SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

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Feasibility of Joining Techniques for Thermoplastic and Thermoset Polymers

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Abstract

In industry, ultrasonic welding is a well-known technique for thermoplastics; however, less is known about the ultrasonic welding of thermosets. Similarly, friction stir spot welding is known to be successful for high density polyethylene (HDPE), a thermoplastic but for few other polymers. Joining techniques such as ultrasonic welding and friction stir welding have advantages because of their reproducibility, ease of automation, and short welding time, over other polymer joining techniques such as adhesives, solvent welding, or mechanical fastening. This study aims to evaluate the joining techniques of FSSW and USSW for a thermoplastic, polycarbonate, and a thermoset, EPON 828:DETA epoxy.

Introduction

Within the last 50 years, plastics technology has advanced incredibly ("The Polymer Revolution"), to the point that manufactured plastic items are so large or complicated that they cannot be fabricated with one mold. In many cases, parts must be fabricated from several smaller pieces joined together, making the joining method a crucial step. Common methods available are adhesives, mechanical fastening such as with nuts and bolts, spin welding, friction stir welding, vibration welding, thermal welding, and ultrasonic welding (Rashli). The methods of mechanical fastening and adhesives tend to be slow compared to welding. Indeed, ultrasonic welding and friction stir welding are comparatively quick to complete and are easily automated, making these methods attractive for manufacturing processes.

Ultrasonic spot welders (Fig. 1) take in electrical power oscillating at 50 to 60 Hz and increase the frequency to or above 20,000 Hz. This high frequency electricity converts to mechanical energy through a transducer, often piezoelectric. A booster amplifies the movement and a sonotrode applies the vibrations to the work pieces to be welded. The vibrations oscillate through the work pieces to heat the interface. In addition to the vibration applied by the sonotrode, a downward force applies a weld pressure to the work pieces. For this reason, components to be ultrasonically welded must be able to support pressure at the joint.

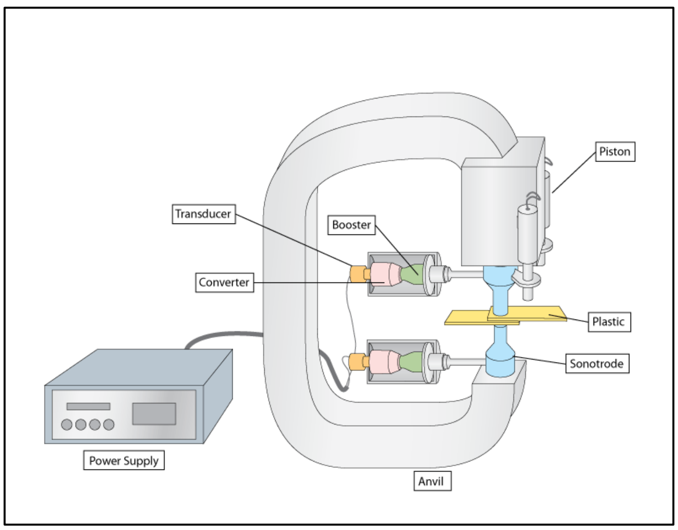

Figure 1: Schematic of Sonobond Ultrasonic Welder at SDSMT (Author's Work)

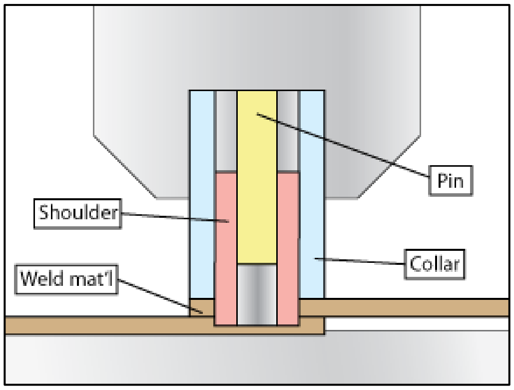

Figure 2: Schematic of the Side View of the Refill FSSW Process (Author's Work)

Unlike ultrasonic spot welding (USSW), friction stir spot welding (FSSW) operates by spinning an end mill on the parts to be welded (Fig. 2). The collar descends into the workpiece, holding it in place. Then, the spinning shoulder descends into the material while the pin rises. As the shoulder ascends out of the material, the pin descends so that it is flush with the shoulder, creating a flat, filled FSSW joint.

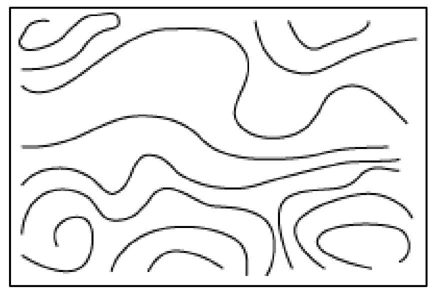

Figure 3: Polymer Chains without Crosslinks (Author's Work)

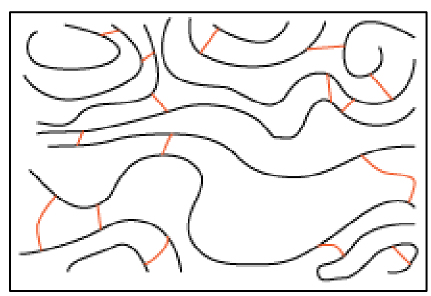

Figure 4: Crosslinked Polymer Chains (Author's Work)

Both USSW and FSSW are known to join thermoplastic polymers by localized melting and solidification at the surface to be joined. Thermoplastics are comprised of linear, chemically unlinked polymer chains (Fig. 3). Thermosets are comprised of chemically crosslinked polymer chains (Fig. 4) and do not melt because of these chemical crosslinks. Both types of polymers exhibit a glass transition temperature, where Young's modulus suddenly decreases with respect to temperature. While the chemical crosslinks prevent melting, upon reaching and exceeding the glass transition temperature, a thermoset's viscosity will decrease dramatically. Thermoplastic polymers have been shown to be ultrasonically welded successfully above the glass transition temperature, but below the melting temperature, (Ageorges) so we hypothesize that thermosets be successfully joined if the vibrations or friction created during welding of the ultrasonic welder raise the temperature of the samples above the glass transition temperature.

Broader Impact

Thermoplastic polymers are widely used in the packaging industry for their ease of formation, low cost, and their ability to be reworked (Rashli). Thermoplastics work well in low-temperature applications, and certain thermoplastics have a very high impact strength, mechanical strength, and temperature resistance (GEHR plastics PC polycarbonate). They can even be reinforced with fibers, in some applications.

Fiber reinforced polymers (FRPs) often use a thermoset matrix and knowledge from this study on the joining of a common thermoset could be extended to apply to the field of FRP structure manufacturing. Ultrasonic welding provides an alternative bonding method that can be better and easier to automate than adhesives, mechanical bonding techniques, and other welding techniques. Most of the joining methods listed above disturb the fibers at the joint, require long curing times, or create stress concentrations. Ultrasonic welding is fast and does not disturb the fibers or create stress concentrations. Welding FRPs could reduce the time, and thus the cost, of joining FRP components. Since they are strong and lightweight, FRP components give a serious advantage over metal, concrete, and other materials.

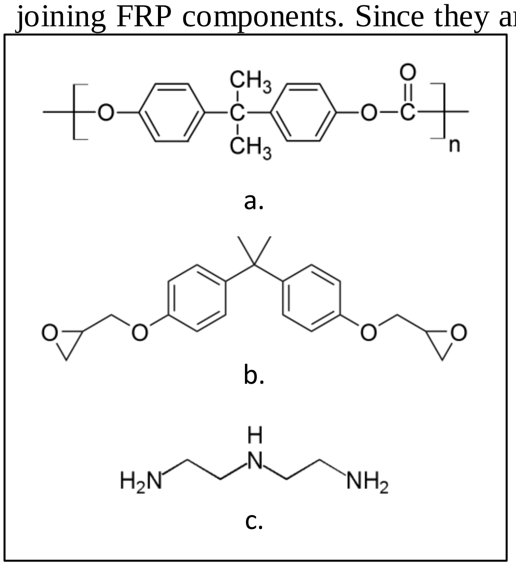

Figure 3: Chemical Structures of (a.) PC, (b.) EPON 828, and (c.) DETA (Public Domain)

Procedure

Materials

The thermoset used was a two part epoxy of EPON 828 and diethylene triamine (DETA) The DETA was mixed at a ratio of 8 parts per hundred (pph) parts of EPON 828. When cured at 24 hours room temperature

(RT), 24 hours 35°C, 1hour 135°C, it had a glass transition temperature of 72°C. (Caruso)

For comparison, polycarbonate (PC) a well-known thermoplastic was also used. It has a clear appearance and melts at 149°C (Plastic properties of polycarbonate).

Equipment and Procedures

Samples of epoxy and PC were produced (1”x4”x1/16”). In order to make appropriately sized samples of epoxy an aluminum master mold (Fig. 6) was cut to shape with a CNC mill. Miller Stephenson polytetrafluoroethylene (PTFE) spray acted as a release agent and silicone (one made with Sylgard 184 cured 22 hours RT and 2 hours 70°C, one made with Contenti Room Temperature Vulcanizing Silicone Rubber No. 179-050 cured 24 hours RT, Fig. 7) was poured into the master mold to create the mold in which the epoxy samples would be formed. After the silicone molds were cured, the epoxy was mixed at 8 pph, de-gassed at 650 mm Hg for 5 minutes and cured for 24 hours at room temperature, 24 hours in a Lindberg Blue M Mechanical Convection Oven at 35°C and 1 hour at 135°C in a Lab-Line Programmable Vacuum Oven.

Figure 5: Master Mold (Author's Work)

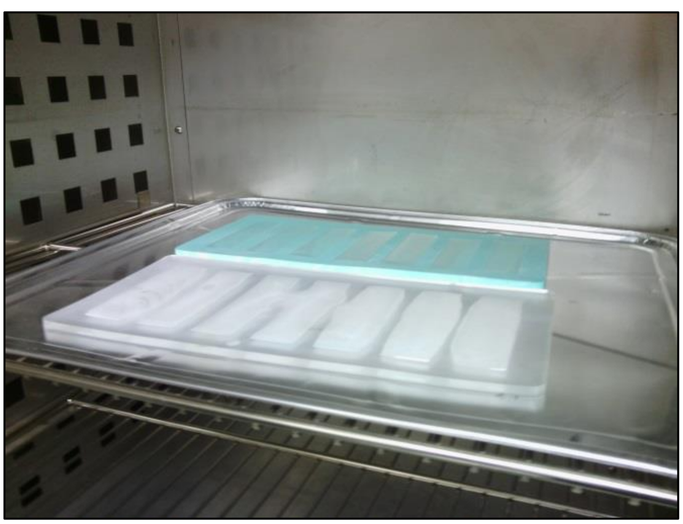

Figure 4: Silicone Molds (Author's Work)

For all welding methods, lap shear samples were created with 1" overlap (Fig. 8). For USSW of polycarbonate, samples were 1/8"thick. The ultrasonic welder's variable parameters are power, time, pressure (weld force), and impedance, and the sonotrode is 0.50 inches in diameter.

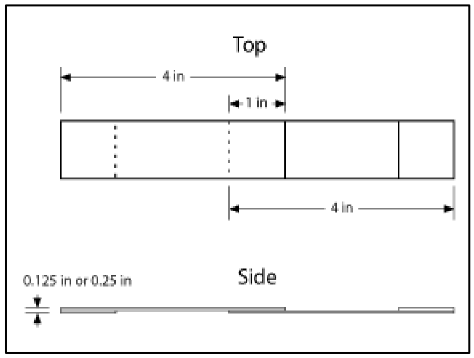

Figure 8: Schematic of Lap Shear Design and Proportions (Author's Work)

The PC and epoxy were filled friction stir spot welded with a HF Webster RFSW1, varying rotation speed, time to descend, depth of descent, and pressure. The diameter of the shoulder is 0.35 inches. Tabs of the sample thickness were added to the ends to be gripped to ensure proper alignment during testing. Weld strength was tested in a lap shear tensile test with an MTS 858 Mini Bionix II tensile tester with a displacement rate of 0.05 inches per minute, as shown schematically on Figure 9. Figure 10 shows an example of the load and displacement characteristics for each test.

Table 1 shows the parameters used for USSW of the 1/8 inch thick PC, done by Navaraj Gurung. Weld time and power multiply together to create the weld energy, by which USSW were characterized for this study. Table 2 shows the parameters used for FSSW of 1/16 inch thick PC. Parameters used for FSSW of the Epoxy are shown in Table 3.

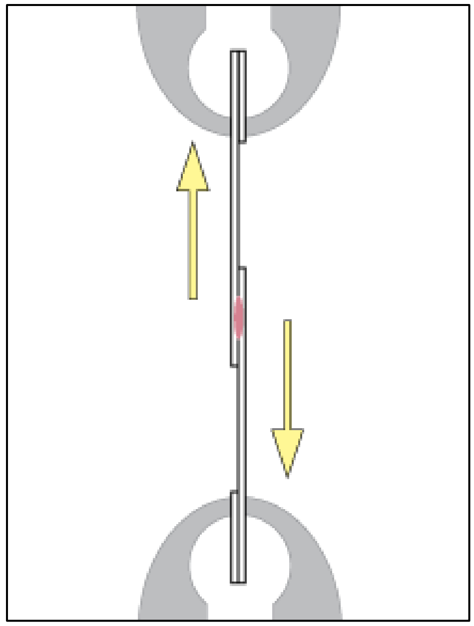

Figure 9: Schematic of Lap Shear Tensile Test (Author's Work)

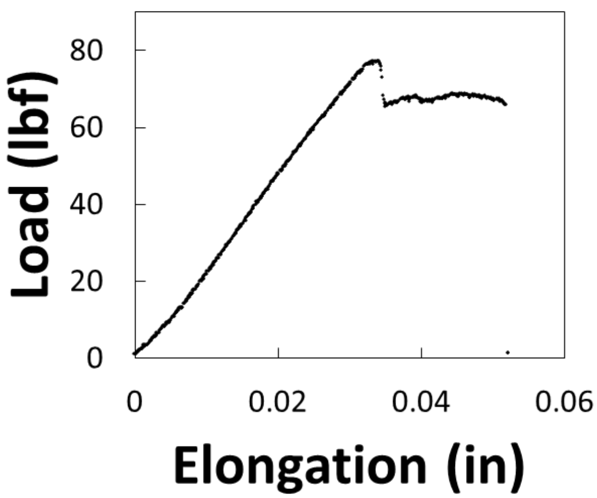

Figure 10: Sample of Load vs. Elongation as Collected from the MTS Tensile Tester (Author's Work)

Table 1: Experiment Parameters for USSW on PC (Navaraj Gurung)

Welding Energy (Joules)	Sample I. D.	Input Power (Watts)	Weld time (Sec.)
300	4A	100	3
	4B	120	2.5
	4C	150	2
	4D	200	1.5
	4E	300	1
600	4F	150	4
	4G	200	3
	4H	240	2.5
	4I	300	2
	4J	600	1
900	4K	225	4
	4L	300	3
	4M	360	2.5
	4N	450	2
	4O	900	1
1200	4P	300	4
	4Q	400	3
	4R	480	2.5
	4S	600	2
	4T	1200	1
1500	4U	375	4
	4V	500	3
	4W	600	2.5
	4X	750	2
	4Y	1500	1
1800	4Z	450	4
	4a	600	3
	4b	720	2.5
	4c	900	2
	4d	1800	1
2000	4e	500	4
	4f	670	3
	4g	800	2.5
	4h	1000	2
	4i	2000	1

Table 2: Experiment Parameters for FSSW on PC (Author's Work)

Sample I.D.	Plunge Rate (in/min)	Spindle Speed (RPM)	Pressure (psi)
1	2	150	60
2	2	150	60
3	2	150	60
4	2	200	60
5	2	200	60
6	2	200	60
7	2	100	60
8	2	100	60
9	2	100	60
10	1.5	150	60
11	1.5	150	60
12	1.5	150	60
13	2.5	150	60
14	2.5	150	60
15	2.5	150	60
16	1.5	150	60
17	2.5	150	60

Table 3: Results of FSSW on Epoxy with Experimental Parameters (Author's Work)

Plunge rate in/min	Plunge Depth (mm)	Time to Depth (sec.)	Spindle Speed (RPM)	Pressure (psi)	Comments
2.2	3.7	4	100	100	Shattered, but bonded some
2.2	3.7	4	50	100	Crushed the sample
1.9	3.25	4	100	100	shattered.
4.0	4.93	2.9	500	60	Crushed the sample, shattered
1.0	3.73	8.81	100	60	Shattered, but bonded some

Results

The lap shear strength of polycarbonate ultrasonic spot welds peaked when the weld energy was 1500 joules as shown in Figure 11 (Navaraj Gurung). When friction stir spot welding was attempted on polycarbonate, the strongest bonds were observed when the spindle speed was high and when the plunge rate was low. Unfortunately, friction stir spot welds on epoxy did not meet much success. For each attempt, the welder head shattered the epoxy. However, in two cases, a bond appeared. When the weld pressure was low and the plunge rate was very slow, the shattering was not as violent.

Figure 12 shows examples of FSSW on polycarbonate. In these bonds, the area where the shoulder descended into the material was white and grainy, but the centers remained intact. However, some voids were observed in the white area. For friction stir spot welding of epoxy, the entire area where the both the pin and the shoulder of the friction stir spot welder appeared powdery and white, while the rest of the epoxy shattered (Figure 13).

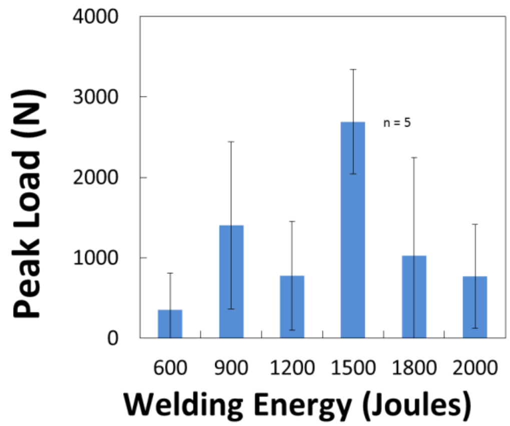

Figure 11: Peak Load vs. Welding Energy for USSW on PC (Navaraj Gurung)

Figure 12: An Example of FSSW on 1"x 1" PC (Author's Work)

Figure 13: FSSW on Epoxy. The short dimension of the original epoxy sample is 1" wide. (Author's Work)

Lap shear testing of friction stir spot welded PC shows loose trends across welding parameters. As the spindle speed increased, so did the peak load (Figure 14) and as the plunge rate increased, the peak load decreased (Figure 15).

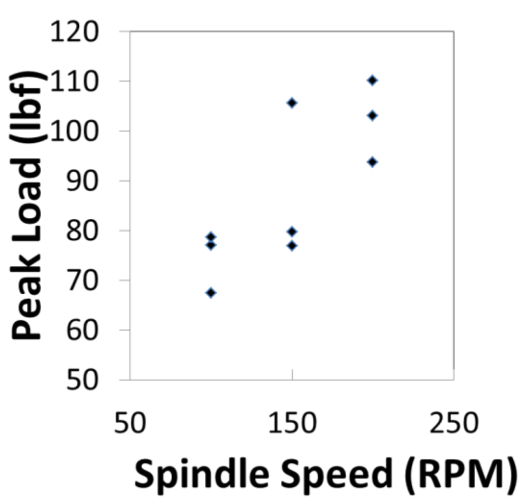

Figure 14: Peak Load vs. Spindle Speed for FSSW on PC (Author's Work)

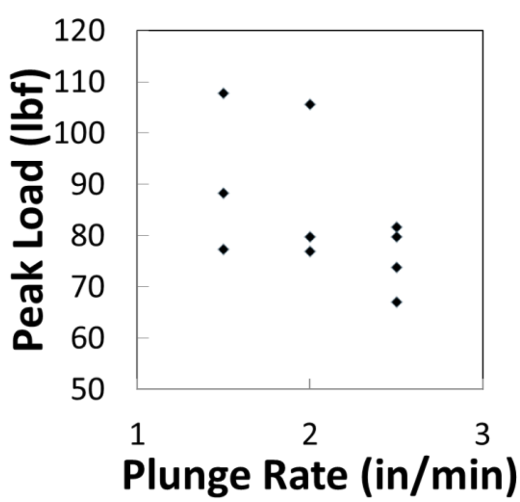

Figure 15: Peak Load vs. Plunge Rate for FSSW on PC (Author's Work)

As Figure 11 shows, the peak load of the USSW joints on PC was at 1500N joules, and beyond that point, bonds became weaker. Below, in Table 3, the qualitative results of FSSW on epoxy are shown. All samples were shattered or crushed, but some formed some sort of bond in the white center as shown in Figure 13.

Discussion

Polycarbonate was successfully joined with both FSSW and USSW, but the epoxy was not successfully joined with FSSW, and due to instrument issues, was not able to be joined with USSW. During welding, the polycarbonate demonstrated ductile behavior, while the epoxy demonstrated brittle failure. Since the polycarbonate had stronger friction stir spot welds when the spindle speed was higher and the plunge rate was lower, we hypothesize a stronger PC bond could be achieved with more heat. Perhaps, as the ultrasonic spot welding of PC displayed, there may be a parameter set for which peak strength may be attained.

Every epoxy sample that was friction stir spot welded shattered. However, when the plunge rate was extremely low and the pressure was also low, the epoxy bonded some at the location of the welder head, even though the rest of it shattered (Fig. 13). A possible reason that a small bond was created was because the slow plunge rate allowed the friction of the welder to heat the material more than the other samples.

Conclusion

The feasibility of USSW and FSSW of polycarbonate and epoxy is studied. The amount of heat generated during both joining techniques plays a crucial role in welding and should correspond to the glass transition and melting temperatures of the materials for a successful bond

Because a low plunge rate allows for more heating of the epoxy, it is possible that even lower plunge rates or preheated samples could be explored for friction stir spot welding of epoxy in future studies. Additional studies should also experiment with faster spindle speeds and lower plunge rates for FSSW on polycarbonate. Since ultrasonic spot welding could not be attempted on epoxy this summer, that is another area of future work, as it is likely that method will not shatter the brittle epoxy.

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