Evaluation of Amplitude Stepping in Ultrasonic Welding

Amplitude stepping is investigated as a means of increasing strength and preventing tool/part adhesion and part marking

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ABSTRACT

Ultrasonic metal welding has many advantages including speed, weld quality, consistency, and efficiency. Further improvements to this can come from enhancing weld strength and weld strength consistency and reducing tool/part adherence by varying the weld amplitude during the process. A series of experiments was conducted using stepped amplitude and a constant amplitude for comparing corresponding weld strengths and weld quality. It was found that the use of amplitude stepping resulted in higher strength values (~8 kN) compared to the use of a constant amplitude (~5.5 kN) and slightly higher weld strength consistency. In addition, amplitude stepping resulted in relatively shorter cycle times when compared to welds made at constant low amplitude. It was also seen that the benefits of amplitude stepping were more pronounced with 3-mm-thick samples compared to welds made with 2-mm-thick samples.

Introduction and Background

Ultrasonic Metal Welding

Ultrasonic metal welding, invented more than 50 years ago, is a process that joins two metals by applying ultrasonic vibrations under moderate pressure. The high-frequency vibrations (typically 20 kHz) locally soften the faying surfaces to form a solid-state weld through progressive shearing and plastic deformation. The oxides and contaminants are removed by high-frequency motion ("scrubbing") producing a pure metal/metal contact interface between the parts allowing intermetallic bonds to form. Beyer states that "ultrasonic welding of metals consists of interrelated, complex processes such as plastic deformation, work hardening, breaking of contaminant films, fatigue crack formation and propagation, fracture, generation of heat by friction recrystallization, and interdiffusion" (Ref. 1).

Wodara (Ref. 2) has theorized that the solid-state weld formation takes place in three stages. The first stage consists of drawing together the surfaces to be welded (faying surfaces), causing them to self align due to the applied normal stress. The second stage is represented by the activation of the atoms at the joining surfaces (i.e., dislocations take place) and their exchange of electrons (a metallic bond formed). The third stage leads to the formation of a strong joint by chemical exchange (diffusion) of atoms occurring between the metallic substances, both locally (weld interface) and in the surrounding areas (weld zone).

One of the issues that can occur during ultrasonic metal welding is adhesion of the tooling to the samples. The Institute of Materials Science and Engineering of the University of Kaiserslautern conducted an investigation with Al sheets and flexible Al wires to understand the adhesion between the welding tip and samples. They concluded that the adhesion is due to high temperatures by applying a TiAlN-coating to the horn tip or using an interlayer (Ref. 3).

It is important to note that while these works have proposed the mechanisms of ultrasonic metal welding, there remains some varied interpretations on the fundamentals.

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KEYWORDS

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Amplitude and Amplitude Stepping

In ultrasonic metal welding, the amplitudes are typically less than 100 μm_{pp}. In addition, the frequencies are typically between 20 and 60 kHz. Because no system is infinitely rigid, any vibrating tool will have varying amplitude depending on the stiffness of the load — amplitude droop. In this case amplitude droop is a loss of vibration amplitude due to attenuation and deflection. In order to characterize the amplitude droop in the system studied in this paper, the amplitude was measured at the horn tip during a weld cycle, as shown in Fig. 1. As seen in Fig. 2, the amplitude droops from 55 to 23 μm_{pp}. This is nearly a 60% amplitude droop. Amplitude measurements were also made at the center of the horn. As shown in Fig. 3, the amplitude at the center of the horn remains relatively constant. Thus, it is believed the droop is localized to the tip (Refs. 4–7).

Ultrasonic metal welding has the advantage of a relatively short cycle time (< 2 s), but its disadvantages are tool/part adhesion and part marking (Refs. 8–13). This paper evaluates a method to improve these disadvantages by using amplitude stepping instead of constant amplitude. Other research evaluated the use of buffer sheets to reduce marking but this approach required a third component be added to the weld configuration (Ref. 13), which is a disadvantage.

The amplitude in ultrasonic metal welding is defined as the peak-to-peak displacement of the horn at its work face as expressed in μm or inches. While most systems operate with constant amplitude at the converter, the amplitude can be con-

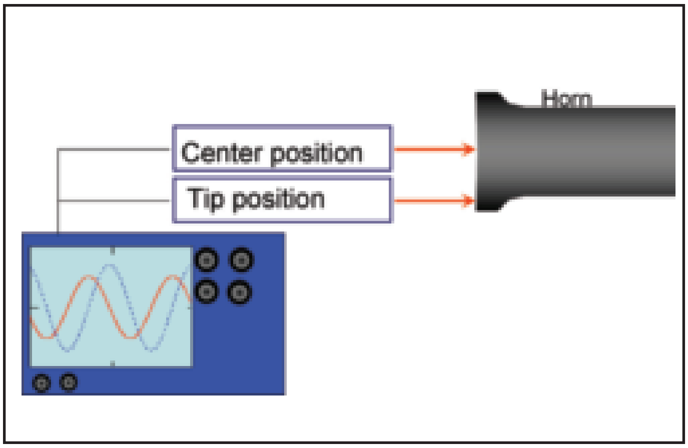

Fig. 1 — Details amplitude measurement at the horn tip.

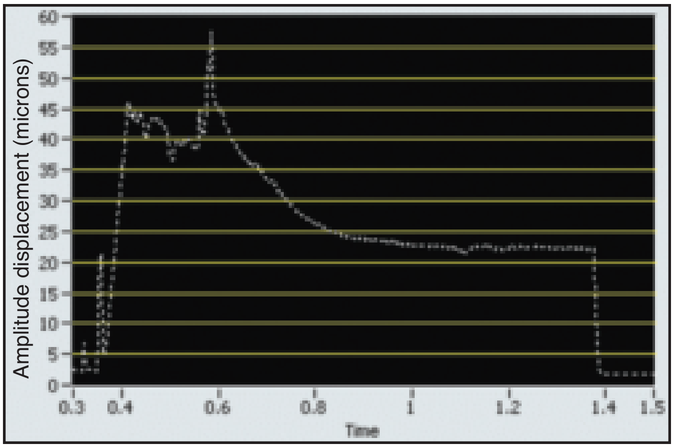

Fig. 2 — Amplitude (microns) at tip as a function of time (ms).

trolled electrically by adjusting the voltage into the converter. Amplitude stepping basically performs a weld using two different amplitude settings. Conventional welds are made with a single preselected value. In the case of amplitude stepping, the first amplitude setting is called the A setting and the second setting is the B setting (relative to a controller with a product code WPC-1 from Branson Ultrasonics). The trigger point for the A to B transition during the weld can be made in a number of ways, such as time, energy level, and peak power value. During the aluminum welding studies, the trigger point was based on time. The time mode was selected based on previous experience and ease of interruption.

Amplitude stepping typically starts with a high A amplitude and drops to a lower B amplitude with a trigger time of 0.2 s for coupons of 2-mm thickness and 0.4 s for coupons of 3-mm thickness. The process generally dissipates high amounts of power into weld samples during the A amplitude phase and power dissipation drops during the B phase — Fig. 4. In this case, it is proposed that the amplitude is profiled to match the various stages of the welding process. For example, the amplitude is relatively high at the start of the welding process where the weld interface is solid/solid and requires significant velocities (amplitude) to promote heating. At the end of the weld cycle, the amplitude is decreased to reduce heating and softening of the sample. In addition, the lower amplitude reduces shearing as the weld forms, reducing sample damage. While the stages of welds are not readily distinguishable, it is proposed that the start and end of stages are significantly different, requiring different amplitudes for optimized conditions. While not previously reported for ultrasonic metal welding, it has been reported for ultrasonic plastics welding (Ref. 14). In addition, it is important to note that because the dampening of the horn and stack assembly (converter, booster, and horn), the response of the mechanical system will be highly dependent on the load (weld). Small, less-stiff loads will not reduce the amplitude as quickly as highly stiff loads regardless of the change of voltage to the converter.

While amplitude stepping varies the displacement of converter, the final vibrational displacement at the weld tip is also dependent on the stiffness of the system as previously detailed in terms of droop. It is believed that the relative droop (%) is relatively independent of converter amplitude.

Objective

The objective of this work was to characterize the use of amplitude stepping and determine whether there are any benefits to its use in terms of weld strength, time, and consistency.

Table 1 — Analysis of Variance for 2-mm-Thick Coupons Comparing the Two Methods: with and without Amplitude Stepping

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F
Amplitude	1	263760.67	263761	10.5284	0.0037
Error	22	551149.33	25052		
C. Total	23	814910.00			

Experimental Procedure

Experimental Design

Welds were made at various energy levels, where the energy level was measured by the power supply. In this case, the power supply digitally integrated the electrical power curve and the ultrasonics remained active until the preset level of energy was dissipated. The typical range of preset energy levels was between 500 and 5500 J, with increments of 10, 200, or 500 J, depending on the weld quality and the equipment capacity. For example, if the energy level was too low, the weld was not complete, and if the energy level was too high, part marking was excessive and the power supply frequently overloaded. This range was selected based on screening experiments and experience. Ten welds were made with each energy level in increasing order of the weld energy level setting and were not randomized. Weld amplitudes that were studied ranged from 40 to 60 μm_{pp}. Additional details of the amplitude settings are defined in the equipment section. The weld force setting was approximately 3360 N.

In the screening experiment, welds were made over a wide range of energy values with constant and amplitude stepping to compare the benefits of amplitude stepping. As further detailed below, the amplitude stepping was controlled by a time setting.

Materials

The ultrasonic metal welding was completed with aluminum 5754 coupons of two different thicknesses: 2 and 3 mm. The pretreated and prelubricated AA5754-H111 aluminum alloy was used in "as-received" condition. The pretreatment

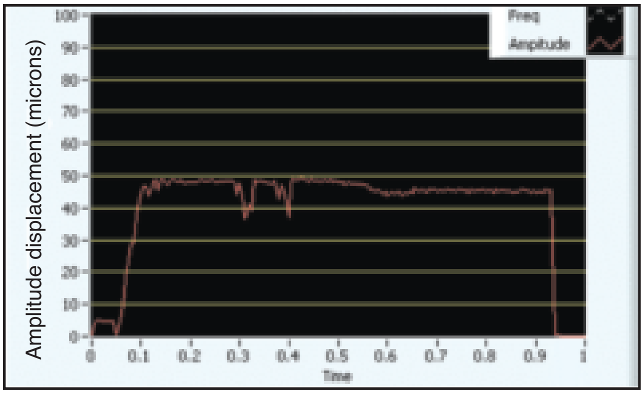

Fig. 3 — Amplitude (microns) at center of horn as a function of time (ms).

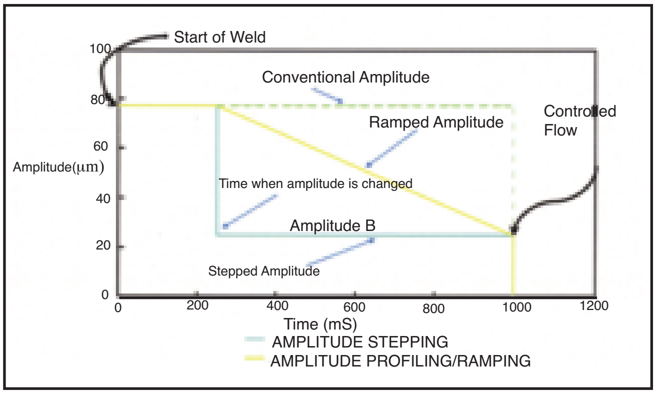

Fig. 4 — Example of amplitude profiling.

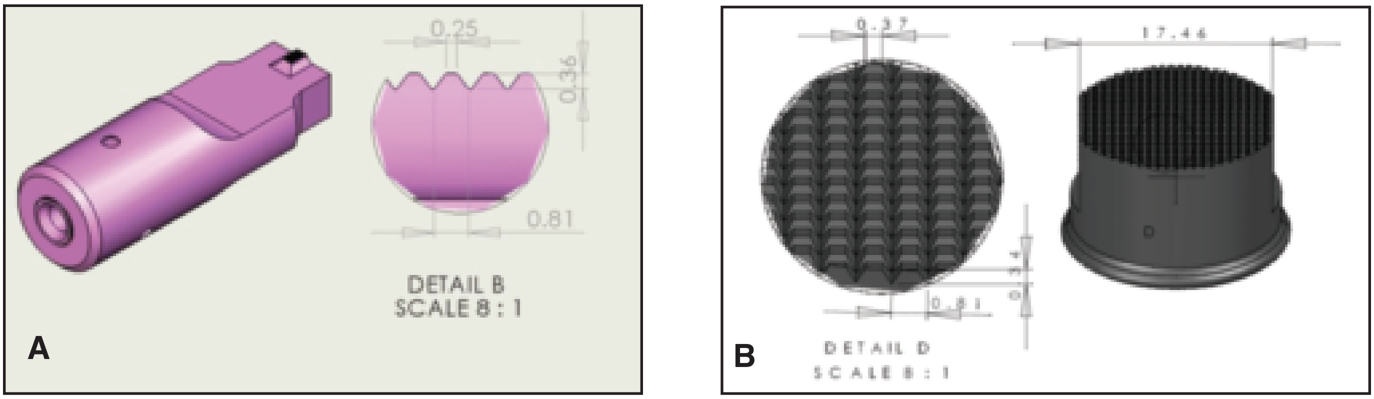

Fig. 5 — A — Details of welding tip; B — anvil tip design (in mm).

was a silicate coating and the lubricant a dry-film lubricant. The aluminum was purchased from Novelis, Inc. The weld samples were made from two 25.4- × 100-mm overlapping coupons, with a 25.4-mm (1-in.) overlap and the weld centered on the overlap.

Equipment

The weld amplitudes were varied by a WPC-1 controller manufactured by Branson Ultrasonic Corp. The controller has the ability to vary the amplitude profiling at two separate values (A and B) with several switch-over modes. The switch-over mode is the parameter that defines when the amplitude is switched from value A (typically 60 μm_{pp}) to B (typically 43 μm_{pp}). In this work, only time was evaluated as this is the simplest mode to visualize and it was decoupled from other welding parameters. In screening experiments, different amplitudes (50 and 58 μm_{pp}) were also studied, but the resulting weld strength and consistency was slightly lower (~3000 N) than those described in this paper. In addition, screening experiments showed that best results were obtained with an amplitude profile of 60 (amplitude A)–43 (amplitude B) μm. Welds were made at various energy levels, where the energy level was measured by the power supply. The welding system was manufactured by Branson Ultrasonic Corp. The horn was a knurled tip and the anvil was a "flex" anvil. The details of the horn and tip are detailed in Fig. 5. The tip of the horn face was 7.8 × 5.1 mm². The weld force was held constant at 3360 N. A squeeze time of 0.2 s was used to allow the force to fully develop prior to sonic activation. Sufficient time (2–3 min) was allowed between the welds, and the tooling temperature remained consistent.

Characterization

All welds (10 samples for every energy level) were tested in tension at a cross-head speed of 10 mm/min resulting in shear loading at the weld zone. The maximum sustained load was used to calculate the ultimate strength. Shims were not used in the grips with the sample and thus bending stresses were not minimized. It is important to note that while weld size was generally proportional to weld energy, it was not recorded and only final weld strength was reported in terms of maximum load.

Results and Discussion

Amplitude stepping experiments were conducted on coupons of 3- and 2-mm thickness, and weld strength was studied as a function of the preset energy values calculated as described in the introduction.

Study of the Shear Weld Strength Function of Weld Energy

In the experiments comparing amplitude stepping and constant amplitude for 2-mm-thick coupons, weld strength as a function of weld energy is seen in Fig. 6.

Table 2 — Analysis of Variance for 3-mm-Thick Coupons Comparing the Two Methods: with and without Amplitude Stepping

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F
Amplitude	1	1246237.8	1246238	14.2505	0.0026
Error	12	1049427.1	87452		
C. Total	13	2265664.9			

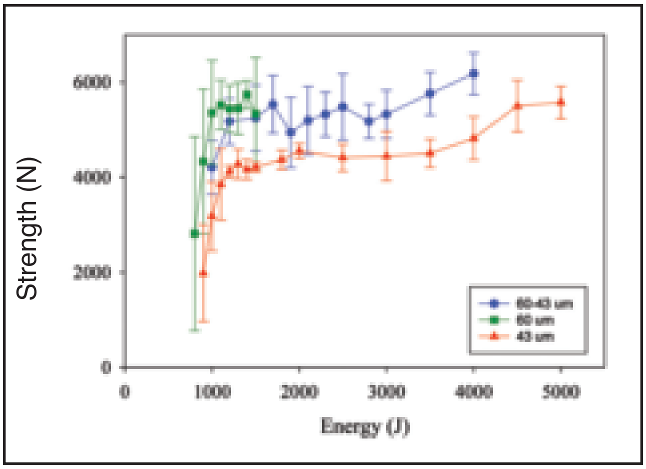

Fig. 6 — Strength as a function of energy for amplitude stepping and constant amplitude for 2-mm coupons (um = μm).

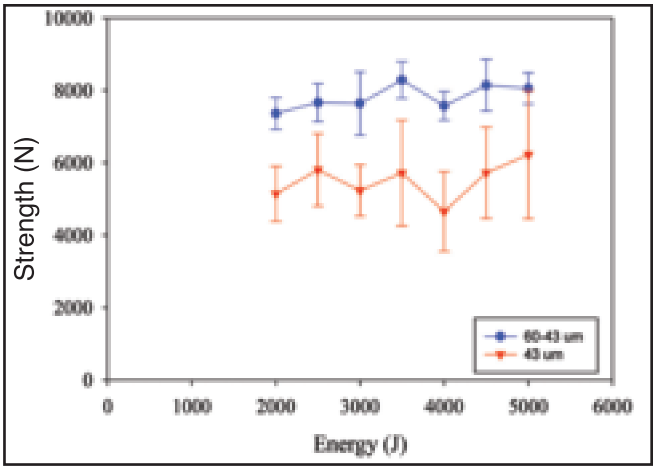

Fig. 7 — Strength as a function of energy for 3-mm-thick coupons at constant amplitude of 43 μm and amplitude stepping of 60–43 μm.

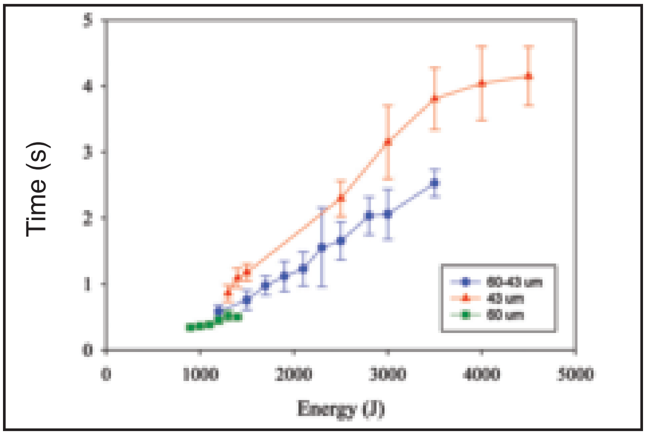

Fig. 8 — Time as a function of energy for 2-mm-thick coupons at constant amplitude of 43 and 60 μm, and amplitude stepping of 60–43 μm.

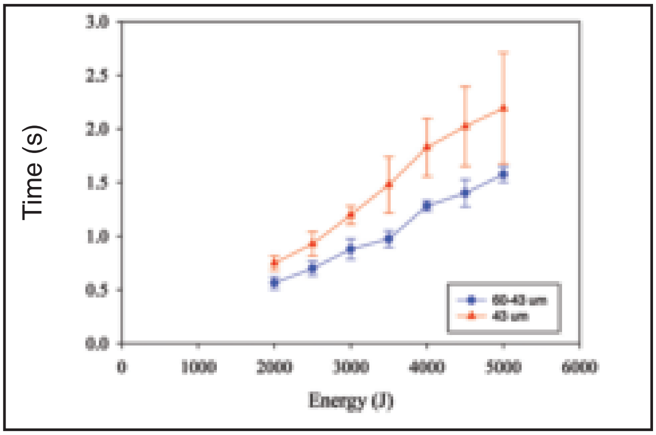

Fig. 9 — Time as a function of energy for 3-mm-thick coupons at constant amplitude of 43 μm and amplitude stepping of 60–43 μm.

The benefits of using amplitude stepping of 60–43 μm over the constant amplitude of 40 and 60 μm, respectively, is seen in the increased strength. That is to say, with amplitude stepping there are slightly lower variations and higher values in terms of weld strength. In more detail, the amplitude stepping resulted in maximum weld strength of over 6.0 kN. In comparison, the maximum weld strength achieved by using both constant amplitude of 40 and 60 μm, respectively, was only slightly over 5.5 kN. It is important to note that with amplitude stepping, final amplitude of 40 μm was not used because of frequent power supply overloads. By slightly increasing the constant amplitude value to 43 μm, it was found that overloading could be eliminated. It is also important to note that higher energy levels with a constant amplitude of 60 μm resulted in significant part marking and reduced sample strength as noted in the decrease in strength at an energy level of 1500 J.

It is important to note that the higher constant amplitude, 60 μm, resulted in higher weld strength variation and more part marking and tool/part adherence compared to the other amplitudes/profiles studied. Due to these problems, the 60 μm constant amplitude was not evaluated for the 3-mm-thick coupons.

Figure 7 shows shear weld strength as a function of the weld energy for 3-mm-thick coupons welded at constant amplitude and amplitude stepping, respectively. Welding with an amplitude stepping of 60–43 μm results in maximum shear weld strength of approximately 8.3 kN. In comparison, welding at constant amplitude of 43 μm results in a lower maximum shear weld strength value of approximately 6.2 kN. Thus, there is an approximately 34% increase in the shear weld strength when welding 3-mm-thick coupons at amplitude stepping compared to constant amplitude. It was also important that the weld time (cycle) for the welds made with amplitude stepping were typically less than 50% of the weld times for a given energy level for those welds made with a constant amplitude of 43 μm. This was expected because of the relationship between power and amplitude (Ref. 4).

Study of the Weld Time Function of Weld Energy

For the 2-mm-thick coupons, Fig. 8 shows weld time as a function of weld energy with both a constant amplitude of 43 μm and amplitude stepping of 60–43 μm. It can be seen that with amplitude stepping of 60–43 μm, the weld time is lower when compared to the weld time with constant amplitude of 43 μm. Thus, for coupons of 2-mm thickness, a reduction in weld time of approximately 60% was achieved by using amplitude stepping over the constant amplitude of 43 μm. This is expected since with amplitude stepping the higher amplitude portion of the weld cycle dissipates more energy. It is also seen that for the constant 43-μm amplitude there appears to be an inflection point at approximately 3500 ms. It is believed that this corresponds to the time to develop a rigid, fully developed and solidified weld,

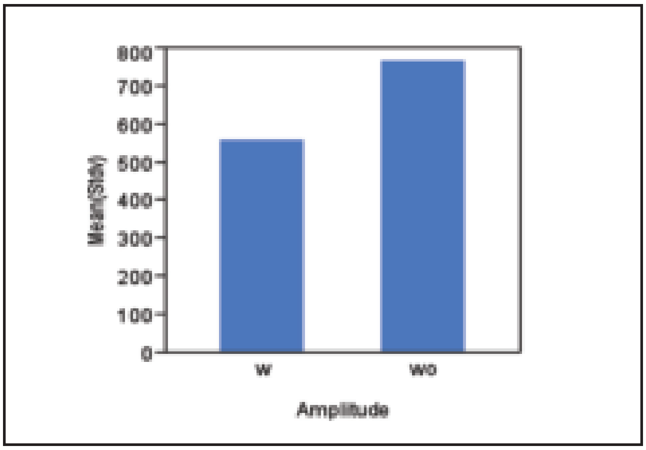

Fig. 10 — Bar chart showing the mean of the standard deviations (N) for 2-mm-thick coupons with (W) and without (WO) amplitude stepping.

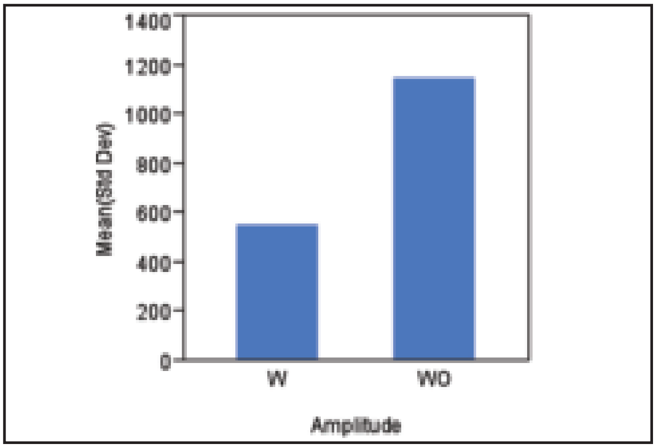

Fig. 11 — Bar chart showing the mean of the standard deviations (N) for 3-mm-thick coupons with (W) and without (WO) amplitude stepping.

which dissipates high energy levels. That is to say, the stiffness of the weld is sufficiently high to dissipate higher power (rate of energy) levels, reducing the time required to dissipate additional energy.

Weld time as a function of weld energy for the 3-mm-thick coupons at both a constant amplitude of 43 μm and amplitude stepping of 60–43 μm is illustrated in Fig. 9. Again it is seen that for any given energy value, the weld time is less for amplitude stepping compared to a constant amplitude. For coupons of 3-mm thickness, an approximate reduction of 70% in weld time was achieved when using amplitude stepping over the constant amplitude.

Statistical Study Comparing the Amplitude Stepping with Constant Amplitude

To confirm the significance of the difference in consistency, a statistical comparison between the two groups (Group 1: standard deviations of the weld strength values resulted from welding with amplitude stepping, and Group 2: the standard deviations of the weld strength values resulted from welding with constant amplitude) was performed.

Table 1 details the analysis of variance tested between the two groups for 2-mm-thick coupons. It can be seen that the probability p-value is less than 0.05, which indicates that there is a significant difference between the means of the standard deviations of the two groups. To further characterize the difference between the two groups, Fig. 10 shows that Group 1 (welding with amplitude stepping) resulted in a lower value of the standard deviation. Thus, with welding 2-mm-thick samples, amplitude stepping leads to more consistent welds.

Table 2 represents the analysis of variance tested between the two groups for the 3-mm-thick samples. It is seen that the p-value is less than 0.05; thus, there is a significant difference between the means of the standard deviations of the two groups. In more detail, Fig. 11 shows that the Group 1 (welding with amplitude stepping) has a lower value in standard deviation, proving that welding 3-mm-thick samples with amplitude stepping results in more consistent welds.

Conclusions

In this study it was demonstrated that amplitude stepping allows for better matching of amplitude to the various stages of the weld. For example, by initiating the welding process with relatively high amplitude, fast heating and efficient welding can be promoted. Once the material is softened, the amplitude can be reduced to minimize shearing of the weld. Thus, amplitude stepping increases weld strength and reduces weld time. However, it was seen that amplitude stepping did not affect tool/part adhesion, thus there was no noticeable improvement of the horn adhesion.

Thus in summary:

- Amplitude stepping allows better matching of amplitude to the various stages of the weld.
- Amplitude stepping increases weld strength and reduces weld time.

In conclusion, independent of the thickness of the coupons to be welded, amplitude stepping has positive impacts on the shear weld strength, time, and consistency. However, the benefits of the amplitude stepping appear more pronounced for the 3-mm-thick coupons compared to the 2-mm-thick coupons.

Acknowledgment

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