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Technical Paper

Simulating microstructure evolution of battery tabs during ultrasonic welding

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ABSTRACT

Ultrasonic welding offers ability to weld thin layers of malleable metals at low temperature and low power consumption. During ultrasonic welding, intensive material interactions occur due to the severe plastic deformation (SPD) and frictional heat generation, which leads to the microstructural change. Different grain microstructures have been observed after different ultrasonic welding conditions. Theory of the microstructural evolution was for the first time hypothesized as three regimes, namely SPD, dynamic recrystallization (DRX) and grain growth according to the material thermomechanical loading conditions. A novel metallo-thermo-mechanically coupled model was developed to model the temperature-dependent mechanical deformation and microstructural evolution during the ultrasonic spot welding process. The numerical analysis was carried out with a three-dimensional (3D) finite element model using DEFORM 11.0. The material constitutive model considered cyclic plasticity, thermal softening and acoustic softening. Dynamic recrystallization and grain growth kinetics laws were applied to simulate the microstructural evolution under different welding time durations. The simulation results demonstrated that the essential characteristics of the deformation field and microstructure evolution during ultrasonic welding were well captured by the metallo-thermo-mechanically coupled model. The numerical framework developed in this study has been shown to be a powerful tool to optimize the ultrasonic welding process for its mechanical properties and microstructures.

1. Introduction

Battery electric vehicles have drawn great attentions in recent years. The battery pack for a battery electric vehicle is assembled from a large amount of battery cells. Due to the virtues of low power consumption, rapid solid-state joining and environment friendliness, ultrasonic spot welding has been applied as a practical and efficient solution for joining of metallic battery tabs to a bus [1]. Ultrasonic welding is often used to create a joint between thin malleable metals such as aluminum (Al), copper (Cu) and nickel (Ni) [2]. It is also applied to join multi-layer dissimilar metals with varying sheet thicknesses.

The performance of ultrasonic spot welding has been extensively studied for battery tab joining in recent years. Lee et al. [1], conducted a thorough experimental analysis of ultrasonic spot welding of copper battery tabs and defined several key weld attributes, i.e., bond density, post-weld thickness, weld nugget size and thermomechanically affected zone size, to determine the weld quality. Their study also revealed that the resultant microstructure and material strength of the weld high depended on the welding process parameters. Lee et al. [3] experimentally investigated the performance of multi-layer ultrasonic weld by joining four coupons of Cu with various thicknesses. A high speed imaging technique was used to capture the displacement of horn and different coupons for ultrasonic welding using different knurling tools. The effect of vibration on weld formation from top to bottom layers was investigated from the analysis, which concluded that weld quality deteriorates from top to bottom layers due to less heat generation at the interfaces of bottom layers. Wu et al. [4] investigated the welding and failure mechanism of the Al/Cu ultrasonic welding using the mechanical testing and microstructural analysis. Online monitoring system was developed using welding power and horn displacement [5]. The weld quality was evaluated in terms of post-weld thickness and bond density based on the online signals for process control. Zhao et al. [6] developed a fatigue life cycle model to predict the life of Al/Cu ultrasonic weld tab joints by monitoring electrical resistance. The mechanical response of the Cu or Al/Cu tabs and ultrasonic welding system were studied to understand its effects on the weld quality and to reduce energy loss [7,8].

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Considerable research efforts have also been devoted to characterize the thermal field in the weld zone. The thermal contact conductance between thin metal sheets was determined as a function of contact pressure [9]. The real-time temperature and heat flux change have been measured and monitored near the weld zone using thin-film thermocouples [10] and thin-film micro-sensors [11]. Different weld formations were studied for various welding time durations from 0.6 s to 1.5 s. Based on the history of heat flux change rate, Li et al. [11] proposed a bonding mechanism for ultrasonic welding consisting of three continuous stages within one operation, which were firstly friction heating, then bonding by plastic work, and finally diffusion bonding.

Materials often demonstrate a significant softening phenomenon under ultrasonic loading. The softening effect during ultrasonic spot welding is considered in two main mechanisms of thermal softening and acoustic softening. Thermal softening is attributed to the frictional heat generation from the high frequency vibration. The thermal energy is uniformly absorbed by the metal material. The acoustic softening contributes more on the flow stress reduction. The acoustic energy generated by ultrasonic sonotrode is transmitted to the metal and locally absorbed at defected crystal lattice, e.g., vacancies, dislocations and grain boundaries [12]. As a result, the activation energy of the dislocation line movement is considerably reduced [13]. The increased mobility of dislocations drastically attenuates the work-hardening, so flow stress can be extremely reduced.

Numerical modeling studies have been attempted to model the thermomechanical coupling effect during ultrasonic spot welding. Elangovan et al. [14] developed a two-dimensional (2D) finite element (FE) model for ultrasonic welding of dissimilar materials. In their model, the effective heat generation terms were adopted from a previous study [15] for modeling heat generation due to deformation and friction under ultrasonic vibration. Lee et al. [16] developed a three-dimensional (3D) thermomechanical FE model and used a combined explicit/implicit multi-step numerical approach to predict ultrasonic spot welding of multi-sheet dissimilar materials (Al and Cu). However, the acoustic softening effect on material flow stress under ultrasonic loading was not considered in these aforementioned studies.

Siddiq and Ghassemieh [17] developed a material phenomenological constitutive model to consider the acoustic softening effect in the combined isotropic/kinematic hardening model under cyclic loading. This model was successfully implemented in a 3D thermomechanical FE model for an ultrasonic seam welding process of Al ally 6061 using a sonotrode with smooth cylindrical surface. The temperature-dependent friction coefficient was calibrated and applied to predict the frictional heat generation under ultrasonic vibration. Siddiq and Ghassemieh [18] applied this numerical approach to model ultrasonic seam welding of Al ally 3003 and investigated the effects of various process parameters, such as applied load, ultrasonic vibration amplitude, and tool velocity, on weld material response. Siddiq and Sayed [19] further proposed a micromechanics-based crystal plasticity model by incorporating the phenomenological acoustic softening term and simulated the ultrasonic assisted deformation of both single crystalline and polycrystalline Al materials. With this model development, the workpiece material textural change was simulated for ultrasonic consolidation at sub-micron scale [20].

Different from ultrasonic seam welding using a smooth cylindrical sonotrode, for ultrasonic spot welding of battery tabs, a sonotrode and an anvil with diamond knurl patterns are used to significantly enhance the welding process capability. During the process, weld forms from compression and ultrasonic in-plane sliding of the diamond knurling tool, which induces severe plastic deformation (SPD) in the workpiece material. Experimental results of ultrasonic spot welding from Lee et al. [1] showed complex

Table 1
Experimental conditions [1].

Materials	C11000 Cu (tab) Ni-plated C11000 Cu (bus)
Coupon thickness (mm)	0.4 mm (tab) 1 mm (bus)
Load (psi)	40, 50, 60
Vibration amplitude (μm)	30
Frequency (kHz)	20
Welding time (s)	0.2, 0.4 0.6, 0.8, 1.0

coupling effects among mechanical deformation, heat transfer, and microstructure change for various welding time durations. Their study revealed the material microstructure underwent different evolution routes with varying thermal and deformation histories. There is a great challenge in modeling such a metallo-thermo-mechanical coupled process under ultrasonic vibration. The available numerical approaches in literature are not capable to simulate the complex weld formation and microstructural evolution for the ultrasonic spot welding process.

Our present study is to develop a predictive metallo-thermo-mechanically coupled model to simulate severe plastic deformation and microstructural change during the ultrasonic spot welding process for battery tabs. Multiple 3D coupled thermomechanical FE simulations are conducted with DEFORM 11.0 to simulate the deformed weld shape and temperature change after different process durations. The microstructural evolution and the microhardness change are predicted using a post-processing user routine.

2. Principle of ultrasonic welding

The principle of the ultrasonic welding is discussed based on a systematic experimental study carried out by Lee et al. [1]. In their experimental study of ultrasonic welding for tab-bus joining in automotive battery cell, two C11000 Cu sheets (99.9% pure) were joined by an AmTech Ultraweld® L-20 high power welder with a maximum output electric power of 4 kW. The top and bottom sheets were 0.4 and 1 mm in thickness, respectively. The bottom sheet was plated by a thin Ni layer (~3 μm thick). The ultrasonic vibration was implemented in the workpiece transverse direction with an amplitude of 30 μm at 20 kHz frequency. The clamping force was applied along the vertical direction and varied from 40 to 60 psi. Multiple experiments were performed for different welding time from 0.2 to 1.0 s. Different knurl and anvil patterns were applied in their experiments. All the experimental parameters were listed in Table 1.

The weld joint microstructure was examined near the joint interface. The as-received sheets were rolled and annealed before the welding experiments, which had strain-free grains for both top and bottom coupons as shown in Fig. 1a. Fig. 1b–f examine the microstructures obtained after ultrasonic spot welding under a clamping pressure of 50 psi with varying welding time durations observed by [1]. It can be recognized that the material microstructure underwent different evolution routes as the welding time increased. For a short welding time of 0.2 s, a great amount of elongated grains can be seen in Fig. 1b on both side of the joint interface. As the welding time increased to 0.4 s, the elongated grains became dissolved, and newly formed strain-free-like fine grains can be seen in Fig. 1c. Similar microstructure with newly formed fine grains near the weld interface was also observed after a 0.3 s ultrasonic spot welding of Al alloy 6111 under a similar ultrasonic loading condition [21]. In Fig. 1d, fine equiaxed recrystallized grains were formed with very clear grain boundaries in most area of the specimen cross-section after 0.6 s welding. As the welding time increased to 0.8–1.0 s, coarse grains were mainly