Generating Ultrasonically Welded Parts with Improved Strength and Reliability for Critical Applications in Medical Device Manufacturing by Utilizing Advanced Melt Flow Controls of Servo Driven Ultrasonic Welding Equipment.

Alex Savitski, Ph.D., Leo Klinstein, Kenneth Holt, David Cermak, Dukane Corporation

Abstract

Ultrasonic welding of thermoplastics is widely used by many industries to fuse together two parts in a short time without additional consumables. The development of servo-driven ultrasonic welders introduces unique levels of control. This study pursues previous research and investigates the capabilities of servo-driven welders to produce stronger welds. It focuses on developing a more robust and better controlled joining process for medical devices that increases the strength and reliability of welds without fully collapsing the joint or creating excessive weld flash. Experiments were completed in which the weld velocity was varied, and the resulting strength and appearance of the welds were evaluated against the *intense* requirements of the medical industry. Analysis of weld cross sections suggests that higher weld strength was associated with a linearly increasing weld velocity profile.

Introduction

Welds for medical applications must meet very stringent requirements. For example, medication delivery devices often require thousands of welds tested without a single leak for the process to be qualified for manufacturing. At the same time, engineers have to be mindful of limiting the collapse to avoid weld flash being extruded from the joint area, a result which would disqualify the weld based on appearance and performance criteria. Given real-life variation of energy director height resulting from molding process variations, this process typically runs in a very narrow window.

During a typical ultrasonic welding cycle most of the plastic melting takes place in the energy director body, and its molten material forms a bond [1]. Generating maximum weld strength when using pneumatic welding systems typically requires that the weld distance be set close to the nominal energy director height, so the energy director will be completely melted. Failure to achieve full melt often results in lower strength, incomplete welds, and poor appearance of welded assemblies. As the actual height of the energy director varies, there is always a risk that some of the parts with a shorter energy director will have excessive flash, and if the programmed weld distance is reduced to avoid that, then there is a risk of generating non-hermetic welds.

This study investigates the effect of weld velocity profiling on developing a more robust and better controlled joining process capable of achieving strong and reliable welds without fully collapsing the joint while minimizing the risk of excessive flash.

Experimentation

These trials were conducted as a continuation of research undertaken by Dukane in 2015 and reported at ANTEC 2015 [2]. The data generated in that study was used to set the initial parameters for these experiments. In these trials, the total weld collapse was programmed to be 68-70% of the 0.406 mm ED height.

Microscopic characterization of the weld zone was undertaken. The effect of the precise control and variance of the weld velocity was explored. Three different weld velocity profiles were investigated for their effect on strength and process repeatability.

Analysis of the data correlates visual inspection and tensile strength of welded samples resulting from the use of various weld velocity profiles. The resultant parts were sectioned and studied under a microscope, using both polarized and non-polarized optical elements for the visual inspection. Tensile tests were conducted and peak breaking force was recorded.

Materials

The parts used for this experimentation were Dukane ISTeP parts with rounded, 0.406 mm radius energy directors (EDs), molded of Sabic Lexan grade 121R polycarbonate as shown in Figures 1, 2 and 3. This part was developed by Dukane to provide a test specimen for ultrasonic welding, and can be manufactured with four different joint designs [3].

Figure 1: Innovative ISTeP Test Part.

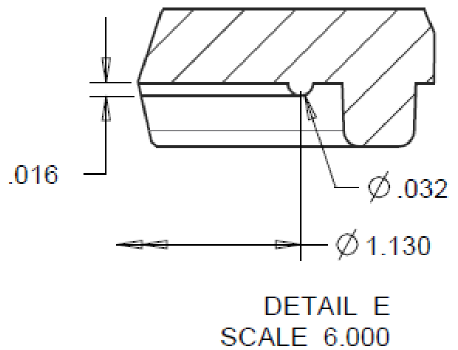

Figure 2. ISTeP round ED design (Imperial units shown).

Figure 3. A cross-section of a round ED on an ISTeP part prior to welding.

Equipment

Experiments were conducted using Dukane's 30 kHz 1800 W iQ Servo Ultrasonic Welder, model # 30HS180-2Q-P7, with Melt-Match® technology and an HMI running iQ Explorer II software for data collection and analysis. The tooling was a flat-face, high-gain horn (with a gain factor of 2) and a custom-made, drop-in style fixture as pictured in Figure 4.

Advanced control features of the servo-driven system were utilized in this experiment including Melt- Detect™, which allows the press to hold its position on the assembly at the initiation of welding until a drop in force is detected. When the magnitude of the force drop reaches a user programmable value, expressed as a percentage, the downward movement of the stack continues. This drop in force indicates the presence of an initial molten layer [4]. The Melt-Match® feature controlled weld velocity. These features are significantly different than those traditionally utilized in pneumatic welders, and based on previous research, allow precise control of the welding process [4, 5, 6, 7, 8, 9, 10, 11].

Figure 4. Welder and tooling used in experimentation.

For tensile testing, a Com-Ten Industries ComTouch Total Control System with Variable Speed Test Stand and TSB3A load cell with 22,250 N capacity (accuracy of +/- 0.5%) was used with a custom designed fixture, as in Figure 5. Failure load was identified by peak tensile force at break.

Figure 5. Custom pull test fixture.

Results and Observations

Three different velocity profiles were examined: 1.0 mm per second constant profile, 0.5 mm per second constant profile, and a linearly increasing profile from 0.25 to 0.4 mm per second. Samples for each profile were fractured on a tensile testing machine, and the load at break was recorded in Figure 6.

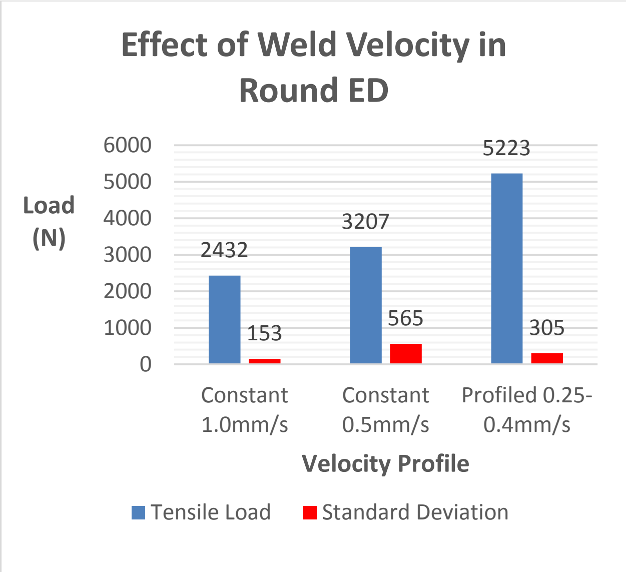

Figure 6. Average failure load as a function of weld velocity. Thirty samples evaluated at each velocity profile.

The welds produced using the linearly increasing velocity profile were strong despite the fact that the energy director collapse during weld was limited to 68-70% of the nominal height. Worthy of note is the fact that significant numbers of these welds failed through parent material, not the weld joint, and that the failure load of others was close to parent material strength. An example of failure through parent material is shown in Figure 7.

Figure 7. Typical tensile failure through parent material.

Parts were cross-sectioned through the weld area and the shape of the heat affected zone was measured on a microscope using imaging software. Cross-sectional images of the weld areas resulting from different velocity profiles show a strong correlation between the shape of the zone and the strength. A smaller, bean-shaped weld zone, not completely covering the full width of the contact area between the parts, showed less strength. These results were consistent with constant velocity profiles, as in Figures 8 and 9. A larger and more uniform melt layer, proliferated into both parts, was characteristic of linearly profiled velocities and produced stronger welds, as in Figure 10.

The depth of penetration was observed as 361 microns for the sample produced with a uniform melt velocity of 1 millimeter per second, while the zone for the sample produced with a linearly increasing weld velocity profile was 690 microns, or nearly twice as deep. It appears that the precise control of the melt achieved with a linear profile allows greater heat propagation early in the weld cycle, and results in a deeper, more consistent and therefore stronger weld. The generation of this deeper melt zone had not been envisioned by this team prior to this investigation, and has also been observed in parts other than those used in this study.

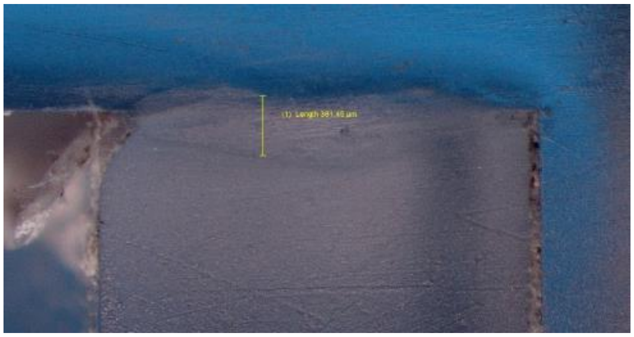

Figure 8. Constant weld velocity of 1.0mm/s. Melt penetration 361 microns. Average Failure Load 2432 N.

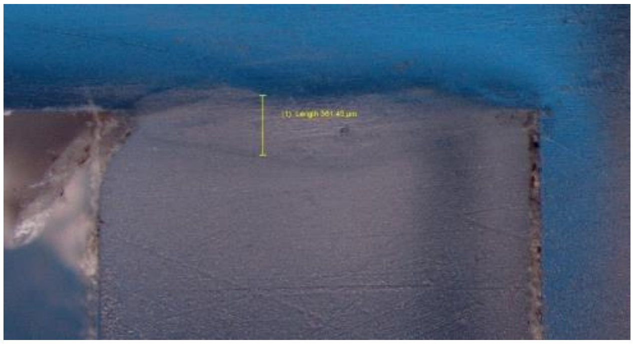

Figure 9. Constant velocity profile of 0.5mm/s. Melt penetration 379 microns. Average Failure Load 3207 N.

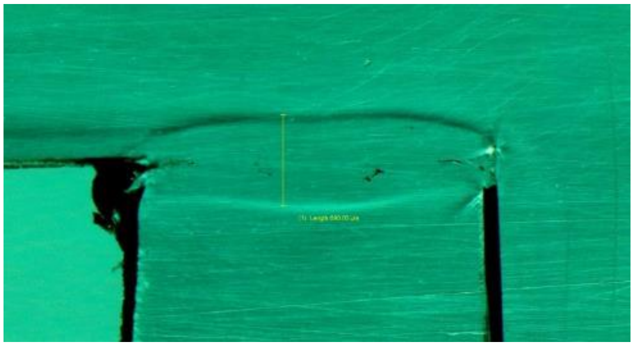

Figure 10. Linearly increasing velocity profile from 0.25 to 0.4mm/s. Melt penetration 690 microns. Average Failure Load 5223 N.

In welds performed with a linearly increasing velocity profile the melt layer buildup takes place not only in the volume of the energy director, but also within the mating part surfaces. This forms a uniform melt layer in the contact area of both parts and is apparent in the melt zone shape observed under the microscope. This zone extends into both parts of the assembly, and its size correlates strongly with high strength welds.

Cross sections were next analyzed under a microscope using a polarized light filter. This technique is commonly used to evaluate residual stress levels within transparent plastic parts. There is always some level of residual stress within welded parts due to melting, reforming and cooling during the weld. Per J. Feingold's article, "when viewed with polarized light, stressed areas of polymers are visible to the eye as a series of multicolored bands or fringes. This fringe pattern, sometimes referred to as birefringence, can be interpreted as varying levels of stress at a specific point and in a particular direction through the material" [12].

Characterization of these samples shows a marked decrease in residual stress levels in the weld boundaries of those parts generated with a linearly profiled weld velocity. When viewing the photos, note the reduction of the number of colors in Figure 13 when compared to the weld region in Figures 11 and 12. Color changes are so tightly packed in the 1.0 millimeter per second sample (Figure 11) that the weld region appears almost grey. Conversely, the sample with a linearly profiled velocity has five distinct color bands in the weld region (Figure 13). This is indicative of lower residual stresses in that weld.

Additionally, the preponderance of fringes towards the edges of the weld region shows the changing levels of internal stress. More closely packed fringes, as in Figure 11, indicate higher, more varying stress levels than the more homogeneous region seen in Figure 13. The frequency with which these fringes appear in the weld region correlates to strength, with fewer fringes resulting in stronger parts.

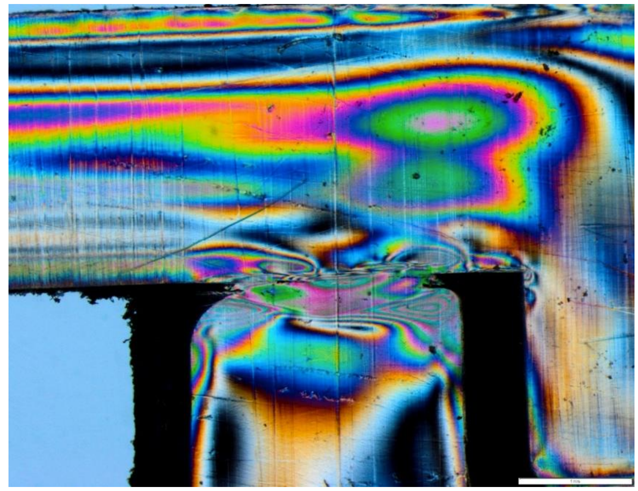

Figure 11. Melt Zone Image for Sample Welded with Weld Velocity 1.0 mm/sec photographed in polarized light.

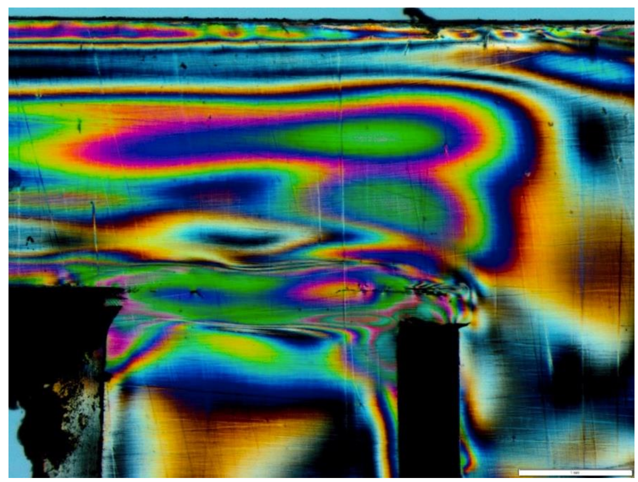

Figure 12. Melt Zone Image for Sample Welded with Weld Velocity 0.5 mm/sec photographed in polarized light.

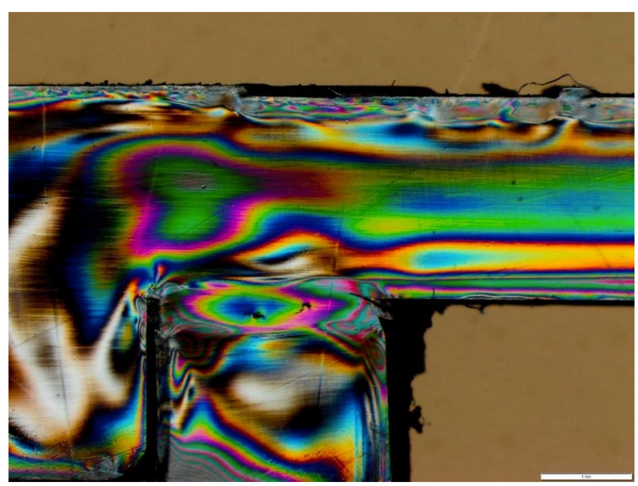

Figure 13. Melt Zone Image for Sample Welded with Profiled Weld Velocity photographed in polarized light

Conclusions

The findings of this current research into weld zone characterization explain the higher tensile strength observed with linearly increasing velocity profiles. A prolonged low-force phase (by utilizing the Melt-Detect™ feature and appropriate weld velocity profile) at the early stage of the welding cycle allows increased melt propagation in the depth of material and melt layer growth at the interface [4, 13]. Data generated in the course of this investigation correlates strongly with the results of a study conducted at The Ohio State University in 2011, which has shown that by using a defined velocity profile with a slower speed during melt initiation and a faster speed in the middle and end of the weld, strength could be increased with less weld time and reduced surface marking [11].

A large process window is important in the development of robust and repeatable weld processes. Welding to a distance less than the height of the energy director allows for a larger weld process window and has less propensity for generating excessive weld flash. Elimination of excessive weld flash is a key concern when welding medical parts. Given the variation of size and shape of energy directors that can occur both over molding runs (typical dimensional variations) and over the life of the molding tool, any change allowing a wider process window is useful. The opportunities afforded by a linearly increasing weld velocity profile for producing strong, consistent welds, reducing scrap and reject rates, and opening the option of ultrasonic welding to previously inaccessible parts are exciting and warrant further investigation.

Microscopic investigation conducted in this study provides insight into the physical characterization of the weld regions. The length and depth of the weld zone correlates closely with the tensile strength of the samples, with a larger zone producing higher tensile strength values. Samples that had full coverage of the contact area, as well as resultant deeper penetration, showed high strength. These larger, more uniform melt regions penetrated well into the surrounding material.

Observation of the samples with a polarized light source shows an additional improvement in the welding process afforded by a servo-driven welder. Optimizing the weld speed throughout the cycle allows the molecules to become less oriented and retain more of the amorphous structure that yields higher strengths [9,11]. A reduction in number of colors, as well as the number of fringes, is evidence that these samples have less residual stress resulting from the welding process.

The lessening of residual stress levels will be a key factor in many industries. High levels of stress can accelerate failure of plastic parts when subjected to a wide variety of environmental factors, such as ultraviolet exposure, chemical attack, sterilization processes, as well as normal wear. These factors all hasten the failure of a welded plastic assembly, and any process that can minimize residual stress levels caused during welding will help mitigate their impact. This stress reduction can be considered a safety improvement in many products. Further work on quantifying the levels of stress, as well as the effect of different linearly increasing velocity profiles on the weld region should be pursued.

In summary, associating a specific weld velocity profile with formation of a homogeneous melt layer in the interface of the assembly offers a key approach to selecting optimum welding parameters. The significantly enhanced capabilities of servo-driven welders in controlling material flow and the rate of material displacement during every stage of the welding cycle, their high repeatability and accuracy, and the optimal implementation of these tools and features enable users to develop a robust joining process with high strength, lower occurrence of welding flash, and lower residual stresses. This approach is beneficial to the welding of small parts typical in the medical device and electronics industry, where strict requirements for strength and dimensional consistency are common.

References

1. A Savitski, H. Pathak, L. Klinstein, P. Golko, K. Holt, “ A Case for Round Energy Director: Utilizing Advanced Control Capabilities of Servo-Driven Ultrasonic Welders in Evaluating Round energy Director Performance”, ANTEC 2014.
2. Handbook of Plastic Joining: a practical guide / M.J. Troughton, 2nd edition, 2008, ISBN 978-0-8155-1581-4
3. Miranda Marcus, Bob Aldaz, Loc Nguyen, Ken Holt, “Benefits of Servo-Driven Ultrasonic Welding for Critical Assemblies”, ANTEC 2013
4. Handbook of Plastic Joining: a practical guide / M.J. Troughton, 2nd edition, 2008, ISBN 978-0-8155-1581-4
5. M. Marcus, P. Golko, S. Lester, L. Klinstein. “Comparison of Servo-Driven Ultrasonic Welder to Standard Pneumatic Ultrasonic Welder” ANTEC 2009
6. T. Kirkland. “Ultrasonic Welding: The Need for Speed Control” *Plastics Decorating*. July/August, 2012
7. US Patent 7,819,158. Oct. 26, 2010. Klinstein et al. Ultrasonic Press Using Servo Motor with Integrated Linear Actuator.
8. H. Turunen. “Ultrasonic Welding for Plastics” Bachelor’s Thesis, Turku University of Applied Sciences, Finland. 2011.

9. A. Benatar. “Servo-Driven Ultrasonic welding of Semi-crystalline Thermoplastics” *39th Annual Symposium of the Ultrasonic Industry Association*. Cambridge, MA. 2010.
10. Miranda Marcus, Bob Aldaz, Loc Nguyen, Ken Holt, “Benefits of Servo-Driven Ultrasonic Welding for Critical Assemblies”, ANTEC 2013
11. A. Mokhtarzadeh and A. Benatar. “Comparison of Servo and Pneumatic Ultrasonic Welding of HDPE Shear Joints” ANTEC 2011
12. J. Feingold, “Stress: Diagnose It Before It Ruins Your Parts”, Plastics Technology, Dec. 2005
13. US Patent 8,720,516. May 13, 2014. Klinstein et al. Ultrasonic Press Using Servo Motor with Delayed Motion