Derivation of characteristic vibroacoustic parameters in Ultrasonic Sheet Metal Welding

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Abstract

Ultrasonic Sheet Metal welding (USMW) is often used in industry to join electro-technical components, such as in welding strands or battery components. The workpieces to be welded are compressed between two machine parts: the horn and the anvil. The horn vibrates at 20 kHz, causing friction between the two workpieces which leads to a friction-induced bond. However, the process still suffers from quality fluctuations, even given the same welding parameters. The goal of this project is to identify vibroacoustic parameters that could be used to monitor the quality of the weld during welding. To do that, a series of experiments was conducted: two thin copper sheets were welded with a welding frequency of 20 kHz. During welding, the oscillations of the horn and anvil and the airborne sound were recorded. The duration of welding was varied, to produce welds in different stages of welding. The data is analysed, up to the fourth harmonic, to identify parameters that could be used to monitor the welding process.

Introduction

Ultrasonic Metal Welding (USMW) is a friction-welding process that is widely used in industries such as the energy, electronic and automobile industry. Its advantages include low energy consumption, short welding times, being highly automatable and being able to weld dissimilar metals. However, despite being so widely used, knowledge of how USMW exactly happens is lacking. Welding machine operators often have to rely on their experience and trial and error to find welding parameters that would work for a specific application, and even then, the strength of the weld can vary. In USMW, two or more workpieces (metal sheets or wires, for example), of thickness often smaller than a millimetre, are welded. The main welding components of a USMW welding machine are the anvil and the horn. The horn provides the pressure and oscillations to the metal sheets, while the anvil provides a supportive surface against which the metal sheets are pushed, and a knurled pattern that holds the lower workpiece in place while the upper workpieces moves relative to it. First, the workpieces, are placed on the anvil. Then, the horn applies a downward, vertical force on the workpieces, pressing them against each other and against the anvil, before vibrating horizontally at its welding frequency. This oscillation and pressure lead to friction between the two metal sheets, which leads to the formation of a solid-state bond. A more detailed explanation of the procedure can be found in [1], [2], [3] and [4].

In USMW, the machine operator can vary multiple welding parameters, such as the pressure, the amplitude of vibrations, or the energy input into the system, which controls the duration of the welding process. This study focuses on time variation in USMW. Keeping all other welding parameters constant if the welding process is too short, the energy converted into the welding site is too little; the weld has not had time to fully form, and the workpieces are said to be underwelded. If the welding area receives the right amount of energy, so if the welding takes the right amount of time (keeping all else constant), then the weld strength is in its strongest range. In the following text, these welds will be referred to as basic welds. If the welding process is too long, then, after reaching its optimal strength, the weld weakens, fatigued by the extra oscillations, and the workpieces are said to be overwelded. These different categories of welds can also be characterized by different failure modes when doing tensile strength tests, as shown in [1], [3] and [4].

In this paper, laser Doppler vibrometry measurements of the oscillations of the horn and anvil along the direction of welding and airborne sound measurements are used to monitor the welding process, and find parameters that might be used to monitor USWM. Similar measurements have been used in [3], [4] and [5] to study USMW and spot welding.

Experimental procedure

For this paper, a total of 120 welds were created, 40 of each category. For all welds, the welding pressure was kept constant. The workpieces were copper (CW-008A) sheets, of dimensions 125 mm x 45 mm x 0.5 mm. The surfaces of the workpieces were cleaned. To get the three types of welds, the total energy input into the system, which is given to the welding machine as a parameter, was varied, which lead to a difference in welding time. The optimal range of the energy parameters used were determined by preliminary experimental tests. To mitigate effects such as heating of the tools or ambient temperature, the welds were made in a specific order: one underweld, followed by one basic weld, and then one overweld. This cycle was repeated, until the total number of welds was reached. However, strength testing the welds showed that both the strengths of the overwelds and their failure mode were too similar to those of the basic welds. This meant that overwelding had not been successfully achieved. The overwelds were actually basic welds with a longer welding time. In the rest of the analysis, these overwelds will be referred to as basic welds +.

As for the sensors, two Polytec CLV-2534 laser Doppler vibrometers (LDV) measured the velocity of oscillation of the horn and anvil during welding, and along the direction of oscillation, as shown in Figure 1. The measurement location of the horn LDV was just above the welding site. For this to be possible, the setup had to account for particle emissions that happened during welding, and that interfered greatly with the laser beam: an adaptor piece was 3D printed and connected to a vacuum cleaner placed outside of the welding laboratory. With this apparatus, most of the welding projections were sucked away from the path of the horn laser beam, and data acquisition was made possible. In addition to the LDVs, a GRAS 40BF 1⁄4” free-field microphone mounted on a GRAS 26AC-11/4” preamplifier was placed 15 cm away from the welding site, and directed towards the welding site, perpendicular to the oscillation direction. The data from the microphone was fed to a NEXUS amplifier, then sent to the analogue-digital converter (ADC). The LDVs and the microphone were synchronized through a LabVIEW interface. The sampling rate of the whole ADC was 250 kHz, for a maximum measurable frequency of 125 kHz. The maximum frequency measurable by the microphone was 100 kHz, and over 1000 kHz by the LDVs.

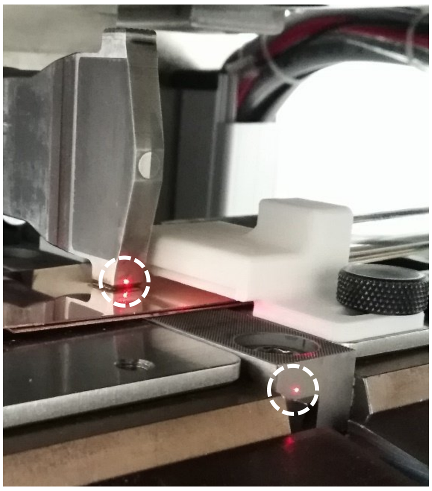

Figure 1: In the white circles, the red dots are the measurement positions of the LDVs on the horn (top) and anvil (bottom)

It is important to note that, during the experiments, the measurement positions of the LDV had to sometimes be changed between different welds to avoid particle emissions, which is a possible cause for some differences in the measurements of different welds.

Processing the data

Looking at the data, the vacuum adaptor had not been completely effective. Some of the horn recordings showed short, local wide-band peaks, which are due to ejected particles interfering with the laser beam. The corrupted recordings were discarded for all sensors, leading to a final number of 27 basic welds +, 26 basic welds, and 21 underwelds, for a total of 74, instead of the initial 120.

The frequency plot and spectrogram of the horn, anvil and microphone during welding (not shown here) showed that the energy was mostly concentrated around the welding frequency of the welding machine, 20 kHz, and its harmonics, namely 40 kHz, 60 kHz, 80 kHz, 100 kHz and 120 kHz. Therefore, it was decided to monitor the changes in energy at these frequencies, as they offer the best signal to noise ratio. The energy was integrated in frequency bands spanning 1 kHz around the harmonics. However, in the horn measurements of each weld, the peak frequencies with the maximum energies were slightly different, with variations usually less than 0.1 kHz between different measurements. Therefore, for each weld, the horn data was analyzed to find the exact peak around each harmonic and the fundamental. Then, the data from the horn LDV, anvil LDV and microphone was filtered around those peak frequencies in 1 kHz bands centered on the peak frequencies. Finally, the LDV data was integrated to get the displacement data.

Results

To stay consistent with the highest measurable frequency in the microphone, and although the LDVs could measure up to 125 kHz, Figures 2 to 15 show the displacement amplitude or sound pressure for the 20 kHz, 40 kHz, 60 kHz and 80 kHz bands only. In those figures, the displacement or sound pressure of all three weld categories are plotted together. In addition, the y-limits were chosen in a way that best shows the displacement in time, leading to some peaks in the beginning of welding to be truncated, such as in Figure 3. Those peaks are due to particle projections during welding. Since they happened very early in the welding process, the data was kept.

The horn displacements are shown in Figures 2, 5, 8, 11, 14 and 15. In each frequency band, the displacements of the different welding categories are similar, showing the same behaviour in time across different welds. In addition, for all frequencies, there is an inflection point around 0.7 s, which coincides with the end of the underwelds: at 20 kHz, shown in Figure 2 and 14, the horn displacement increases with a decreasing slope until a constant displacement value is reached around 0.7 s. After 0.7 s, the displacement amplitude increases again, with an increasing slope. At 40 kHz, (Figure 5), 60 kHz (Figure 8) and 80 kHz (Figures 11 and 15), around 0.7 s, the displacement amplitude starts decreasing, after having increased since the beginning of welding.

The anvil displacements are shown in Figures 3, 6, 9 and 12. Here too, the displacements of the different welding categories show similar behaviours in time across welds. At 20 kHz, the displacement amplitude increases until a maximum around 0.9 s, then decreases. At 40 kHz, the spread is too large to identify a strong trend. At 60 kHz, the displacement reaches its maximum magnitude between 0.5 s and 0.7 s, and then starts decreasing. At 80 kHz, around 0.7 s, the displacement goes from increasing to decreasing.

The pressure measured by the microphone is shown in Figures 4, 7, 10 and 13. For all frequencies, the spread is large, and no noticeable trend can be identified.

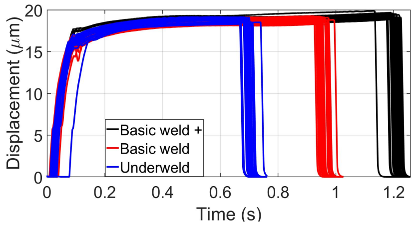

Figure 2: Horn displacement during welding around 20 kHz

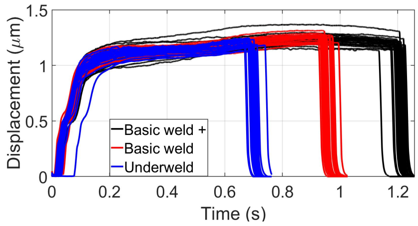

Figure 3: Anvil displacement during welding around 20 kHz

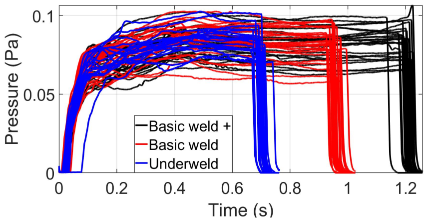

Figure 4: Microphone pressure around 20 kHz

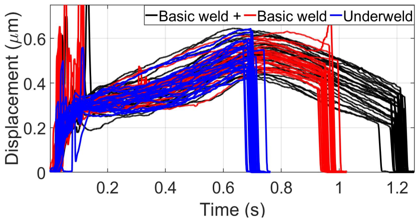

Figure 5: Horn displacement during welding around 40 kHz

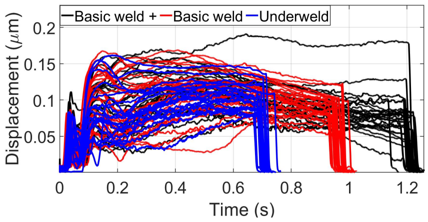

Figure 6: Anvil displacement during welding around 40 kHz

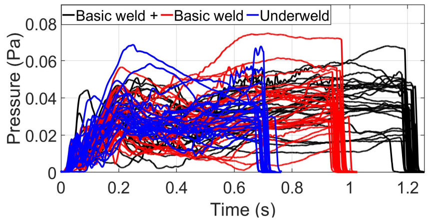

Figure 7: Microphone pressure around 40 kHz

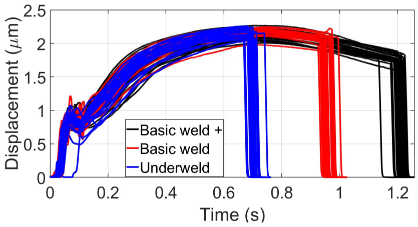

Figure 8: Horn displacement during welding around 60 kHz

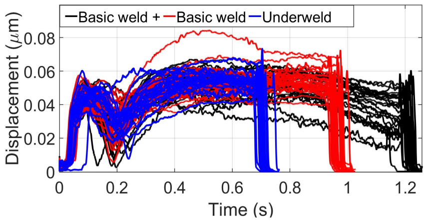

Figure 9: Anvil displacement during welding around 60 kHz

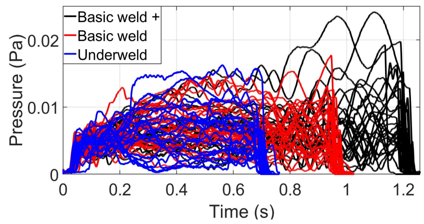

Figure 10: Microphone pressure around 60 kHz

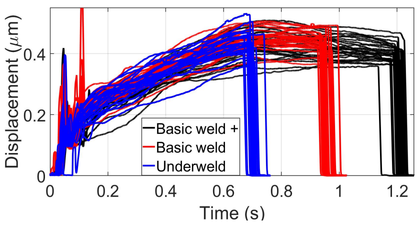

Figure 11: Horn displacement during welding around 80 kHz

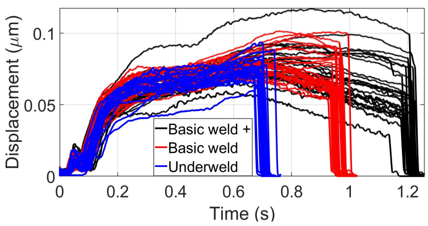

Figure 12: Anvil displacement during welding around 80 kHz

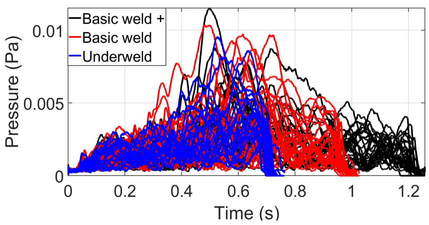

Figure 13: Microphone pressure around 80 kHz

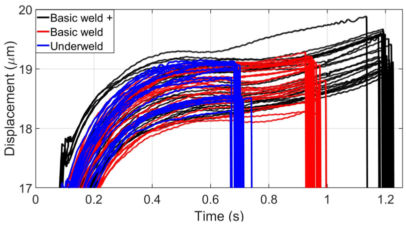

Figure 14: Looking closer at the horn displacement at 20 kHz shows an inflection point at 0.7 s

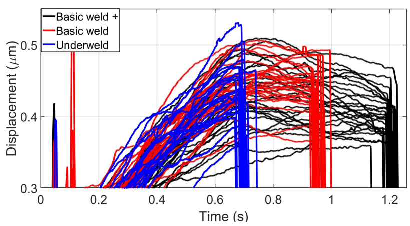

Figure 15: Looking closer at the horn displacement at 80 kHz shows an inflection point at 0.7 s

Analysis of the results

Looking at the horn results, the inflection point is a very strong indicator of passage from underwelds to basic welds. By detecting the change of slope in the displacement, it would be possible to monitor welding and avoid stopping welds too early. To monitor the weld in the basic weld phase and avoid overwelding, one might use a percent change of the amplitude from the inflection point, and stop welding after a certain amount of change. This amount of change would still need to be defined, as it cannot be ascertained from this experiment. This would be possible because the behaviour of the horn seems to stay the same once in the basic weld phase. In addition, based on the obvious change of behaviour of the displacement, the best frequencies to do that would be 20 kHz and 60 kHz: the changes in the trend of the displacement mean obvious changes in its derivative, which is the velocity. Since the velocity is directly measured by a LDV, using it to monitor the welding process might offer faster processing than integrating to get the displacement.

From the anvil results, it might be possible to identify basic welds using the 20 kHz band, because the displacement amplitude reaches its maximum at the end of the basic welds, and decreases for basic welds +. It might also be possible to use the anvil displacement at 80 kHz to identify the passage from underwelds to basic welds by using the inflection point around 0.7 s. However, due to the larger spread between welds, it might not be a very reliable monitoring parameter. As for the 60 kHz band, it does not show strong monitoring potential. However, this does not necessarily mean that the anvil itself is an unreliable monitoring agent. The larger spread in the displacement could be due to other parameters, such as the change in measurement position on the anvil for example. Although the measurement positions of the lasers of both the horn and anvil were changed, the horn does not exhibit as much spread as the anvil. It could be that the anvil is more susceptible to such changes, specially noting the smaller displacement amplitudes of the anvil. If a good measurement position can be found for the anvil, without the need to reposition the laser, the laser might show better results.

The microphone results showed no distinctive pattern between the different welding types, for any of the frequencies. With the experimental setup and the processing used in this analysis, a microphone does not seem to provide any monitoring possibilities.

Conclusion

With the experimental procedure and processing applied in this paper, the sensor with the most monitoring potential is a LDV measuring the oscillations of the part of the horn closest to the welding site, especially around 20 kHz and 60 kHz. Although measurements at that position can be challenging due to particle projection during welding, with an adequate system to deal with the particles, consistent measurements there should be possible. The anvil oscillations also showed potential at 20 kHz and 80 kHz. However, its measurement setup should also be improved. As for the airborne sound, monitoring welding using the current technique was not successful. More research into finding the right processing for the airborne sound is needed.

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