considering acoustic softening effect, it is easier for the specimen to get plastic deformation and flow. As can be seen in Fig. 5(b), most areas of adjacent surfaces between two plates get intimate contact, which indicates fine joint. Nevertheless, the situation is different in the results obtained from the model ignoring acoustic softening effect. As indicated by red circles in Fig. 5(a), there are some none-contact regions (voids) between the adjacent surfaces of the specimens. The reason for the formation of voids is that there is not enough plastic deformation and flow of the material to spread to the blank areas and form joints. Therefore, it is reasonable to say that the acoustic material softening effect contributes to intimate contact and high-strength joint between specimens.

![Fig. 5. Deformed shape of specimens at the end of welding: (a) without AFE; (b) with AFE; With A denoting the sonotrode, B denoting the anvil, C denoting the Cu plate and D denoting the Al plate.](image)

In order to illustrate the influence of acoustic softening effect quantitatively, some parameters from the calculated results are obtained and compared between the two models. The labels of C and D in Fig. 5 mark the centre place at Cu plate and Al plate, respectively. As can be seen from Fig. 6, the plastic strain obtained from the model incorporating acoustic softening effect is much larger than ignoring the effect of acoustic energy. That is because plastic deformation is much easier to occur under the applied acoustic energy. It can also be induced that the plastic deformation in the upper plate is much larger than that in the lower plate by comparing Fig. 6(a) with Fig. 6(b). There are two possible reasons to explain this phenomenon. One is that the upper plate is under the combined loading of vertical pressure and cyclical shear force exerted from the sonotrode, which is much more severe than the lower plate. The other reason is that there is much heat generation by friction and plastic deformation in the upper plate, resulting in more deformable material property.

![Fig. 6 Evolution of equivalent plastic strain at marked locations: (a) at location C; (b) at location D.](image)
4. Conclusions

A three dimensional coupled thermal-mechanical finite element analysis model has been developed to simulate the ultrasonic spot welding process. The results of two separate models, considering the acoustic softening effect or not, have been discussed in detail. The following conclusions can be drawn:

1. The material acoustic softening effect has certain effect on the mechanical behavior of the welding process. Most areas of adjacent surfaces between two specimens get intimate contact and display no obvious ‘void’ in the model considering acoustic softening effect. Therefore, the joint between workpieces will be formed with high strength.

2. The influence of acoustic softening effect on heat generation is not obvious. Heat generated by plastic deformation accounts for nearly one third of the whole heat generation, so it cannot be ignored.

3. The maximum temperature during the welding process has not reached the material welding point, suggesting that the ultrasonic welding is a solid-state welding process.

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