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Technical Paper

# Improving process robustness in ultrasonic metal welding of lithium-ion batteries

Lihang Nong[a], Chenhui Shao[b,*], Tae Hyung Kim[a], S. Jack Hu[a]

[a] Department of Mechanical Engineering, University of Michigan, 2350 Hayward St., Ann Arbor, MI 48109, USA
[b] Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, 1206 W. Green St., Urbana, IL 61801, USA

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ABSTRACT

Ultrasonic metal welding is a solid-state joining method popularly adopted in the assembly of lithium-ion battery cells, modules, and packs for electrical vehicles due to its numerous advantages over traditional fusion welding techniques. Ultrasonic metal welding process yields quality welds under optimal conditions, but can result in poor welds when there are disturbances, such as the presence of oil contamination. State-of-the-art controllers cannot detect those disturbances or control the welding process accordingly. In this research, two methods are proposed to improve the process robustness, namely, a real-time controller and a new tool geometry design for the sonotrode. The developed controller monitors the on-line power signal and adjusts the weld clamping pressure through a calibrated step function accordingly. Experimental results show that with oil contaminated workpieces, the new controller yielded an average improvement of 14.5–440% in the T-peel strength over the current controller, depending on the level of oil contamination. Additionally, the process robustness was shown to be improved by the use of a spherical tool in place of a flat tool. Improvements are achieved for all tested clamping pressures, especially when the pressure is outside the optimal range for the flat tool.

## 1. Introduction

Ultrasonic metal welding is a solid-state joining process that creates bonds by the application of shearing vibrations in the ultrasonic frequency simultaneously to two or more stacked metal workpieces [1,2]. The bonding mechanism of ultrasonic metal welding has several advantages over conventional fusion welding processes, including the ability to work for dissimilar metals such as copper and aluminum, low energy consumption, fast processing time, the ability to produce clean welds, and the lack of thermal effects due to the absence of liquid–solid transformations. These advantages make ultrasonic metal welding suitable for a variety of applications such as for the assembly of lithium-ion battery cells, electrical circuits, and medical devices.

Ultrasonic welding process for sheet metals has been investigated extensively in the past [1–8]. The bonding mechanism is primarily solid-state welding, which occurs when two metal layers come into a large area of contact. In order for a significant surface area contact of fresh metals to occur, the oxides and contamination on the metal surfaces need to be broken and scrubbed away, followed by flattening of asperities. Large clamping pressures and repetitive shearing motion from the sonotrode enables the breakage of oxides and the scrubbing of contamination. The vibrations of ultrasonic frequency have been found to drastically soften metals, which helps to increase metal contact area when large shearing and normal forces are applied [9]. High temperatures induced by friction and bulk deformation of the material does not always lead to melting, but helps to soften the materials.

A typical ultrasonic metal welding system consists of five subsystems: (1) a controller, (2) an ultrasonic transducer (or converter), (3) a booster, (4) a pneumatic cylinder, and (5) a horn (sonotrode) and an anvil. Figs. 1 and 2 illustrate the welding system and welding process, respectively. According to process inputs (welding parameters), the controller outputs an electrical signal to the ultrasonic transducer, which oscillates along a direction of the sheet surface during the weld. The sonotrode, which is attached to the transducer, has vertical travel provided by forces from the pneumatic cylinder in order to clamp the workpieces to the anvil. The welding process is marked by the following steps:

(1) The pneumatic cylinder applies clamping force to clamp the workpiece between the sonotrode and anvil.
(2) The controller outputs an electrical signal that is transferred into a mechanical oscillation at the sonotrode by the transducer. The oscillation first breaks up and removes oxides and contamination, which enables the growing contact of fresh metal due to material

* Corresponding author.
*E-mail address:* chshao@illinois.edu (C. Shao).

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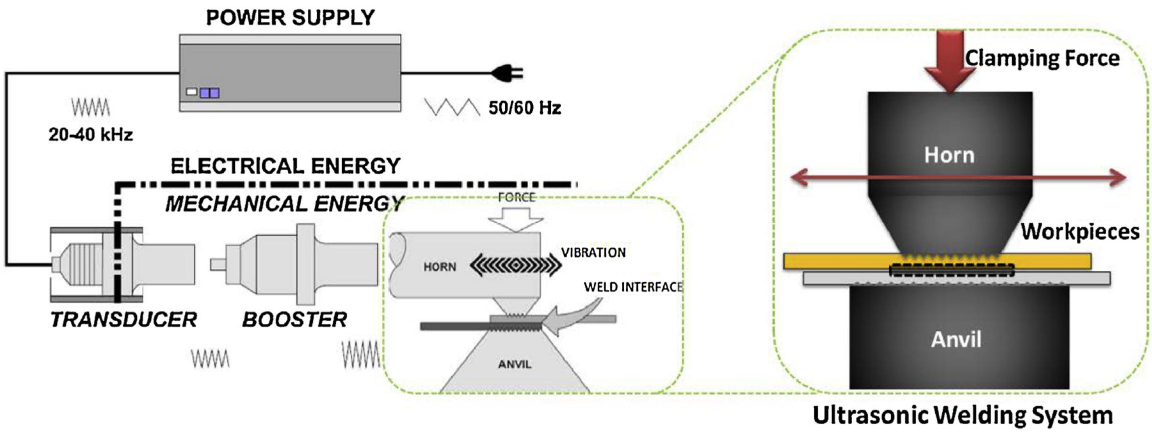


**Fig. 1.** A typical ultrasonic metal welding system [10].

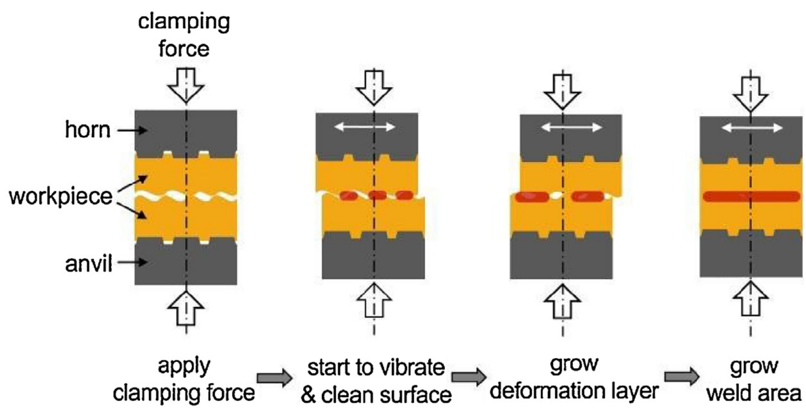


**Fig. 2.** An illustration of ultrasonic welding process [2].

deformation, leading to bonding.

(3) The controller dictates the end of the weld and stops vibrations. The force in the pneumatic cylinder is reversed, causing the sonotrode to lift off from the workpiece.

Ultrasonic metal welding is able to produce good quality welds when the welding conditions are optimal [2,11]. However, process disturbances, such as the presence of oil on the weld specimen and/or tool surfaces, tool wear, and poor fit-up between tool and workpiece, can cause poor welds even with optimal parameters settings [4,12,13]. While some of these disturbances, such as tool wear, have little variation between welds and can be corrected by run-to-run control [12], other disturbances, e.g., oil contamination, have large variations between welds and cannot be easily detected prior to a welding cycle.

Material surface conditions have a strong effect on weld quality [13]. Observations from a battery assembly plant concluded that many of the poor welds were due to the presence of oil on the workpieces. Under such circumstances, the welding process is not robust, and the weld quality has large variations. Furthermore, it was observed that setting the welding parameters appropriate to the surface conditions resulted in similar weld strengths for all conditions. This provides a motivation for real-time control in order to produce good welds regardless of surface conditions by controlling process inputs during the weld.

Although no previous works on real-time control of ultrasonic metal welding could be found in the literature, many previous studies are available on resistance spot welding or other joining processes, e.g., [14–20]. Resistance spot welding uses a different materials joining mechanism. But three parameters in resistance spot welding, welding force, welding time, and weld current, are similar with the ultrasonic welding, especially welding force and welding time. In the literature, most works integrated a method to monitor one or more process outputs that give an indication of weld quality, and a controller to change one or more process inputs that affect the weld quality. Affected process inputs include welding current [15], forging force controlled by a servomotor, and forging force controlled by a pneumatic system.

For ultrasonic metal welding, the relationships between monitored process outputs and the weld quality are not as well established as those for resistance spot welding [21,4], which raises the question of whether a sufficient indication of weld quality can be arrived at by monitoring process outputs in ultrasonic welding. To affect clamping force, which is a process input, a pneumatic system was used in this study. The cycle time for ultrasonic metal welding is typically within 1 s and much shorter than for resistance spot welding, which raises a question to whether the pneumatic system can be responsive.

In addition to real-time control, robustness can be potentially enhanced through better tool design [22]. Currently, the standard welding tool has a “flat” knurl pattern on both the horn and anvil. Here, a “flat” design refers to a tool whose base is flat, i.e., all knurls have the same vertical position. With this tool, the welding process is tolerant to a narrow range of operating conditions and welding parameters. For example, increasing the welding energy and/or clamping pressure above this suitable range leads to part cracking surrounding the weld nugget, or “over” weld. Decreasing the welding energy and/or clamping pressure below this suitable range leads to a decrease in total bonded area, or “cold” weld [2,4]. In the presence of disturbances, such as variations in material thickness or contamination, the optimal parameters typically leading to a good weld may cause a poor weld. In this research, we designed and fabricated a new spherical tool, and compared its robustness with traditional flat tool.