A Case for Round Energy Director*: Utilizing Advanced Control Capabilities of Servo-Driven Ultrasonic Welders in Evaluating Round Energy Director Performance.

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Abstract

Ultrasonic welding of thermoplastics is widely used in many industries to fuse two parts together in a very short time with no additional consumables. The development of the Dukane's iQ series Servo-Driven Ultrasonic Welder with patented Melt-Match® technology introduces unique levels of control, which allow users to overcome less than optimal weld joint designs, material compositions and processes that have long been challenging to pneumatically driven welding presses. This study further investigates the capabilities of the servo-driven welder and focuses on experiments evaluating and confirming the feasibility of using round energy director (ED) designs for the ultrasonic welding process.

Introduction

One of the most important factors in optimization of the ultrasonic welding process is a proper joint design. Parts to be welded are commonly designed to have a small initial contact in the interface area in order to concentrate the ultrasonic energy and initiate melting at the interface [1]. For many applications this is done by means of an energy director (ED), a sharply pointed triangular rib molded onto the surface of one of the parts. As the ED is designed to provide a small pointed initial contact area, its size and shape, or rather its sharpness, roundness, or flatness of the tip, become critical factors in the welding process. The geometrical consistency of the ED, both within a single part as well as on a part-to-part basis, determines to a large degree the process repeatability, weld joint quality, and strength.

Keeping the ED's size and shape consistent on a part-to-part basis in high volume, multi-cavity operations presents a constant challenge to molded part vendors as dimensional variations from cavity to cavity and variations in the molding process are always present. The tip of an ED always has some roundness because it is impossible to mold a perfectly sharp point on a tip. Major contributors to inconsistency in ED shape are caused by unavoidable differences in steel machining for different cavities, problems with venting of some cavities, accumulation of debris in the cavities and machine tool and molding machine equipment ageing. As the requirements for part tolerances become more stringent in modern manufacturing these factors translate to increased QA and maintenance cost for molded parts suppliers. Sharp ED details also present an added expense in mold making. In order to make them as sharp as possible, an EDM (electro-discharge machining) process is used and adds additional engineering, set-up, and machining steps to the mold making process.

Cavity-to-cavity variation in ED shape and size is an everyday challenge for users of these parts. The sophistication and accuracy of modern ultrasonic equipment allows for a highly repeatable welding process based on joint design geometry and material. Part-to-part variation in the size and shape of the ED presents a challenge in maintaining welding the weld process consistency, aesthetics and functional performance. For industries such as medical device manufacturing, electronics, automotive, and others, a more robust design of an ED that eliminates this source of variability in the joining process could aid manufacturing in meeting strict quality requirements and improved assembly line performance, leading to reduced operations cost, higher efficiencies and better quality.

Experimentation

The purpose of this experimentation was to evaluate and compare the performance of round and sharp EDs, using Dukane's "ISTeP" molded test parts, (Figures 1, 2 and 3). Another goal was to further investigate the process control capabilities of the servo-driven ultrasonic welders in improving the welding process and understand the sources of variability in weld strength and the ways to control and eliminate them.

The approach was to develop a welding process that will generate the strongest and most repeatable weld possible for both ED designs and to understand what makes the weld strong based on analyzing the welder's graphical output and microscopic characterization of the weld zone.

Materials

The parts used for this experimentation are Dukane ISTeP parts with a 90˚ (sharp) and R 0.7 mm half round EDs, molded of a common Sabic grade Lexan 121R polycarbonate. This part was developed by Dukane to

*-Patent Pending

provide a test specimen for ultrasonic welding with changeable joint designs. [10]

Figure 1: Innovative ISTeP Test Part.

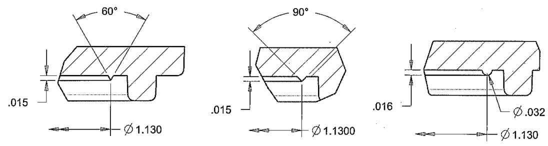

Figure 2. ISTeP ED designs- 60, 90˚ and round.

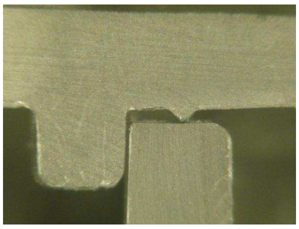
Figure 3. A cross-section of a 90˚ ED on an ISTeP part prior to welding.

Equipment

Experiments were conducted using Dukane 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 is a flat face high gain horn (gain factor= 2) and a custom made drop-in style fixture. Figure 4.

Figure 4. Welder and tooling used in experimentation.

For pull 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, Figure 5.


Figure 5. Custom pull test fixture.

Several advanced control features offered by this servo-driven system were utilized in this experiment, including Melt- Detect™ which allows the press to hold its position on the assembly, following the initiation of welding, before continuing further downward movement until a drop in force is detected. The drop in force indicates the presence of an initial molten layer [5]. Control of the material displacement rate was done by controlling Weld Velocity. These features are significantly different than those traditionally utilized in pneumatic welders and, based on previous research [3, 4, 5, 6, 7, 9, 12], were expected to provide precise control of the welding process.

Establishing Preliminary Process Settings for Parts with Sharp and Round ED Using Full Factorial DOE.

These trials were planned as a continuation of the research conducted by Dukane in 2012 and reported at ANTEC 2013[8]. The data generated in that study was used for setting initial ranges of parameters in a full factorial DOE for both sharp and round ED parts.

While the full factorial design requires more trials and is more costly and labor intensive than other designs, it also provides a more comprehensive evaluation of the variable factors investigated and contains all possible combinations of a set of factors. For this initial phase of experimentation a 3 level and 3 factor design (3X3) was selected. The variables Trigger Force, Melt-Detect™ and Weld Velocity, which exhibited the highest effect on the weld strength in the earlier study [10] were used.

The Weld Distance was set at constant value of 0.254 mm for both, a 0.4 mm tall round ED and a 0.38 mm tall sharp (90-deg.) ED to assure that the failure will occur through the weld during the testing. The sample size was limited to six replications to keep the experiments to a manageable number. Welds were evaluated by tensile testing, using the ComTouch Total Control System. Failure load was peak tensile force at break.

DOE Results

The DOE results show that at a constant amplitude, the main factors affecting weld strength for both sharp and round EDs are Weld Velocity and Trigger Force. The data shows that Weld Velocity appears to be playing the most important role in the weld strength, although Trigger Force also had a significant effect. Higher weld strength was associated with lower Weld Velocity and higher Trigger Force, regardless of the ED shape. Diagrams in Figures 6A, 6B, 7A, 7B, and 8A, 8B show the effects of Trigger Force, Weld Velocity and Melt-Detect™ on weld strength. The effect of the Melt-Detect™ value in these trials wasn't significant and needed to be investigated in further experiments. See Figure 8.

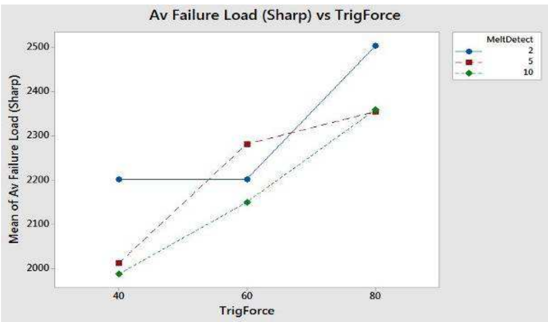

Figure 6A. Sharp ED: Trig. Force vs. Ave. Failure Load

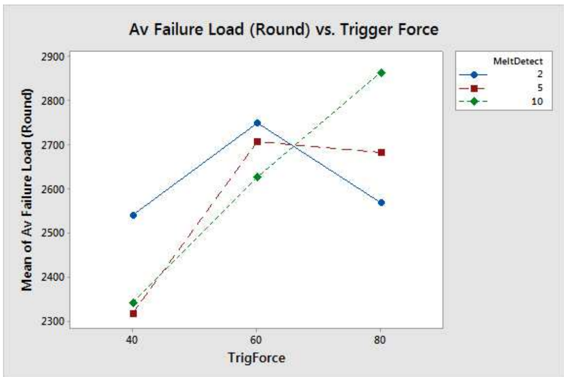

Figure 6B. Round ED: Trig. Force vs. Ave. Failure Load.

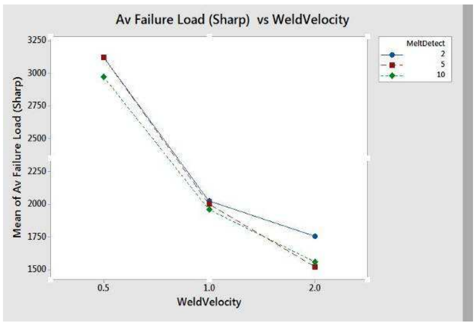

Figure 7A. Sharp ED. Weld Velocity vs. Ave. Failure Load.

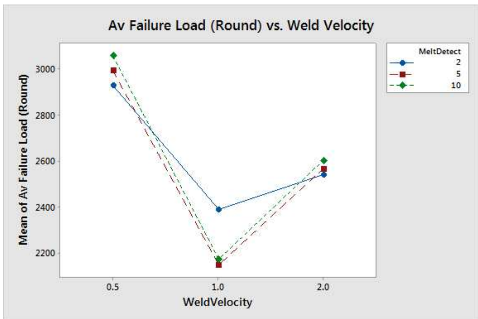

Figure 7B. Round ED: Weld Velocity vs. Ave. Failure Load.

Figure 8A. Sharp ED: Melt-Detect™ vs. Ave. Failure Load.

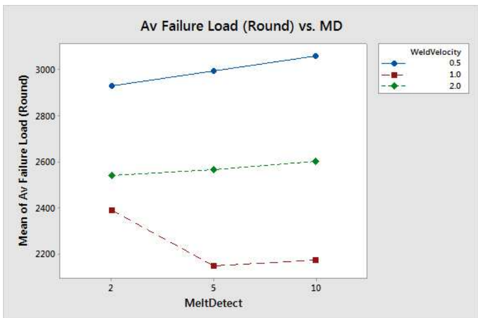

Figure 8B. Round ED: Melt-Detect™ vs. Ave. Failure Load.

The data related to this process parameters' effect on weld strength consistency had a limited value in this series of experimentations based on a relatively small number of samples in each trial. The purpose of this DOE was not to identify the "best" settings for ISTeP parts, but rather to establish a base and direction for further process refinement for joints with both types of EDs, by utilizing the capabilities of the servo-driven ultrasonic welding system. Even at this preliminary stage the data indicated that it is possible to produce as strong a weld with round EDs as with the sharp ones.

Investigating the Effect of Trigger Force

Based on the DOE results the effect of Trigger Force on weld strength is significant, which is in agreement with the findings reported in [10]. In the range from 178 N to 356 N investigated in this DOE, the highest weld strength values correlate with high Trigger Force. Consequent experimentation allowed further refining of Trigger Force value to 400 N, which was based on improved consistency of the test results for both types of ED. See Figures 6A, and 6B. The sharp ED is not damaged by the Trigger Forces of 400N, as parts were inspected under the microscope after applying Trigger Force, but no welding cycle was performed, and no damage to ED was observed in these parts.

Investigating the Effect of Amplitude

The welding amplitude is critical in initiating material melting at the tip of the ED in the initial phase of the ultrasonic welding cycle.[1] As the ED is designed to have a small initial contact area to concentrate ultrasonic energy, its shape, sharpness or roundness, or flatness of the tip, becomes an important factor. These geometrical features and the specific material properties dictate the selection of the appropriate amplitude level. For this reason it was critical to identify a preliminary range of amplitudes for the round EDs and investigate the effect of the amplitude setting on weld strength.

The results of the welding trials in which amplitude was varied, while the rest of the parameters stayed constant, demonstrate that in the range investigated, weld strength increases with increased amplitude. The best results correlated with the highest value, i.e., 36 microns. However, in a later stage, when the weld speed was further optimized, reducing the amplitude to 32 microns allowed greater repeatability of the welding process which resulted in a higher Average Failure Load and reduced Standard Deviation. See Figures 9, 10.

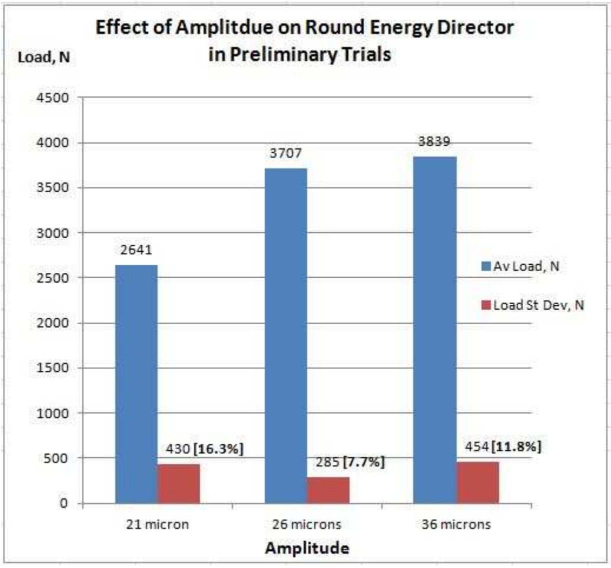

Figure 9. Average Failure Load and Standard Deviation as a Function of Amplitude in Preliminary Trials. Standard Deviation percentages in bold.

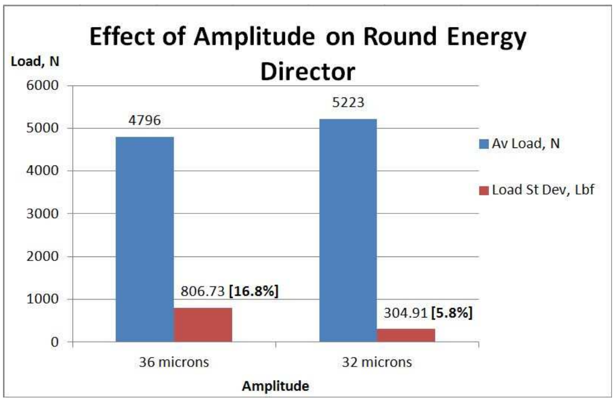

Figure 10. Round ED: Average Failure Load and Standard Deviation as a Function of Amplitude after Weld Velocity was Optimized. Standard Deviation percentages in bold.

For ISTeP parts with the sharp EDs, some very strong welds, some failing through parent material, were produced at all three amplitude levels tested (28, 32 and 36 microns). See Figure 11. However, the highest Average Failure Load (calculated on a sample number of 5 parts) was recorded at 28 microns as shown in Figure 11. This amplitude setting was used in follow-up experiments focused on weld velocity optimization. An ED with a round tip requires slightly higher amplitude to initiate melting than a part with a sharp tip.

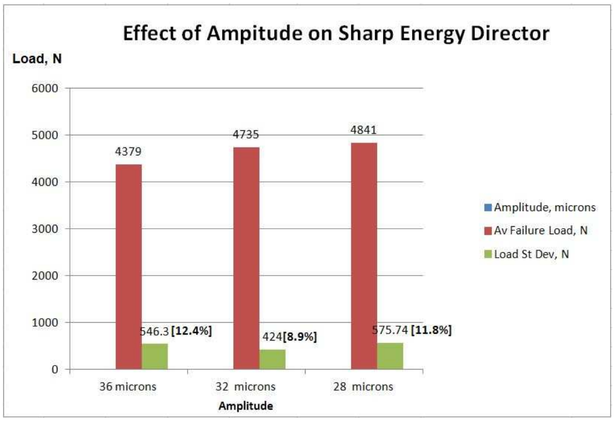

Figure 11. Sharp ED. Average Failure Load and Standard Deviation as a Function of Amplitude. Standard Deviation percentages in bold.

Investigating the Effect of Weld Velocity

Special attention was given to identifying the optimum weld velocity as the DOE results and the previous study demonstrated that it is one of the most critical factors affecting weld strength. During the first stage of experimentation the effort focused on maximizing weld strength without fully collapsing the ED (weld displacement was set at 0.254 mm for both designs).

Initially a number of constant and profiled weld velocities were selected based on DOE results and tested using a sample number of 5 for each setting. Next, when the preliminary weld velocity settings which produced welds with the highest strength were identified, the sample number was increased to 20 in order to assess process consistency. Finally, in the last set of trials the sample number was increased to 30 to confirm the performance of the best settings.

The Force and Distance diagrams generated by the welding system were analyzed for each weld and correlated to weld strength. By comparing graphs related to a strong weld and those associated with the weaker ones, an attempt was made to gain a better understanding of how to control material melting and displacement during different stages of weld formation in order to produce a strong weld. The effect of weld velocity on weld formation was also assessed by microscopic characterization of the weld zone. Representative welds were cross-sectioned, inspected and photographed under the microscope. Plots of the Force and Distance diagrams and a microphotograph of welded part cross-section are shown in Figures 14-15.

Results and Observations

The best results in strength and consistency (Figures 12, 13) were achieved using a profiled weld velocity when it was gradually increased from 0.25 to 0.40 mm/sec, after allowing formation of an initial melt layer in the interface during the Melt-Detect™ phase. Application of low forces to the molten material after the initial melt was detected by the system results in a prolonged low force phase observed on the Force and Distance diagram as a distinct dip in the Force curve. This 120- 140 ms long phase, as shown in the graphs, allows for melt propagation and melt layer build up in both type of EDs and also in the mating part, which is evident by the melt zone shape observed under the microscope (Fig. 15). The application of moderate forces at the later stages of the process generated a steady linear displacement rate (see Distance diagram on Figure 14) while preventing excessive material displacement during the weld.

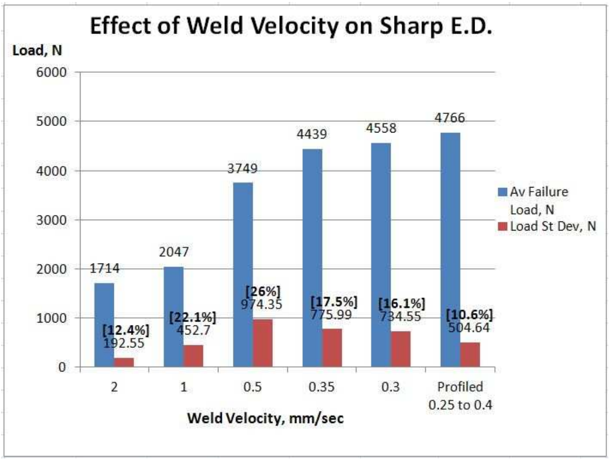

Figure 12. Sharp ED Ave. Failure Load as a Function of Weld Velocity. Standard Deviation percentages in bold.

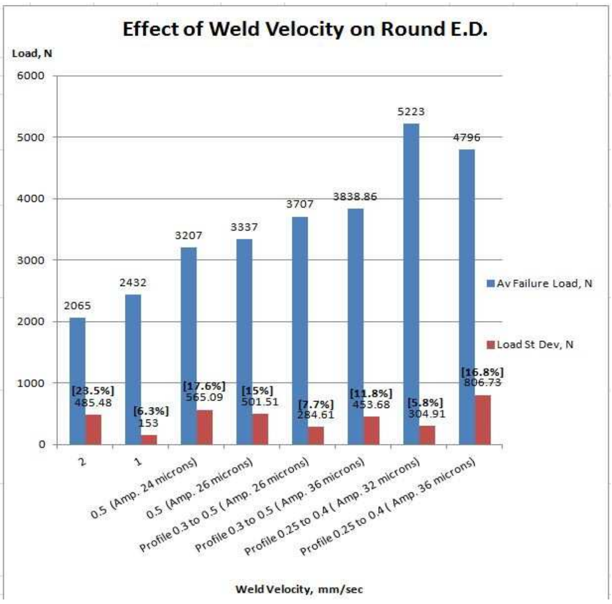

Figure 13. Round E-D. Average Failure Load as a Function of Weld Velocity. Standard Deviation percentages in bold.

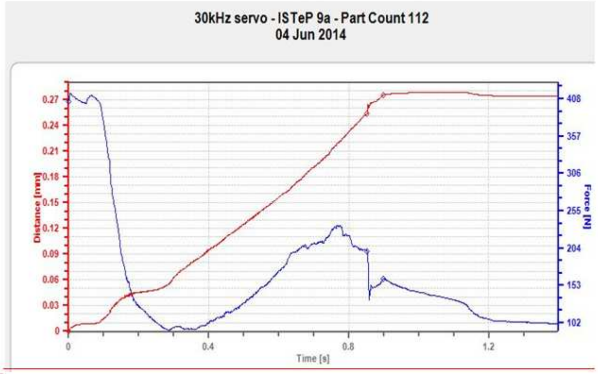

Figure 14. Typical Force Distance Diagram for Welds Produced with Weld Velocity Profile 0.25 to 0.40 mm/sec.

The importance of a steady melt rate which creates a homogenous molecular structure and a stronger weld was noted in earlier publications [1, 11] and was confirmed by the results of these trials. While the total collapse (including the cooling time) recorded for these welds was in the range of 0.274 mm to 0.279 mm, for welds with optimized weld velocity profile, the microscopic characterization of the weld zone shows that the melt has formed a consistent layer proliferating into both parts, fusing them into one part along the whole interface of the assembly. See Figure 15.

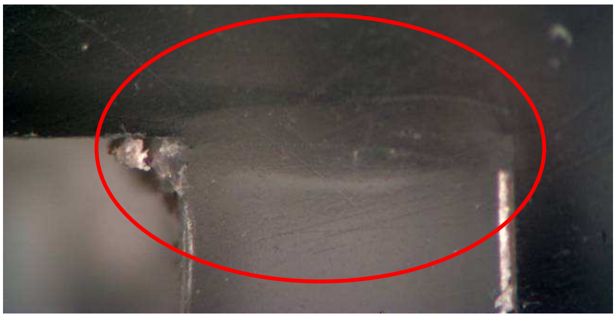

Figure 15. Melt layer image for weld velocity profile 0.25 to 0.4 mm/sec. Note the large homogenous area encircled.

During a typical ultrasonic welding cycle most of the plastic melting takes place in the ED body, and its molten material forms a bond [1]. If the total weld travel (collapse) at the end of the weld cycle is less than the ED height, the ED wouldn't melt fully, which would affect weld strength, and its tightness and appearance as well. In these trials the total weld collapse at the end of the cooling cycle was programmed to be significantly less than ED height but the process was programmed to allow the molten material to propagate through the interface forming a uniform melt layer between both parts. This uniform melt zone extended into both parts and was the main source of high strength of these welds. A significant number of the welds failed through parent material (as shown by the failure of the part walls in Figure 16).

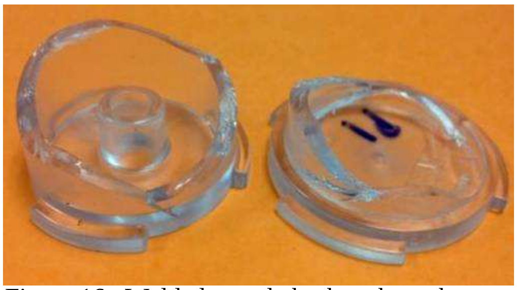

Figure 16. Welded sample broken through parent material.

Investigating the Effect of Melt-Detect™.

In general, it was observed that the specific percentage of the force reduction necessary to confirm the presence of the melt layer in the interface of the joining parts does not have a noticeable effect on the weld strength when other process settings remain constant. The experiments included four settings of the Melt-Detect™ feature; 2%, 5% and 10% and a "No Melt Detect" (Melt Detect™ feature was switched off). The data show that there is no significant difference in the Average Failure Load between 2%, 5% and 10% with the corresponding strengths of 5223N, 5032N and 5118N respectively. However, the consistency of the results was better for 2% setting – 5.84% vs. 8.27% and 9.53%. When the Melt-Detect™ feature was switched off, a noticeable drop in the weld strength and increased Standard Deviation were recorded – 4585N and 14.82%. See Figures 17.

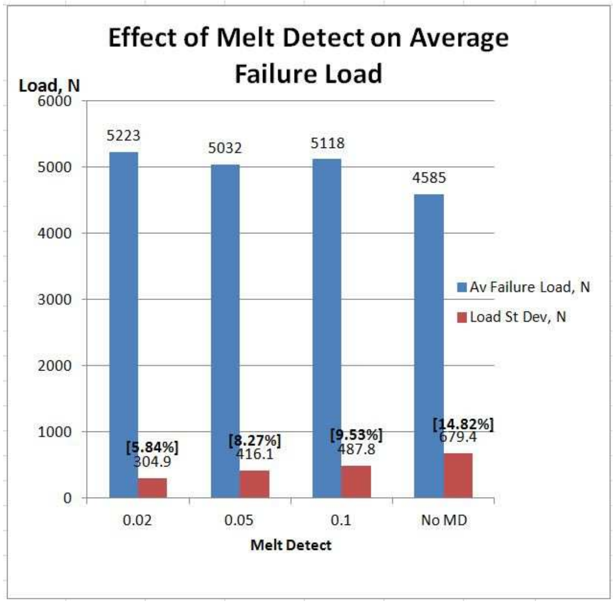

Figure 17. Av Failure Load as a Function of Melt-Detect™ Setting. Velocity Profile 0.25 to 0.4 mm/sec. Standard Deviation percentages in bold.

The Force diagram typical for such welds also shows very different melting conditions compared to welds formed while this feature was activated, regardless of the value set. See Figures 18 and 19.

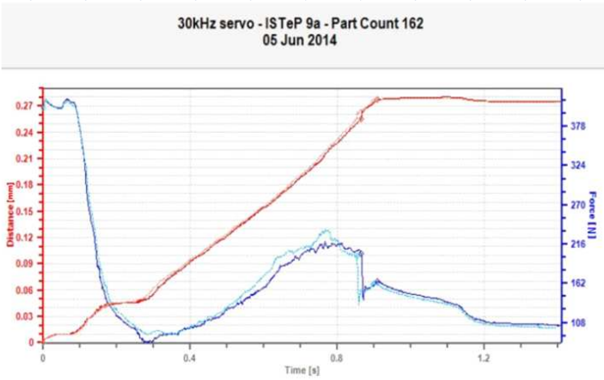

Figure 18. Force Distance Diagram for Melt-Detect™ at 10% Compared to Reference 2%, Velocity Profile 0.25 to 0.40 mm/sec,

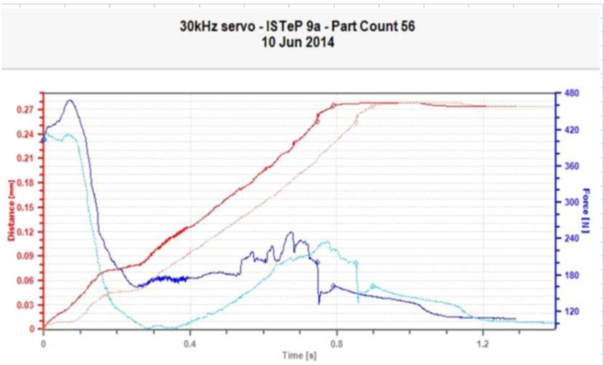

Figure 19. Force Distance Diagram for No Melt Detect Setting (darker red and blue lines) compared to Melt-Detect™ at 2% (lighter red and blue). Velocity Profile of 0.25 to 0.40 mm/sec.

The previous figure shows higher forces being applied during the initial stage of melting. Note that the samples made with the Melt-Detect™ feature de-activated show reduced Average Failure Load and poorer Standard Deviation results. This demonstrates the benefit of controlling initial melt generation in the interface and confirms what was learned prior about the correlation of forces applied at the early stage of the welding cycle to weld strength. The Melt-Detect™ feature facilitates the accomplishment of this task.

Comparing Results for the Round and Sharp EDs.

Although slightly higher amplitude was needed for the round EDs (32 microns vs. 28 microns) the balance of the welding factors investigated were found to have a similar effect on weld strength of both designs of ED. The set of welding parameters at which the strongest and most consistent welds were produced were the same for both designs: Trigger Force 400 N, Melt-Detect™ at 2%, and Weld Velocity profiled from 0.25 to 0.4 mm/sec. Note that the Weld Distance was limited to 0.25 mm for both types of ED. See the last column in Figures 12 and the last two columns in Figure 13.

The best Average Failure Load values recorded for parts with round ED were 9% higher than for parts with the sharp ED – 4766N vs. 5223N. The strength of welds with the round energy directors was also more consistent with Standard Deviation data for welds with the round and sharp EDs calculated for 30 samples tested are 5.85% and 10.59% respectively. See Figure 20. A likely explanation to the superior strength and consistency of welds of the round EDs is that this shape provides a larger amount of material to form the bond than a 90-deg. ED of the same height. Having more material available for forming the bond presents a critical advantage to the joining process on a very basic level presenting as higher strength and better consistency.

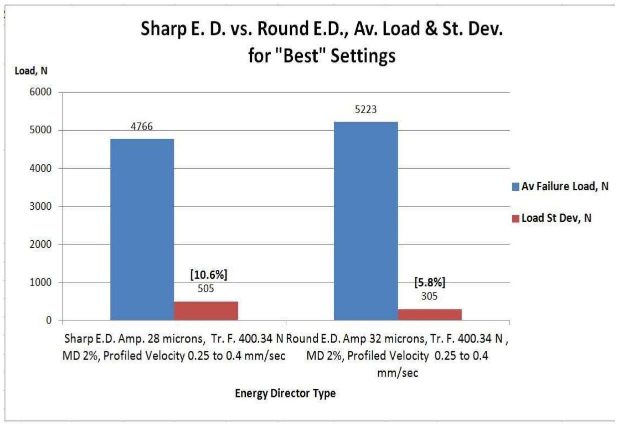

Figure 20. Best Average Failure Load and Standard Deviation results generated for sharp and round EDs. Standard Deviation percentages in bold.

Melt Behavior of Round vs. Sharp ED:

While analyzing Force and Distance diagrams related to joints with round and sharp EDs, it was observed that the melt behavior of these EDs during the weld cycle appears to be different even if the process settings are identical. The Distance diagrams represent the rate of material displacement for both processes and are practically identical but the forces applied to achieve the programmed Weld Velocity and Weld Distance are significantly lower for the part with the round ED. See Figure 21.
One of the possible explanations of this phenomenon is that the round ED, with its higher volume, accumulates more heat in its body during the Melt-Detect™ phase. This additional heat lowers the viscosity of the molten

material resulting in a reduction of the force required to achieve the programmed velocity.

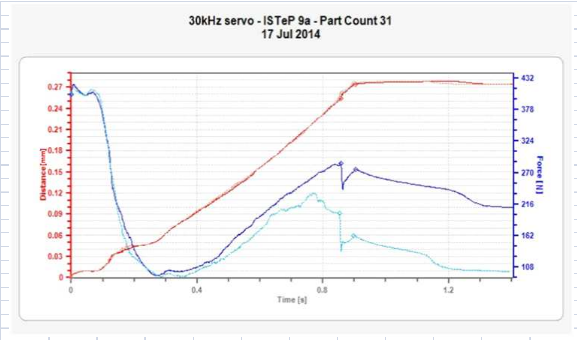

Figure 21. Comparison of Force Distance Diagram for sharp (dark blue) and round (light blue) EDs Welded Using Weld Velocity Profile 0.25 to 0.40 mm/sec

Conclusions

Performance evaluations of the round ED have confirmed that parts with this type of ED can be successfully welded with weld strength and consistency matching and even exceeding similar parts that have a 90-deg ED. Parameters that produced the strongest welds and best Standard Deviation values for both types were found to be similar with the exception of amplitude. For parts with sharp EDs the best results were achieved with an amplitude of 28 microns, while a setting of 32 microns was best for the parts with round EDs. Considering that both types of parts are made from the same material, the difference in amplitude is based on fact that a round tip of ED requires slightly higher amplitude to initiate melting than a sharp tip.

The Average Failure Load values for parts with the round ED welded at optimized conditions were 9% higher than for parts with a 90-deg ED – 5223 N vs. 4766 N. The Standard Deviation of the pull strength results of the round EDs were also better at 5.85% vs. 10.59% for the sharp EDs over the 30 samples tested. A likely explanation for the superior strength and consistency of welds for the round ED is that this shape provides a larger amount of material to form the bond than the 90-deg. ED of the same height. This presents a critical advantage to the joining process on a very basic level which results in higher strength and better consistency.

Considering that implementation of a round energy director design could also significantly simplify molding operations and increase parts consistency, the round energy director can present an attractive alternative to a sharp energy director and is recommended for further evaluation by the industry.

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