AMPLITUDE AND FORCE PROFILING: STUDIES IN ULTRASONIC WELDING OF THERMOPLASTICS

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ABSTRACT

This paper reviews effects of amplitude and force control during the ultrasonic welding cycle of thermoplastics. In a previously published paper, the benefits of amplitude profiling were detailed as increased strength and reduced part marking. This paper reviews the mechanisms for such observations and details additional benefits, such as decreased residual stresses and increased solvent resistance of the resulting bonds. Force profiling was also studied. Similar results were found. However, one notable difference was that force profiling could decrease weld time. Lastly, by combining amplitude and force profiling, weld strength, consistency and weld times were further improved compared to any approach studied so far.

INTRODUCTION

This work was undertaken to study the effects of varying the vibrational amplitude and weld force during the ultrasonic welding of thermoplastic components. Currently, most welds are made with a predetermined vibrational amplitude which is held constant during the cycle. In addition, since most welding systems are pneumatically driven, the weld force is relatively constant or increases during the cycle. Because a thermoplastic goes through several phases during a weld cycle, it has been suggested that each stage may benefit from different vibrational amplitudes and forces to increase weld quality in terms of strength, consistency, cycle time and cosmetics.

STATEMENT OF THEORY AND DEFINITIONS

Ultrasonic welding is one of the most common techniques for joining thermoplastic sub-assemblies, such as computer diskettes. Its primary advantages are its short cycle times and moderate capital costs. Typical manual cycle times are less than three to five seconds, resulting in production rates above 500 units per hour.

The technique works by applying relatively high stresses to the parts being joined to induce hysterisis heating at the bond line. Figure 1 shows a schematic of the process. After loading the parts and initiating the cycle, the ultrasonic tooling is moved towards the parts to be joined. The ultrasonic energy is activated when a particular distance or force has been reached by the tooling. The tooling applies an up and down motion at a frequency between 20 and 40 kHz to the upper part to be joined. The ultrasonic energy propagates through the upper part and is concentrated at the faying surfaces (surfaces to be joined) by means of an "energy director". The energy director is a molded-in stress concentrator that locally deforms under the actuator force and stress induced by the ultrasonic energy. The local deformation of the energy director initiates heating and melting from hysterisis losses of the plastics. While there are other types of joint designs for ultrasonic welding of thermoplastics, such as shear joints, this work focused on the energy director design. The average heating rate (Qavg) of the energy director is governed by the general equation:

$$\dot{Q}_{avg} = \frac{\omega \varepsilon_o^2 E''}{2} \qquad (1)$$

ε_o = Strain ≈ amplitde

ω = frequency

E' = Complex Loss modulus

Once melting occurs, the molten energy director flows across the faying surface forming a weld bead. The rate of flow is determined by a number of variables but is primarily effected by the temperature of the melt and the force applied to parts. The melt solidifies under pressure to form a fused joint after the sonics are discontinued.

An important component of Equation 1 is that the complex loss modulus is strongly temperature dependent. As the plastic approaches its glass transition or melt temperature, its ability to transform mechanical energy to thermal energy increases several fold as a result of the increased loss modulus of the plastic. Thus, once heating is initiated, the bond line temperature rises very rapidly, typically over 1000°C/S.

Equation 1 defines that heating is proportional to the square of the applied strain, which is proportional to the vibrational amplitude of the horn/tool face. Thus, bond line heating can be controlled by varying the amplitude. Thus, it is theorized that the amplitude is a critical variable in the squeeze flow rate of the plastic. At higher amplitudes, the average bond line heating rate is higher which inturns causes the temperature to rise to higher levels as defined in Equation 1. This results in the melt having a higher flow rate. High flow rates result in relatively strong molecular alignment and significant flash. Usually this alignment is orthogonal to the desired loading stress and can result in fractures initiated at discontinuities. In addition, flash is usually not desired because of cosmetic considerations.

While there are undesirable effects to high vibrational amplitudes, they are necessary to achieve proper melting at the bond line and fully weld along the faying surface. Insufficient amplitude can also result in nonuniform melt initiation and/or premature solidification of the melt.

Work described in this paper explored using controlled profile of vibrational amplitudeand force to achieve a more robust and repeatable bond in a minimal cycle time.

DESCRIPTION OF EQUIPMENT AND PROCESSES

In the majority of this work, the proposed American Welding Society (AWS) sample, detailed in Figure 2, was used. In most experiments, the samples were tested in tension using a Tinius Olsen Tensile Tester 5000 (22,241 N Load Cell with a 50% range setting). The cross head speed was 0.003 mm/S. The highest load supported by the sample was recorded. Most samples failed in fracture; however, some yielded prior to fracture. The materials used in this study were ABS, Polycarbonate (PC) and Polyamide. The parent material strengths were 46.9, 64.5 and 76.2 MPa, respectively.

The amplitude and force was controlled by a specialized D/A plug-in board in an IBM-based PC. The D/A plug-in board allowed the amplitude and force to be varied at multiple levels. The actuator was a Branson 900 series AES actuator fitted with a proportional valve. The average force change rate was 9186 N/S. The power supply was a Branson 920MA.

APPLICATION OF EQUIPMENT AND PROCESSES

In all welding trials, unless otherwise noted, the samples were welded with a cycle time that resulted in collapse or displacement of 0.48 mm.

There were three tasks in this study. Below is a summary of these tasks and the experiments conducted in each:

1. Determine mechanisms of increased weld strength by amplitude profiling by comparing the results of the following tests of welds made with and without amplitude profiling (PC only):
    - Measure residual stresses in bondline using GE solvent test ;
    - Measure molecular alignment of polymer chains within the bondline using FTIR microscopy; and
    - Measure polymer degradation within bondline using GPC of the weld flash.
2. Determine benefits of force profiling with the following experiments (PC, ABS and Nylon):
    - Prepare welds with constant weld and hold forces between 220 and 1334 N (trigger force=weld force);
    - Evaluate the effect of weld and hold force on weld strength and weld time; and

- Evaluate the effect of force profiling on weld strength and weld time and compare these results to welds made without force profiling.

3. Determine the benefits of combined amplitude and force profiling in the following experiments (PC, ABS):

    - Prepare welds with various constant weld and hold forces at various amplitudes (50 to 125 ⌨mpp); and

- Prepare welds with varying force and amplitude profiles over the ranges detailed above; and
- Evaluate the effect of force and amplitude profiling on weld strength and weld time and compare these results to welds made without profiling.

PRESENTATION OF DATA AND RESULTS

Table 1 contains the conditions used to weld the PC AWS samples that had the level of residual stresses measured. Table 1 also contains the results of these tests.

It is seen that there is a 34% decrease in residual stresses when amplitude profiling is used. The average weld strength for welds made without profiling is 27.3±9.9 MPa and with profiling the average strength is 45.0±8.1 MPa, a 64% increase (Sample Size {n}=30). Thus it may be theorized the increase weld strength is only partially due to the decrease in residual stresses.

Figure 3 shows the results of the FTIR microscopy of welds made with and without profiling. The Y axis indicates the orientation function. A value of 1 indicates that all the chains are perfectly aligned in the direction of weld (parallel to the weld surfaces). A value of -0.5 indicates that all the polymer chains are perpendicular to the weld direction. If a weld is loaded in pure tension, this would provide the maximum strength, since the load would be carried by primary bonds. The weld line distance value (X-axis) indicates the distance from the weld-center-line where the measurement was taken. As can be seen in Figure 3. most of the chains are randomly orientated (indicated by an orientation function=0). However, in the weld made without amplitude profiling, the chains are slightly more orientated in the direction of the squeeze flow, which results in a weaker structure when loaded in tensile. It is interesting to note that the orientation is not symmetrical about the weld-center-line, especially for the weld made without amplitude profiling. There appears to be slightly more orientation in the direction of weld (flow) on the energy director side of the weld.

The last study measured the molecular weight of the weld flash to determine why welds made with amplitude profiling are stronger than welds made without amplitude profiling. It was assumed that any polymer degradation in the bondline material would be proportional to degradation of the flash. Table 2 summarizes the results.

It is seen that compared to the as molded material (un-welded sample), there is no measurable loss of molecular weight in any of the samples. In fact, there appears to be a slight increase which is indicative of further polymerization or cross-linking. Because the chemistry of PC would not suggest that cross-linking would occur, it is believed that indicated increase in M.W. is strictly an artifact of the measuring technique which has an accuracy of 1000 g/mole. Thus, there is no evidence that amplitude profiling aids in reducing polymer degradation.

Results of determining benefits of force profiling

The first experiments evaluated the effect of weld force (no force profiling) on weld strength and weld time. Table 3 contains a summary of the welding conditions used in these experiments.

Figure 4 shows the relationship of weld strength and weld/hold force for the materials studied. It is important to note that all samples were welded with the same amount of collapse (0.48 mm). It is seen that weld strength is generally inversely proportional to weld force. This is consistent with other studies and other welding processes that detailthat high weld force promotes strong molecular alignment and results in weaker welds. At the lower weld forces (<455 N) this relationship does not hold true due to sample warpage.

Figure 5 shows the required weld time to achieve the same amount of collapse for the different weld forces. As expected, the weld time is inversely proportional to weld/hold force. Thus, from a manufacturing perspective, higher weld forces will result in the highest production rates, but with less quality/strength parts. However, by varying the force during the weld cycle it was found that both short cycle times and strong welds could be achieved simultaneously. This is seen in Figure 6. Force profiling resulted in maximized weld strengths while the weld times (noted besides the relevant bar graph) were decreased by 43% and 28% for PC and Polyamide respectively. The welding conditions are summarized in Table 4. In PC the weld strength is not increased as expected since the final weld force is low and allows the polymer chains to solidify in a relaxed state. However, with Polyamide there is a significant increase in strength, from 24 to 41 MPa, a 71% increase. Micrographs of the weld zone revealed that the increase is due to an increase in weld area resulting from the energy director being driven in the bottom part during the high force stage of the welding cycle. This can be seen in Figure 7, a cross-sectional micrograph of welds made with and without force profiling, respectively. It is seen that within the weld made with force profiling, the energy director is enbedded into the lower sample.

Results of determining benefits of combined amplitude and force profiling

Based on the results of the previous experiments, welds were made where the amplitude and force were both profiled. Figure 8 show the result from the PC and ABS samples. It is seen that benefits from both amplitude and force profiling can be seen compared to welds made without any profiling; increased strength and decreased weld time (again noted besides the relevant bar graph). The increased strength comes from the reduced molecular alignment, as previously detailed. The reduced cycle time is a result of using high weld forces to initiate the weld. Thus, in summary, a relatively high amplitude and force is used to start the weld quickly and a relatively low amplitude and force is used complete the weld with minimal molecular alignment. Figure 9 shows a typical cycle graph for welds made with amplitude and force profiling.

CONCLUSIONS

The Conclusions/Figures from this study are:

1) Amplitude profiling promotes stronger welds due to reduced residual stresses and increased molecular randomness.

2) Amplitude profiling does not reduce polymer degradation.

3) Force profiling can reduce cycle times by 28 to 43%.

4) Force profiling can increase weld strength with relatively low modulus materials, such as nylon.

5) The combination of amplitude and force profiling can increase weld strength and decrease cycle times.

FIGURES

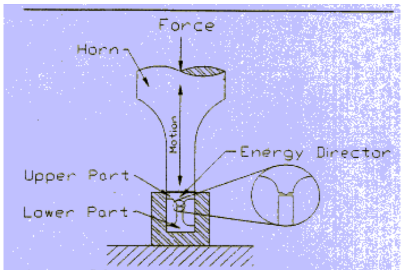


Figure 1. Schematic of Ultrasonic Welding Process

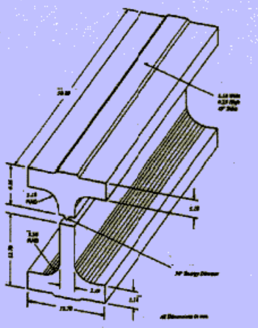


Figure 2. Details of AWS Sample

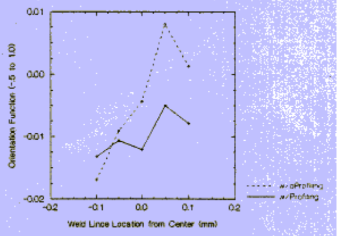


Figure 3 Polymer Orientation in Weld Line (PC)

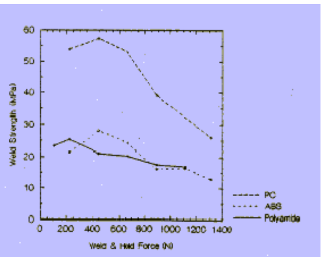


Figure 4 Plot of Weld Strength as Function of Weld Force

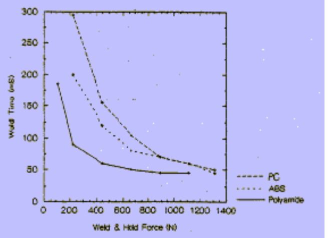


Figure 5 Plot of Weld Time as Function of Weld Force

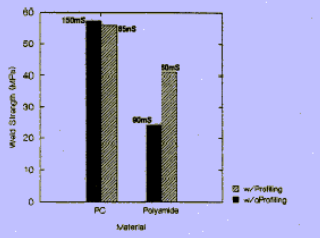
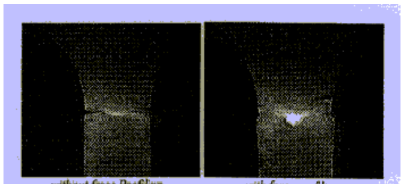


Figure 6. Comparison of Welds made with and without force profiling (Constant Collapse=0.48 mm)



without force Profiling *with force profiling*

Figure 7. Micrograph of Nylon Joint Area Made with and without Force Profiling

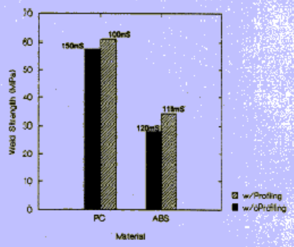


Figure 8 Comparison of Welds Made with and without Amplitude and Force Profiling(Constant Collapse=0.48 mm)

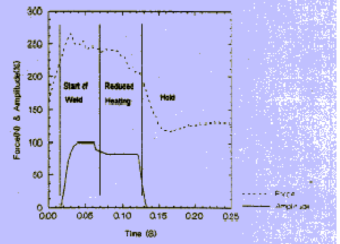


Figure 9 Typical Cycle Graph of Weld Made with Amplitude and Force Profiling (ABS)