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Classification of Ultrasonic Weld Quality using Acoustic Signatures Acquired During Manufacture

September 2022

Curtis J Larimer

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Abstract

Ultrasonic welding is a process is based on generating a solid-state bond between two metals by applying moderate pressure and high intensity sound waves (20-70 kHz frequencies) at their interface. During the solid-state process numerous material, surface, instrument, and environmental factors contribute to bond formation, strength, and durability. The inherent difficulty of measuring and controlling each of these factors has, to date, made predicting bond quality elusive. In this work, a Sonics model MWB20 ultrasonic spot welder with integral base, was used to produce a variety of welds of different metal foils under varying weld conditions. Acoustic measurements were recorded throughout the measurement process. Subsequent analysis of the signals using metrics that approximate the energy dispersed during the weld proved to successfully predict weld quality. Two metrics based on normalized energy differential and Renyi entropy were developed into Python and C++ scripts for direct analysis of weld acoustic data.

Acknowledgments

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1.0 Introduction

Ultrasonic welding harnesses sound waves to weld metal layers and composites in a low temperature solid-state process. The quality of these bonds, particularly in industries like aerospace and automotive, have significant quality and safety implications for the performance of the product. For example, ultrasonic joining systems are used in the manufacture lithium batteries used in electric vehicles. However, there is not currently an accepted way to non-destructively predict weld quality before, during, or after a weld. Failed ultrasonic welds in consumer electronics have resulted in multi-billion-dollar safety recalls. For this reason, large US-based automotive companies are actively investigating process monitoring techniques to assure consistent and reliable welds, but the problem is far from solved.

While ultrasonic welding was developed in the 1950’s it has recently found increasing application in many areas of modern manufacturing. When held together under pressure, ultrasonic vibrations deform, shear, and flatten local surface asperities to improve metal-to-metal contact resulting in a solid-state bond between surfaces. Ultrasonic welding is an effective alternative to thermal welding because this solid-state joining process does not require high temperature or melting of the component metals. The maximum processing temperature is typically no higher than 50% of the melting point of the metals being joined (e.g., only 100°C for aluminum). As an added benefit, mixed materials that cannot be bonded by traditional welding (due to melting point differences) may nonetheless be joined by ultrasonic welding.

Unfortunately, the parameters necessary to ultrasonically join mixed materials are currently developed on a trial-and-error basis and have to be deduced each time a new metal material is introduced or a new combination of metals is joined. This process limits how quickly the ultrasonic consolidation process can be optimized before proceeding with fabrication. Optimizing welding parameters so materials can be joined without "over-welding" is equally important as it minimizes material damage and also enables joining with delicate composites such as metallic foams. Thus, a key question tied to the broader application of this technique is: How can optimal ultrasonic joining parameters be predicted to allow for truly rapid ultrasonic weld prototyping? Development of dynamical models that identify the number of control variables and define their interactions places this prediction problem firmly in the realm of mathematical optimization and thus provides a concrete framework to both pose and solve this problem.

2.0 Technical Approach

Ultrasonic welding is a process is based on generating a solid-state bond between two metals by applying moderate pressure and high intensity sound waves (20-70 kHz frequencies) at their interface. The process is highly nonlinear. During the solid-state process surface contaminants are incorporated into the weld region. Hence, not only physical but chemical interactions play a significant role in bond formation, strength, and durability. The core of the apparatus used in this study is an off-the-shelf welder that has been customized and outfitted with a suite of multi-physics sensors and data collection systems.

The early stages of the welding process can indicate process conditions that will result in a bad weld. For example, the power in the early period can change depending on surface contamination. Differing power levels lead to unequal material deformation and changes in ultrasonic horn displacement. Thus, the energy, $E(t)$, absorbed from the horn and the indentation depth, $D(t)$, in early stages are two important signals. Results described below show that these are highly correlated with the acoustic field generated during the welding process and hence may be used as surrogates for $E(t)$ and $D(t)$, and features derived from them. In prior work, two such features have been shown to be strong predictors of weld quality. They are the energy at the mid-point of the welding process, $Emid$, and the indentation depth at the mid-point of the welding process, $Dmid$. In this work, several quantities that generalize energy and indentation were found to be observable via acoustic signals.

3.0 Results and Discussion

A Sonics model MWB20 ultrasonic spot welder with integral base, was used to produce all ultrasonic welds used in this study. The spot welder head is labeled in Fig. 1. On its bottom side is located the active region of the spot welder. The spot weld area is specified by the manufacturer to be 80.65 mm^2. Also indicated by white dashed lines is the opposing passive (bottom) region of the welder's anvil. Welding times and power levels were performed by adjusting the range preset amplitudes to range from 25 to 65μm in 5μm increments. A total of six different acoustic signatures were acquired during each weld. The locations of the microphones used are shown in Fig. 1.

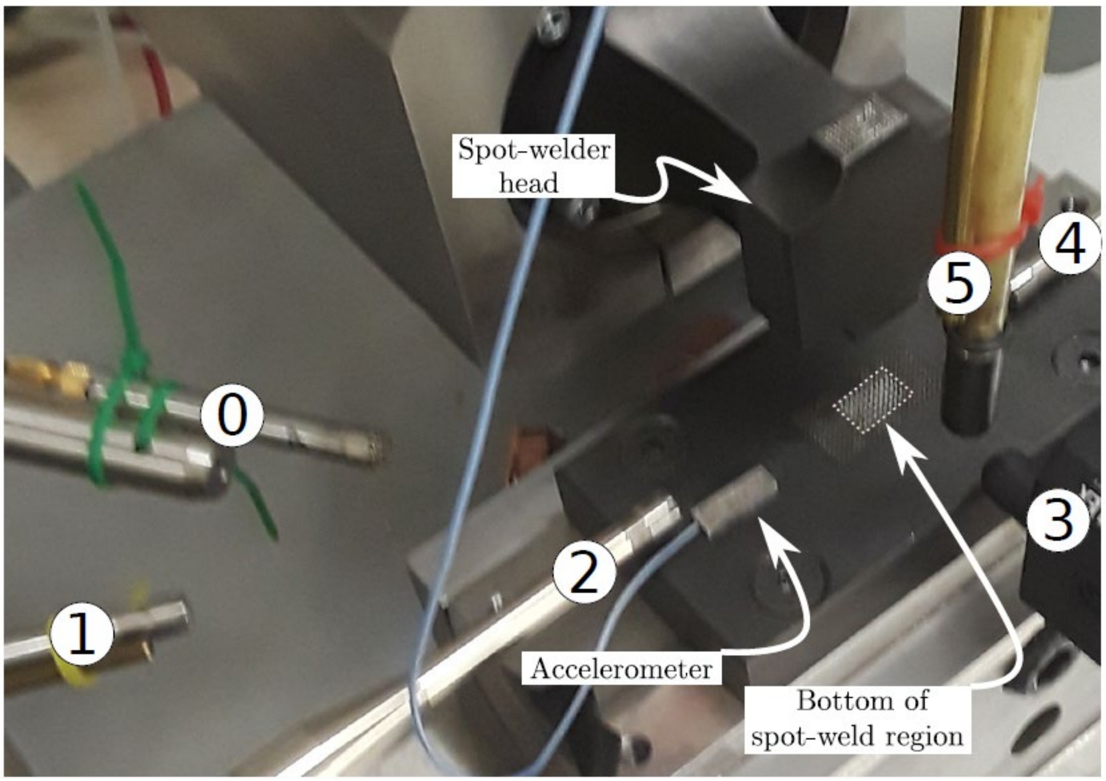

Figure 1. Placement of the six microphones used for acquisition of acoustic signatures produced during ultrasonic welding. An accelerometer was mounted on the welder base as an additional source of data (however, not reported in this study). The "passive" area of the bottom spot weld region is also indicated.

Table 1. Make and model of each microphone as well as the digitizer used to capture the acoustic signature produced by each microphone during the welding process.

Microphone No.	Manufacturer	Type	PreAmp	Terminus	Channel
0	Bruel&Kjaer	4944-B	Bruel&Ljaer Type 2829	Gage CSXXX	CH4
1	Bruel&Kjaer	4944-B	Bruel&Ljaer Type 2829	Gage CSXXX	CH3
2	Bruel&Kjaer	2669	Bruel&Ljaer Type 2829	Gage CSXXX	CH2
3	Bruel&Kjaer	8103	None	Tek MSO56	CH3
4	Bruel&Kjaer	2669	Bruel&Ljaer Type 2829	Gage CSXXX	CH1
5	Bruel&Kjaer	8103	None	Tek MSO56	CH4

Digitized data were analyzed to produce 16 different quantities; all intended for use as classifiers of weld quality. The first six were energy based although different normalizations were used. The remaining eleven were information-theoretic in nature. Previous studies have shown that these are often more sensitive the changes in acoustic signature than are energy-based components.

Twenty-two quantities were derived from the acoustic signatures collected using six microphones and it was found that two quantities were good predictors of weld quality as measured by a destructive pull test performed after the weld. The two weld pieces were weighed before the weld and again after a controlled T-peel pull test. A greater difference in weight after the weld indicated a stronger bond. The two successful predictors of weld quality were:

1. Normalized energy differential: $\left|\frac{\int_0^1 f(t)dt}{\int_0^1 f(t)^2 dt}\right|$

2. Renyi Entropy, α = 0.1:

$$\frac{1}{1-\alpha}\sum_j p_j^\alpha, \alpha = 0.1$$

Two examples of successful weld quality prediction are shown in Fig. 2 and Fig. 3.

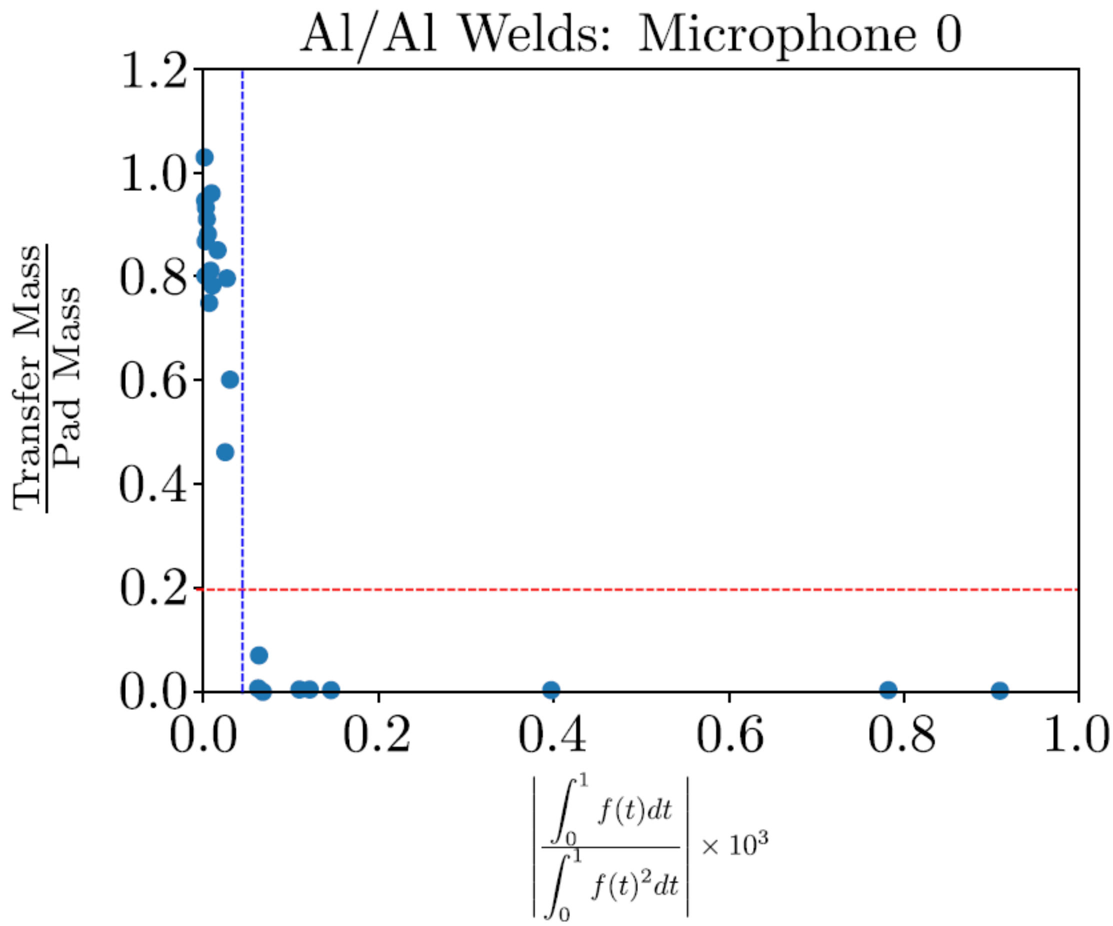

Figure 2. Summary plot of mean weight change vs. normalized energy differential for all aluminum-to-aluminum welds. The vertical axis is a proxy for a good weld (higher is better). Red line shows presumed cutoff between good (left of dashed blue line) and bad (right of dashed blue line) welds. Using this cutoff there are zero false positives and zero false negatives. Once qualified, data such as those shown above could be used to produce a bone fide receiver operator curve.

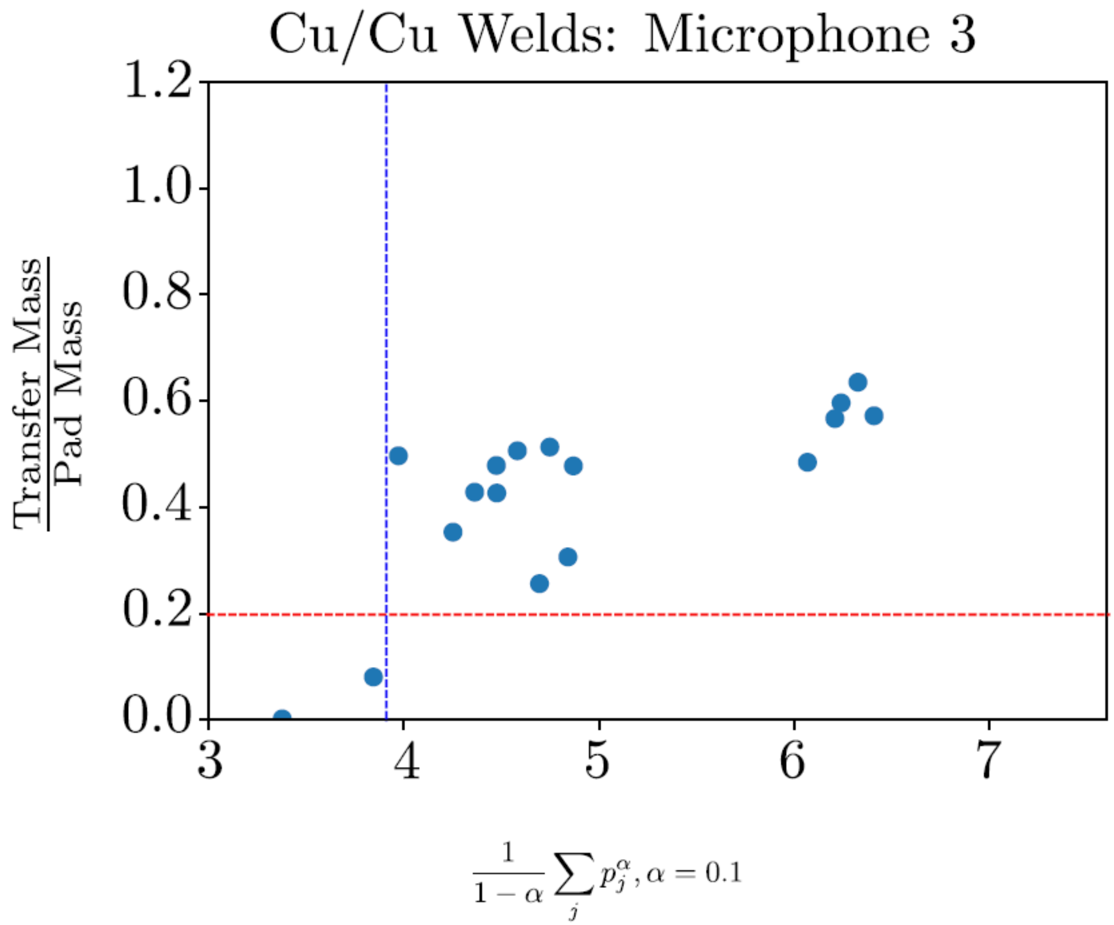

Figure 3. Summary plot of mean weight change vs. Renyi entropy, for all copper-to-copper welds. Vertical axis is a proxy for a good weld. Red line shows presumed cutoff between good (left of dashed blue line) and bad (right of dashed blue line) welds. Using this cutoff there are zero false positives and zero false negatives. Once qualified, data such as those shown above could be used to produce a bone fide receiver operator curve. Observe that the Renyi entropy of order 0.1 appears to separate the welds into three groups: "low-strength", "intermediate-strength", and "higher-strength".

From these observations we can conclude:

- Normalized energy differential, $\left|\frac{\int_0^1 f(t)dt}{\int_0^1 f(t)^2 dt}\right|$, is useful for discriminating good from bad welds for Aluminum-to-Aluminum, Aluminum-to-Brass, and ,although the cohort has a limited number of bad welds, Copper-to-Copper.
- Placement of microphones is critical: for Aluminum-to-Aluminum off axis, i.e., 330°, acoustic capture worked best, for Aluminum-to-Brass, off axis acoustic capture worked best, for Copper-to-Copper on axis capture proved optimal. The axis refers to the direction of motion of the ultrasonic spot welder head.
- The Renyi entropy measures provide a source of potential feature vector components that are independent of the energy-based components. The Renyi entropy of order α = 0.1 also appears to exhibit greater ability to discriminate weld quality into three distinct groups.

Normalized energy differential and Renyi entropy are both metrics that can be calculated quickly and thus are also good candidates for *in situ* evaluation. To that end, both were developed as standalone python scripts. The scripts were architected to operate directly on binary acoustic sensor data in either a static post-process mode or a dynamic in-process mode. Metrics are calculated from a simple array of signal times and amplitudes. The Python code was validated using the variety of weld data described above. It was then ported to C++ and validated again. In this form, the software is ready for copyright and transfer to commercial entities who wish to use it to improve their industrial welding processes.

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