COMPARISON OF SERVO-DRIVEN ULTRASONIC WELDER TO STANDARD PNEUMATIC ULTRASONIC WELDER

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Abstract

Ultrasonic welding is one of the most widely used processes for bonding polymers, valued for its speed, flexibility, and low cost. Recently there has been a call for more controlled and consistent welding processes, especially in the medical field. Dukane has worked to meet this demand through the development of a new iQ series Servo-Driven Ultrasonic Welder with MeltMatch™ technology.

Careful comparison, detailed here, has shown that the servo-driven welder can provide more consistent results than the standard pneumatic welder can. The newly developed welder also offers a number of user friendly ergonomic features, superior Graphic User Interface with Ethernet connectivity (iQ Explorer) as well as more accurate process control capabilities.

Introduction

Although ultrasonic welding was first developed over 45 years ago (1), and has been widely used in the industry for over 25 years (2), there have been few fundamental design changes in the process. Ultrasonic welders have long been a popular choice for joining thermoplastics in the industry due to several factors.

The equipment is compact, easy to incorporate into automation (3), and economical. Additionally, ultrasonic welders can produce welds that are high quality (4) in a short cycle time. The greatest advantage of ultrasonic welding, however, is the ability to use very precise process control (5).

Ultrasonic welding can be defined as the "joining […] of thermoplastics through the use of heat generated from high frequency mechanical motion (6)." This end is achieved through the use of a generator, transducer, booster, and horn (6). The generator converts standard line power into high frequency AC voltage that is then passed through the transducer (1).

The transducer consists of piezo-electric ceramics that expand and contract at the same frequency as the current when alternating voltage is applied to each side of the ceramics (7). This sinusoidal mechanical vibration is then passed through the booster and horn into the part (1).

As the vibrations travel through the part, they generate intermolecular friction at the joint interface, which creates melt and lead to molecular bonding (6). The amplitude of the wave can be increased or decreased by changing the booster gain ratio (7).

This process depends on several important factors to obtain a robust weld: amplitude, weld time, weld pressure, weld speed, hold time and hold pressure are a few of the most important factors (1). Dukane's iQ Servo Welder allows novel ways to control these welding parameters.

Weld and hold speed, pressure, time, and distance are interdependent factors that can not be easily correlated using a standard pneumatic welder. The use of a servo-driven ultrasonic welder, however, offers shorter control-system acting times, allowing faster application of weld pressure (8) and greater control of the welding process.

Previous studies have demonstrated that a constant velocity, such as can be obtained using a servo-driven process, provide increased weld strength, reduced standard deviation, and a generally more robust process (9). A servo-driven weld process provides a constant velocity during the weld, a dynamic applied force, and precise distance control.

As early as 1980, research has shown that the welding pressure has a significant effect on weld strength when using ultrasonic welding (2). The application of a static force has long been used to provide good contact between the horn and parts for improved energy transfer and to promote flow of the energy director (10). Research has suggested, however that a dynamic force can produce greater weld strength when properly applied (11). Force profiling, generally decreasing the weld pressure during the weld, has been shown to maximize weld strength while simultaneously decreasing weld cycle time (1).

Velocity of the weld has historically been more difficult to control than weld pressure, but previous studies have indicated that weld speed has a significant effect on ultrasonic welding results (12). It has also been shown that, when a constant force is applied, the welding speed varies depending on the type of polymer used. Specifically, it has been found that semi-crystalline polymers have a faster welding speed than amorphous polymers. This is due to their different melt properties; semi-crystalline thermoplastics have an absolute melting temperature while amorphous thermoplastics have a gradual melting temperature (9). Thus, the use of a servo-driven welder presents an unprecedented opportunity to match the weld velocity to the natural melting properties of the material being welded through the used of MeltMatch™ technology.

The iQ Servo-Driven Ultrasonic Welder also offers significantly more precise control of weld distance. This is very important as the residual melt layer thickness is directly related to weld strength (8). In fact, the collapse distance of the weld was identified nearly ten years ago as the most dominant factor affecting weld strength (13).

One of the most persistent problems preventing easy and even more wide spread use of the ultrasonic welding as a joining method is the difficulty of finding an optimum welding parameter set (8). The development of a new servo-driven welder is an important step to ease the process of weld application set-up by providing superior process control.

Experimentation

Servo Experimentation

Due to the fundamental difference between the new Dukane Servo-Driven Ultrasonic Welder and the standard pneumatic-driven ultrasonic welder, a whole new approach to welding had to be implemented. In order to discover the effect of the newly available operating parameters, extensive experimentation had to be completed.

These trials were completed using the AWS standard I-Beam welding test specimen for thermoplastics. Figure 1 shows a simplified drawing of this design. ABS was chosen for these initial experiments for its ease of weldability. A custom fixture and horn, and EDM'd pull testing apparatus were manufactured specifically for these experiments, as shown in Figure 2.

The first concern was to determine the repeatability of the servo motor. Therefore, three consecutive parts were welded and their weld speed graphed in the first trial. Further tests investigated constant velocity at varying speeds, rising velocity, and falling velocity to determine their effect on weld strength.

Also studied was the effect of pre-loading the parts; every previous trial used a pre-trigger. Each of these subsequent experiments were completed using both the shear and energy director joint. Additional process optimization was later completed using polycarbonate round parts. The focus of these later runs was to reduce standard deviation. A simplified drawing of the part used for these trials is shown in Figure 3.

Servo vs. Pneumatic Comparison

All comparative testing was performed using the new Dukane iQ series Servo-Driven Ultrasonic Welder with MeltMatch™ technology and the standard Dukane pneumatic welder. Testing was performed using the same transducer, booster, and generator with both presses to minimize variation.

These tests were done using the AWS standard I-Beam welding test specimen for thermoplastics, with a shear joint (Figure 1). The material chosen for these tests was polycarbonate. The same fixturing was used as is documented in Figure 2.

Multiple testing stages were implemented to fully compare the two welders. First, three hundred parts were welded on each welder. These samples were run using optimized parameters on the pneumatic welder and the closest matching parameters on the servo welder. Both the weld strength and the collapse distance were measured for these trials. Collapse distance was measured by using a drop gauge to measure the height of the parts before and after welding. A gauge reliability and reproducibility experiment was run on this measurement process to ensure repeatable results. The settings used for these tests are shown below in Table 1.

Table 1: Weld Parameters for 300 sample run

	Trigger Force	**Weld**			**Hold**		
		Distance	Speed	Pressure	Distance	Speed	Pressure
Units	N	mm	mm/s	kPa	mm	mm/s	kPa
Servo	133.4	0.762	6.35	-	0.127	24.5	-
Pneumatic	133.4	0.762	-	241.3	0.127	-	275.8

After this, a follow-up experiment was run with fifty parts welded on each machine. For this second set, the same basic parameters were used for the pneumatic welder, but optimized settings were used for the servo. The settings used for these tests are shown below in Table 2.

Table 2: Weld Parameters for Follow-Up Trials

	Trigger Force	**Weld**			**Hold**		
		Distance	Speed	Pressure	Distance	Speed	Pressure
Units	N	mm	mm/s	kPa	mm	mm/s	kPa
Servo	133.4	0.762	8.89	-	0.127	24.5	-
Pneumatic	133.4	0.762	-	206.8	0.127	-	275.8

Results and Discussion

Servo Parameter Optimization

The first trial set showed excellent repeatability of the servo motor. These results are graphed in Figure 4. The time vs. distance curves for three welds at the same settings are virtually identical. This result is very important as it demonstrates consistency of the Dukane iQ Servo-Driven Ultrasonic Welder. Once this is established, subsequent efforts can be focused on using the new features made available by this machine to improve weld quality and repeatability.

Figure 5 shows the time vs. distance and power curve for the speed profiling experiment using the shear joint samples. It was demonstrated that increasing speed resulted in the greatest weld strength for the shear joint, while decreasing speed resulted in the greatest weld strength for the energy director joint. Table 3 below shows average weld strength for each speed profile tested.

Table 3: Speed Profiling Weld Strength Results

Speed Profiling Weld Strength Results (N)						
#	Shear Joint			Energy Director		
	Constant	Rising	Falling	Constant	Rising	Falling
1	3350	4030	2887	2260	1597	2197
2	3398	4239	2202	1499	1797	1917
3	3608	3648	3314	1050	1859	2019
Ave.	3452	**3972**	2801	1603	1751	**2045**

This information indicates a fundamental difference in the melting characteristics of the two joint designs that should be noted. Falling weld speed creates forced compression of the shear joint which could prevent melt initiation at the surface and allow less heat in the joint, leading to fracture instead of welding. Rising weld speed, on the other hand, would cause a slow initiation of melt, allowing plenty of heat to dissipate into the shear, and then a fast push through the joint. This phenomenon likely explains why falling speed led to the lowest strength with the shear joint, while rising speed led to the highest.

The energy director joint, however, would react differently to the speed profiling. A rising speed may not achieve the same level of melt initiation with the smaller contact area of an energy director. Then the parts are quickly propelled together, squeezing out the melt rather than mixing it between the two parts. A falling speed on the other hand causes quick melt initiation, for which the small contact area of the energy director is better equipped. Then the parts are slowly compressed, allowing more time for melt mixing at the joint, for a stronger weld.

Figure 6 shows the time vs. distance and power curves for the speed variation experiments using the energy director samples. It was demonstrated that slower speed resulted in the greatest weld strength for both joint designs. Table 4 below shows average weld strength for each speed magnitude tested. It is unsurprising that slower speeds resulted in greater strength as this allows more time for melt to form.

Table 4: Speed Variation Weld Strength Results

Speed Variation Weld Strength Results (N)						
#	Shear Joint			Energy Director		
	1.27 mm/s	2.54 mm/s	3.81 mm/s	1.27 mm/s	2.54 mm/s	3.81 mm/s
1	3323	2665	2411	2758	1775	552
2	3203	3212	2113	3198	2998	672
3	2184	2607	3172	2589	2731	334
Ave.	**2903**	2828	2565	**2848**	2501	519

A graph of time vs. distance and power when pre-loading of the parts was implemented is shown in Figure 7. Pre-loading the parts consists of applying force to the I-Beam before triggering the ultrasonic vibration. Using this feature was found to increase weld strength for the shear joint with increased load, while decreasing weld strength for the energy director joint with increasing load, as shown in Table 5 below.

Table 5: Pre-Loading Weld Strength Results

Pre-Load Weld Strength Results (N)						
#	Shear Joint			Energy Director		
	98 N	240 N	378 N	98 N	240 N	378 N
1	2473	2304	3323	2758	2464	2807
2	2184	2696	3202	3198	2055	2046
3	2326	2807	2184	2589	2166	2042
Ave.	2328	2602	**2903**	**2848**	2229	2298

These results are most likely due to the different amount of initial contact area for each part. The shear has greater initial contact area, and therefore benefits from more compression prior to welding, allowing the surface asperities over the large surface area to be brought into more intimate contact. On the other hand, the energy director provides a very small initial contact area; greater pre-loading is not necessary and may lead to flattening of the peak.

Experimentation with the round parts using the Dukane iQ Servo-Driven Ultrasonic Welder resulted in a standard deviation of 1.9% of the weld strength at the optimum weld parameters. Figure 8 shows the effect of weld speed and amplitude on standard deviation for a sample set of ten to fifteen parts. Decreasing weld speed and amplitude were found to decrease the standard deviation, while weld distance and hold distance had no independent effect.

Servo vs. Pneumatic Comparison

In the initial run of three hundred I-Beam parts, the pneumatic and servo welders produced very similar results. Samples welded with the servo welder, however, showed slightly greater weld strength and lower standard deviation of that weld strength and the collapse distance, as shown on Table 6 below.

Table 6: Comparison of 300 Sample Run

	Collapse (mm)		Strength (N)	
	Pneumatic	Servo	Pneumatic	Servo
Average	0.725	0.731	1759	1896
Standard Deviation	0.028	0.025	249	265
Standard Deviation (%)	3.7%	3.4%	14.2%	14.0%

The follow-up experiment results showed that the parts welded with the servo achieved greater weld strength, lower standard deviation in the collapse distance, and equivalent standard deviation of the weld strength to the parts welded with the pneumatic welder. This is due to optimization of the servo welding parameters that was later implemented. Approximating the pneumatic process prevents full realization of the potential of the iQ Servo-

Driven Ultrasonic Welder with MeltMatch™ technology. In these follow-up experiments, the welder was optimized taking into account its unique parameters to increase weld strength and repeatability.

Figure 9 shows the collapse distance and power over the time of the weld for the weakest, strongest, and average weld strength as welded by the servo welder. Figure 10 shows the same for the pneumatic welder.

Figure 11 shows the relationship between weld strength and collapse distance for parts welded by both welders. It is interesting to note here that the collapse distance of the pneumatic welder shows a general positive correlation to weld strength, as is typically reported. This trend is not the same, however, with the servo welder.

This is a great indication of the primary difference between the two welders. The pneumatic welder relies on a static pressure to compress the two parts, collapse distance is based on the amount of melt that is formed and pushed out of the way. Greater collapse means more melt and causes greater strength. The servo welder, on the other hand, will collapse the parts at the same speed, and to the same distance, whether or not there is melt being produced. Therefore, collapse distance cannot be the same indicator of weld strength as it has historically been when using the standard pneumatic welder.

Table 7, below, shows the results of this last experiment in terms of average weld strength and standard deviation obtained with each welder. Here it is obvious that when the servo welder is optimized using its special features, such as MeltMatch™, instead of approximating a pneumatic weld, greater weld strength and more repeatable collapse distance can be achieved.

While the data below shows a small decrease in standard deviation with the pneumatic welder, the difference is not statistically significant. It was noted during pull testing that AWS I-Beam samples would often break on one side first, then this crack would propagate through the weld in a shear mode. This phenomenon is likely the cause of much of the variation of weld strength in these results. It was later determined that round parts could eliminate this effect, and this led to our experiments with them as described in the previous section.

Table 7: Servo v. Pneumatic Weld Results

	Collapse (mm)		**Strength (N)**	
	Pneumatic	Servo	Pneumatic	Servo
Average	0.856	0.907	2119	2474
Standard Deviation	0.033	0.010	404	507
Standard Deviation (%)	3.9%	1.1%	19%	20.5%

Conclusions and Future Work

Two important conclusions can be drawn from these experiments. First, the new Dukane iQ Servo-Driven Ultrasonic Welder with MeltMatch™ technology can generate greater weld strength and more consistent collapse distance than the standard pneumatic welder, when optimized weld parameters are used on both welders. Second, the new servo-driven ultrasonic welder offers a vast array of new possibilities for the future of plastic welding.

With the new Dukane iQ Servo-Driven Ultrasonic Welder, greater control of ultrasonics welding is possible, allowing a level of consistency that has never before been reached.

Many new research opportunities have been opened up by the development of this new equipment. One of the most promising avenues to explore is the possibility of adjusting the servo welder speed profile to match the natural melt layer formation in the part. It would also be informative to pursue the further comparison of the pneumatic to the servo welder using the round parts, to improve repeatability of the weld strength results.

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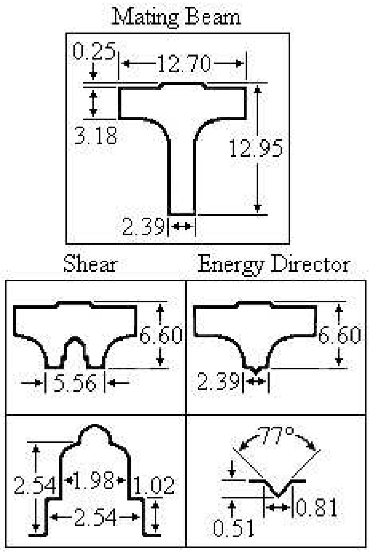

Figure 1: AWS I-Beam Welding Test Specimen (mm)

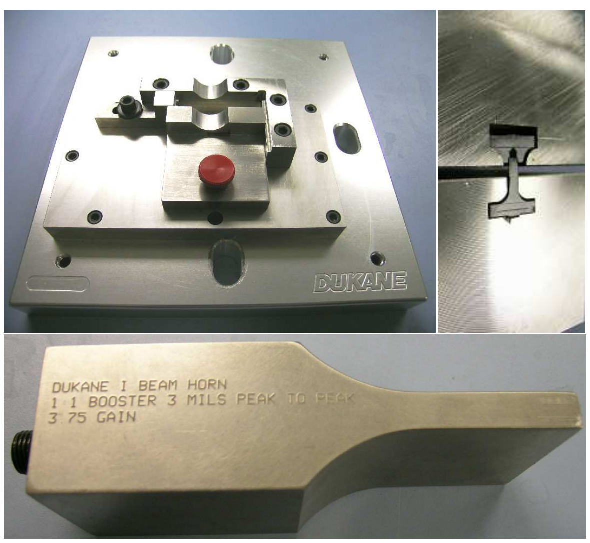

Figure 2: Horn, Fixture, Pull-testing Apparatus

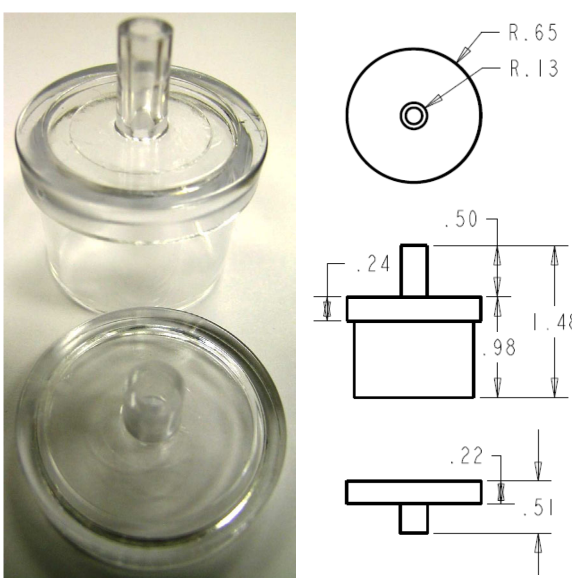

Figure 3: Round Parts

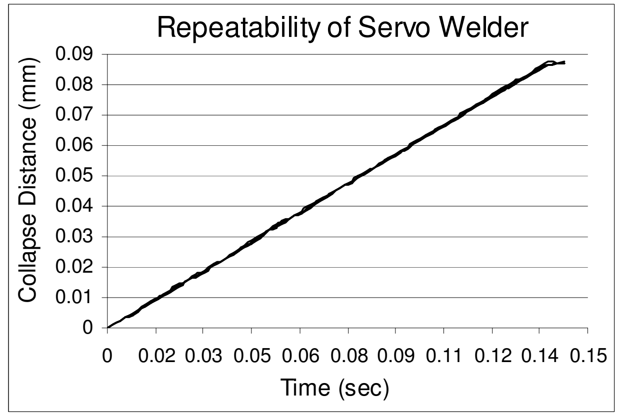

Figure 4: Repeatability of Servo Motor

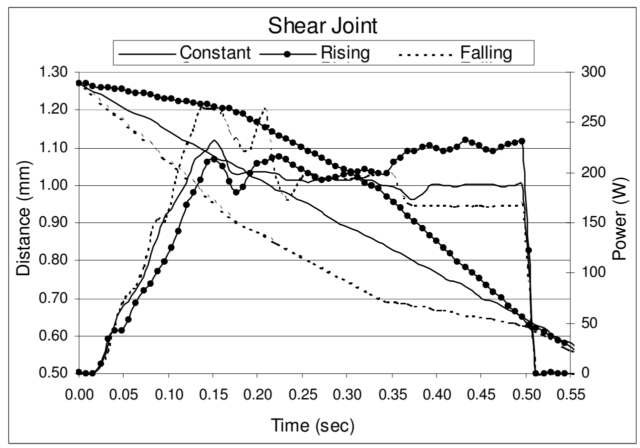

Figure 5: Speed Profiling with Shear Joint

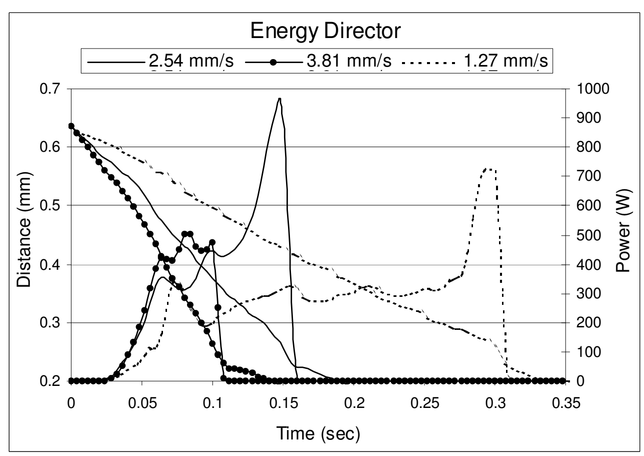

Figure 6: Speed Variation with Energy Director

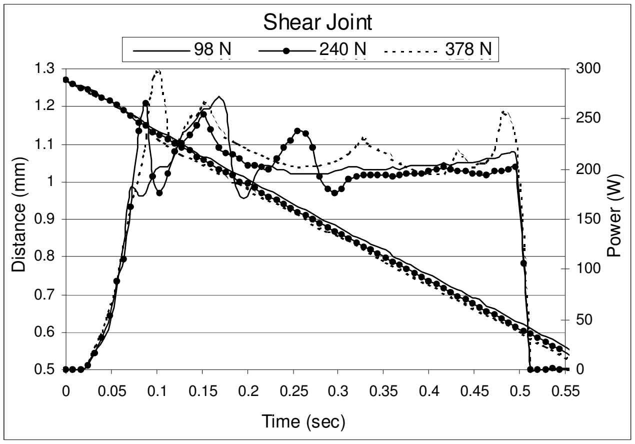

Figure 7: Pre-Loading with Shear Joint

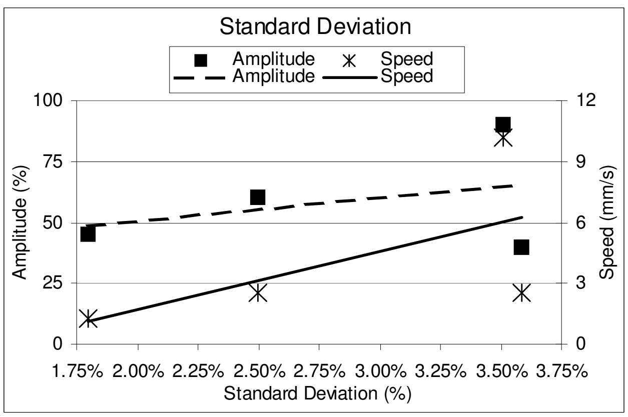

Figure 8: Standard Deviation Results for Round Parts

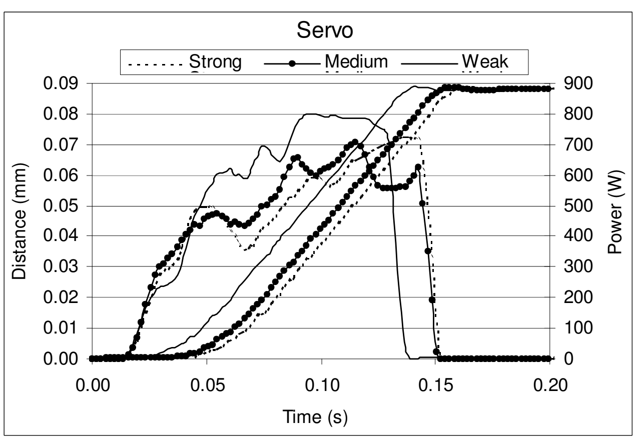

Figure 9: Weld Profile for Servo Welded Parts

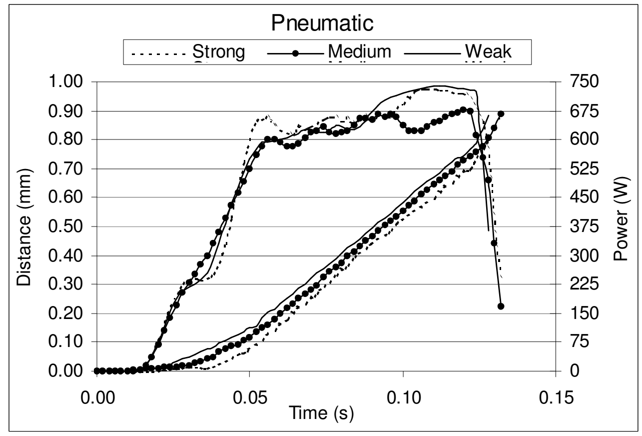

Figure 10: Weld Profile for Pneumatic Welded Parts

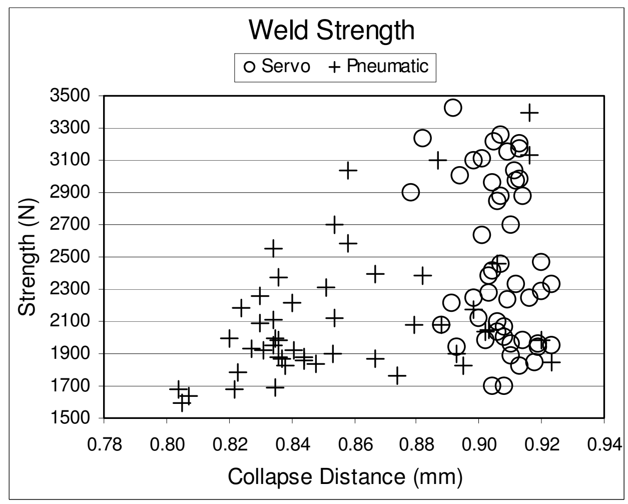

Figure 11: Weld Strength Trends with Collapse Distance