Developments in Ultrasonic Metal Welding Monitoring

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Abstract: Ultrasonic welders provide information pertaining to the input parameters and resulting power usage during the welding operation. This information, however, does not offer the user a high level of confidence in weld quality. Furthermore, analysis of parameter interaction is not known nor provided in the user interfaces of these machines but may improve the effectiveness of tracking weld quality. Prospective sensor technologies for ultrasonic weld monitoring have been identified for this purpose and described in the following study. These sensors measure shear force at the weld, displacement of the horn in the vertical and lateral directions, and the voltage and current supplied to the transducer. All sensors have been installed along a linear ultrasonic welder and are undergoing evaluation for future integration as in situ weld monitoring tools. Preliminary results show correlation of weld quality to signal profiles, especial between shear force and current.

Keywords: Weld Monitoring, Ultrasonic Metal Welding, Weld Quality

In all welding processes including ultrasonic metal welding (UMW), material and environmental discrepancies can result in weld variability even when the same weld settings are used. In many cases, output data (such as weld time or power) collected from faulty welds still fall within the acceptable limits set by the operator. Frequently, the resulting weld passes through visual inspection and is installed in the final product.

However, this weld may not meet strength requirements and may fail during use. Tracing the root cause of this failure can be nearly impossible given the limited amount of output data available and the confidence level of data interpretation upon completing the welding operation.

Ultrasonic metal welding is an ideal process for thin, ductile metals such as aluminum and copper. When two sheets of this material are under compression and an ultrasonic vibration is imparted into this stack, the interface of the materials is subject to changes. The scrubbing action causes asperities to collapse and oxide to be dispersed, creating intimate contact between the metallurgically clean surfaces. As electrons share atoms at this interface, a solid-state bond is created.¹

There are a number of products that rely on this bonding mechanism. One of the most common is the electric vehicle battery. With low heat input, ease of automation, and relative low cost of equipment, ultrasonic welding is well suited for this application. However, any defects that develop are challenging to identify prior to failure, and product failure due to faulty welds can be quite costly.

In previous work, EWI has outlined the prospective technologies for in situ UMW monitoring and weld quality assurance.² For this study, several of these technologies were integrated into an ultrasonic metal welding setup to study the use of UMW monitoring technologies to determine good from poor welds. This paper describes preliminary results of these integrations, the ongoing effort to study the technologies, and the anticipated outcomes.

Experiment Details
For this investigation, several sensors were selected as candidates to be used for monitoring the ultrasonic welding process. The sensors were chosen based on previous experience, accessibility, and review of the current literature. While some of these sensors were hard wired or mounted into the welder, none of these methods relied on physical access to the weld materials themselves. This prevented interference of the welding operation and presented the opportunity to qualify welds or diagnose cause of failure. Table 1 includes the sensors selected for monitoring in this phase of the investigation. All sensors were used during the welding operation for in-process monitoring.

<table>
<thead>
<tr>
<th>Monitoring Method</th>
<th>Measurement</th>
<th>Pros</th>
<th>Cons</th>
<th>Installation Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical Signal Capture</strong></td>
<td>Energy, Power</td>
<td>Measures the electrical signal directly from power supply</td>
<td>Requires modification of equipment</td>
<td>Power Supply</td>
</tr>
<tr>
<td><strong>Shear Sensor</strong></td>
<td>Shear Force</td>
<td>Direct measurement at weld zone</td>
<td>Requires tooling of anvil</td>
<td>Mounted directly under anvil</td>
</tr>
<tr>
<td><strong>Laser Vibrometer</strong></td>
<td>Frequency, Amplitude, Time</td>
<td>Non-contact</td>
<td>Cost for industry, unknown requires stable fixturing</td>
<td>Focused on the horn tip</td>
</tr>
<tr>
<td><strong>Linear Variable Differential Transformer</strong></td>
<td>Displacement</td>
<td>Non-contact, already installed in welder</td>
<td>Not calibrated, output is not continuous</td>
<td>Within press casing</td>
</tr>
</tbody>
</table>

Table 1. Selected sensors investigated for ultrasonic metal welding monitoring

Thin copper foil (i.e. 0.127 mm) was selected as the workpiece material. For each weld, two sheets of this copper foil (i.e. 25 x 50 mm) were welded using a knurled sonotrode tip for a single spot weld approximately 5 x 5 mm in size. Screening trials were performed to select weld parameters that yielded good welds, over-welds, and under-welds. These three groups of down-selected welding parameters were used throughout the monitoring study.

In the first phase, repeatability of welding was evaluated. For each of the three groups of weld parameters, 20 welds were produced, and variability of weld quality was evaluated. The evaluation included both signal analysis for all monitoring tools and destructive analysis of the welds. The purpose was to identify changes in the sensor signals that correlate with good or poor weld quality within a set of identically fabricated welds. The sample size for this report was small. Seven welds produced under the same conditions produced both good welds and very light or poor-quality welds. The following sections review preliminary results showing correlation between destructively identified good and poor welds within the same weld-parameter set. Early interpretation of results is provided. In each figure, the green signal is from one weld identified as good, while the red signal is from one weld identified as poor.
**Electrical Signal Capture**

The voltage and current needed to reach the power requirements of the transducer were recorded through electrical connections in the power supply. In Figure 1, the left image shows the good and poor voltage signal while the right image shows the good and poor current signal. The first obvious difference between the signals associated with good and poor welds was that the poor signal had a longer duration, by approximately 10 ms. One can interpret that the extended time for the poor (red) sample was likely due to the loss in current as seen in Figure 1 by the decrease in amplitude of this waveform. The welder could compensate for this loss in current and subsequent loss in power by extending the time so that the weld could still achieve the requested energy by the operator.

![Figure 1: Voltage (left) and current (right) required for welding at the requested energy. Green signal is taken from the good weld, red signal taken from the poor weld.](image)

**Vibration Amplitude and Displacement of Press**

Figure 2 shows examples of the physical movement of the ultrasonic press. In the left image, the amplitude of the horn was recorded by laser vibrometer. Again, there was an extension in weld time for the poor weld. Additionally, there was some discrepancy between the amplitudes of these two welds, where the poor weld appeared to be unstable at the start of welding and continued to have a more irregular and higher amplitude than the good weld. In the right image, displacement is shown as recorded by the built-in LVDT. Outside of the time extension welding, no significant discernible difference was present in the weld signals. Further evaluation of the LVDT will be performed in future studies as this tool is commonly used in industry to distinguish material stack-up errors.
Shear Force

Finally, as seen in Figure 3, shear force was measured at the anvil. A piezoelectric device, shown in the right image, was installed at the base of the anvil. The collected signal showed that the shear force for the poor weld was significantly lower than that of the good weld. Low weld force was likely the reason for the poor weld quality. However, it remains somewhat unclear as to why shear force decreased.

Conclusions

By examining all the presented signals, it appears that the drop in current and adjustment for power and amplitude by the welder did not provide a stable weld cycle required to generate appropriate friction between the workpieces. Therefore, the shear forces experienced by the workpiece were reduced. This minimized the activation of the atoms of the joining surfaces. Electron exchange did not take place effectively which led to a reduction in joint strength. This behavior was also observed in the repeatability study, comparing weld results between weld quality parameter sets (over-weld, good, and under-weld conditions). Early analysis of these results confirmed similar signal changes between weld quality when the parameters expected to control weld quality were enabled.

EWI’s next step is to compare representative data from each of the three weld conditions and the corresponding signals acquired from the monitoring tools to desired weld quality. The goal is to use data from known welding conditions to generate a library of acceptable signals for a given monitoring tool.

Acknowledgements: Any reference to specific equipment and/or materials is for informational purposes only. Any reference made to a specific product does not constitute or imply an endorsement by EWI of the product, or its producer or provider.
References


Lindsey Lindamood is an Applications Engineer in the Ultrasonics group at EWI. She specializes in ultrasonic metal welding, resistance welding, and non-contact ultrasonic inspection. She is currently developing processes for monitoring ultrasonic metal welding, advancing capabilities of ultrasonic metal welding and resistance welding, and expanding applications of laser ultrasonics