Implant Induction Welding of Nylon 6/6

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Abstract

The implant induction welding technique utilizes a heating element material at the joint interface to generate the heat. In this study, three factor two level full factorial design of experiments were performed to evaluate two different types of Nylon 6/6, denoted as A and B, in a lap shear joint geometry. It was found that weld time was the most dominant factor in affecting the weld strength followed by power and pressure. It was also found that the weld strength was proportional to the heating time at constant power and constant pressure. In addition, final sample thickness was inversely proportional to the lap shear strength. Bending of the joint during testing was the major failure mode. The maximum achievable strength for material B is 15% higher than that of material A. Furthermore, vibration welding of these two materials was also performed for comparison. It was found that material B achieved 80% higher weld strength than material A using vibration welding.

Introduction

It is desirable to weld plastic components together without adding extra materials at the joint interface. This enables direct bonding between the two materials to avoid the material incompatibility and reduce cost. Most welding processes require no additional materials at the joint interface such as vibration welding, radio frequency welding and ultrasonic welding. However, in some cases where these welding processes cannot be used due to part/joint complexity, component limitation and accessibility of equipment, other welding techniques must be considered. Implant induction welding is one of the methods that can be considered. Implant induction welding typically operates at frequencies ranging from 40 kHz to 200 kHz or at higher frequency near the mega hertz range. It is important to note that most plastics do not heat under these frequencies. Therefore, implant induction welding utilizes a heating element placed at the joint interface to generate the heat and melt the plastics to create the joint. The induction welding operating frequency can be selected based on the heating element composition. There are two types of heating mechanisms in implant induction welding, joule heating (eddy current heating) and hysteresis heating [1]. Joule heating relies on eddy current generation associated with resistance in the heating element and hysteresis heating relies on magnetic hysteresis losses of a material to produce the heat [2]. Typically, eddy current heating operates at lower frequency and hysteresis heating usually requires higher frequency. In this study, the induction welding was operated at 6.5MHz.

The basic induction welding machine contains a generator, a controller and heating coils. The generator converts line power to a high frequency RF signal through an oscillating tube. The controller controls the power level and heating time. The alternating current from the generator passes through the heating coils and creates an electromagnetic field that heats the heating element, which is usually a composite of the polymer to be welded with metallic filler. Under external pressure, the molten polymer in the heating element flows and creates the bond. The heating coil is made of water cooled copper tubes and its temperature is maintained near room temperature. The heating element has to be placed near the heating coil but not in contact with the coil to achieve higher heating efficiency.

Previous studies of implant induction welding of PC, PBT and PP [3] indicated that the maximum weld strengths were near 50% of the base material strength in butt joint configuration. Induction welding studies of 33% glass fiber reinforced nylon 6 containers was also reported [4] indicated that the burst strength was higher than that of the vibration welded containers. Similar to adhesive bonding, most implant induction applications are designed with a shear joint configuration. Therefore, the lap shear joint was used in this study.

Experimental Procedures

In this study, the induction welding system was manufactured by Ashland Chemical, Emabond Systems model EA-20, 2 kW operating at 6.65 MHz. The heating element was also made by Ashland Chemical using metallic fillers mixed with nylon resin.

Two grades of unfilled Nylon 6/6 materials, denoted as Material A and Material B, were used in this study. Lap shear joint samples were used to evaluate the weldability. Figure 1 shows the experimental set up in which the heating element was sandwiched between two Nylon plates and placed between the heating coils. The heating coil used in this study was a composite coil that contains a hair pin coil with 600 mm in length and 25 mm wide copper plate and a water cooled square copper tube (6.35 mm x 6.35 mm). The diameter of the heating element was 2.4 mm and the Nylon plate thickness was 3.07 mm for material A and 3.09 mm for material B. The width of the nylon plate was 75 mm and the length of the nylon plate was 125 mm. The overlap for welding was 25 mm and the heating element was placed in the center of the overlap as shown in Figure 1. After welding, the sample was cut into a 25 mm wide test coupons. Only the middle sample was tensile tested on Instron 4466 using a crosshead speed of 50 mm/min.

Three factor two level full factorial design of experiments (DOE) was used to evaluate the lap shear strength. The three factors were: heating time, weld pressure and power level. The high setting for heating time was 8 seconds and the low setting was 6 seconds. The high setting for power level was 100% (2 kW) and the low setting for power was 80%. It is noted that this power is the induction generator output power not the power absorbed by the heating element. The weld pressure was read from the pressure gauge on the welder, and the high setting was 0.41 MPa that is equivalent to a force of 1310 N and the low setting was 0.14 MPa that is equivalent to a force of 436 N. Each condition was duplicated three times. In addition to the tensile strength, the final sample thickness was also recorded to estimate the bond thickness. Since the heating element flows under pressure, by using the conservation of mass, the bond width could be estimated from the thickness measurement.

Vibration welding of butt joint samples was also made for purposes of comparison. It is difficult to compare a butt joint to a lap shear joint; therefore, the focus was in the material weldability. A Branson Micro welder was used with constant peak to peak amplitude of 1.75 mm. The weld pressure was varied from 0.5 MPa to 4 MPa and the meltdown was varied from 0.5 mm to 2 mm. Again, the tensile testing speed was 50 mm/min.

Results and Discussion

The full welding matrix and the lap shear weld strength for 8 welding conditions are shown in Table 1. The DOE analysis resulted in the following regression equations for strength.

Material A - strength:

$$\begin{aligned} Strength = 2427 + 372P_r + 993T + 681P - 76P_r \times T \\ - 80P_r \times P - 151T \times P - 118P_r \times T \times P \end{aligned} \quad (1)$$

Material B - strength:

$$\begin{aligned} Strength = 2721 + 431P_r + 1208T + 722P - 167P_r \times T \\ - 44P_r \times P + 9T \times P - 134P_r \times T \times P \end{aligned} \quad (2)$$

In the above equations, weld strength is given in Newton, T is the weld time, P is the power, and Pr is the weld pressure. The values for the above equations are from 1 to -1, where 1 is the high setting and -1 is the low setting. The R-square values are 88.5% and 85.7% for material A and material B, respectively. The coefficients in Equations 1 and 2 indicated that time is the most important factor in affecting the weld strength followed by the power. Pressure has less effect on strength compared to time and power. The coefficients of the cross terms are much smaller than that of the major parameters indicating there is no interaction between the major parameters. By removing the cross terms in the Equation 1 and 2, the coefficients in the regression equations did not change and the R-square values were slightly reduced to 85.9% and 83.9% for material A and material B, respectively.

Figure 2 shows the effect of weld pressure and heating time for both materials. It is noted that high weld pressure always produced higher weld strength especially at short heating times. However, at 8 seconds of heating the weld strength was nearly independent of pressure. It is also noted that increasing the heating time increases the weld strength. However, the rate of increase was reduced at 8 seconds of heating. Furthermore, the maximum achievable strength for material B is about 15% higher than that of material A. The bending during tensile testing of induction welded samples was the main failure mode as shown in Figure 3. Thus, proper joint design should be considered in the induction welding to eliminate the bending such as tongue and groove design.

Figure 4 shows the effect of vibration weld pressure on weld strength with 1 mm of meltdown and peak to peak amplitude of 1.75 mm. It is clear that low weld pressure produced higher weld strength for both materials. The maximum weldable butt joint strength for material A and material B was 29.5 MPa and 54.9 MPa, respectively. The material B achieved 80% higher weld strength than that of the material A. Figure 5 shows the effect of vibration weld meltdown on weld strength using 1 MPa weld pressure and peak to peak amplitude of 1.75 mm. Evidently, the meltdown has no effect on weld strength. Again, the weld strength for material B was 80% higher compared to the weld strength of material A.

As mentioned earlier, for induction welding, sample thickness was measured after welding and correlated to the weld strength. Statistical analysis resulted in the following regression equations for sample thickness.

Material A - thickness:

$$\begin{aligned} Thickness = 6.68 - 0.0821P_r - 0.105T - 0.0863P \\ + 0.0287P_r \times T + 0.0246P_r \times P + 0.0296T \times P \\ - 0.0179P_r \times T \times P \end{aligned} \quad (3)$$

Material B – thickness:

$$\begin{aligned} Thickness = 6.68 - 0.08P_r - 0.112T - 0.0842P \\ + 0.033P_r \times T + 0.0258P_r \times P + 0.0358T \times P \\ - 0.0125P_r \times T \times P \end{aligned} \quad (4)$$

The unit for the thickness is in mm. The values for Pr, T and P are from 1 to -1. The R-square values are 92.8% and 94% for material A and material B, respectively. The cross terms in Equation 3 and 4 could not be eliminated. The total sample thickness before welding is about 8.54 mm for material A and 8.58 mm for material B. The reduction in thickness was produced by the squeeze flow of the heating element. It was also found that the thickness is inversely proportional to the weld strength. Figure 6 shows the relation between the sample thickness and the weld strength. It is seen that thinner samples had higher weld strength. All samples thicker than 7mm had very low weld strengths. Thinner samples correspond to more deformation of the heating element during welding. Therefore, by using mass conservation, one can estimate the bond width. The assumptions used in the estimation were: the thickness reduction was mainly from the heating element, the molten heating element had a uniform thickness and the dimension of the nylon plate was not changed. It is noted that the nylon plate has to melt to create a bond; however, the melt zone was very small compared to the size of the heating element. Figure 7 shows the cross section of a joint welded using 100% power, 7 seconds of heating and 0.41 MPa pressure. Equation 5 is used to estimate the bond width.

$$\frac{\pi d^2}{4} = t \times L \qquad (5)$$

where d is the heating element diameter (2.4mm), t is the heating element thickness and the L is the bond width. The heating element thickness was obtained from the thickness difference before and after welding. Figure 8 shows the relation between the bond width and the lap shear strength. It is seen that wider bond lines produced higher weld strength. The heating element could be squeezed 4 to 5 times wider than its original diameter and the strength data for two materials appeared to overlap with each other. It is important to note that the bond line is not always uniform; therefore, equation 5 is only used for estimation.

Lap shear sample failure modes during the tensile testing were very similar for these two materials. For weld strength above 3000N, the sample failed in a brittle mode and typically shattered into many pieces as shown in Figure 9. The failure always initiated at the edge of the heating element and propagated across the sample as shown in Figure 3. Lower weld strength samples failed in similar modes except the crack propagated through the interface between the heating element and the sample as shown in Figure 10. For all cases, crack created by the bending moment in the base material near the joint area was the main cause of the failure. In many cases, the crack occurred at the edge of the joint and propagated though the sample.

Based on the above observation, it is concluded that sample thickness was not sufficient to sustain the bending during tensile test. Therefore, thicker samples (6mm) were also studied. It is important to know that this increases in thickness also resulted in an increase in the distance between the heating element and the heating coils. Therefore, the heating time was increased from 8 seconds to 24 seconds with 100% of the power setting. The heating pressure was maintained at 0.41MPa. The thicker samples resulted in the similar weld strength as the thinner samples. The increase in strength was less than 5%. However, it exhibited similar failure mode. This indicated that stress concentration at the edge of the weld associated with bending were the major cause of failure in a lap shear joint.

Conclusions

Implant induction welding of nylon 6/6 was demonstrated in this study. Both materials could be welded with relatively high weld strength. The material B showed higher achievable weld strength compared to material A. The maximum lap shear strength for a 25 mm wide and 3.08 mm thick sample was 3916 N and 4552 N for material A and material B, respectively. The statistical analysis indicated that heating time is the most dominant factor in affecting the weld strength followed by power and weld pressure. Weld strength was found to be inversely proportional to the sample thickness after welding. In addition, the weld strength was proportional to the bond width. The major failure mode in the lap shear joint was caused by the stress concentration and bending during tensile testing. The weld strength for vibration welded butt joints exhibited quite different results from the lap shear joint. Butt weld strength of material B was 80% higher than the material A. Based on this study, the weld process and geometry could affect the weld strength dramatically. Choices of process and joint design could enhance or degrade the performance of a weld.

Acknowledgements

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References

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Key Words

Nylon 6/6, Induction Welding, Vibration Welding, Design of Experiments, DOE

Table 1 Three factor two level full factorial design of experiments welding matrix and averaged Lap shear strength

Run #	Power Level (%)	Heating Time (sec)	Pressure (kPa)	Material_A (Newton) with all 3 samples (average)	Material_B (Newton) with all 3 samples (average)
1	80	6	138	0 66 108 (58)	166 0 130 (98)
2	100	6	138	1714 2142 1092 (1649)	1328 1553 1150 (1344)
3	80	8	138	2258 2632 1905 (2265)	2625 2471 2592 (2563)
4	100	8	138	3968 3666 3531 (3721)	4229 4423 4487 (4380)
5	80	6	414	808 1124 706 (879)	1040 1075 1229 (1115)
6	100	6	414	2785 2525 2549 (2620)	2879 2350 2928 (2719)
7	80	8	414	2895 3397 3464 (3252)	3464 3066 3804 (3444)
8	100	8	414	3904 3922 3921 (3918)	4562 4574 4519 (4552)

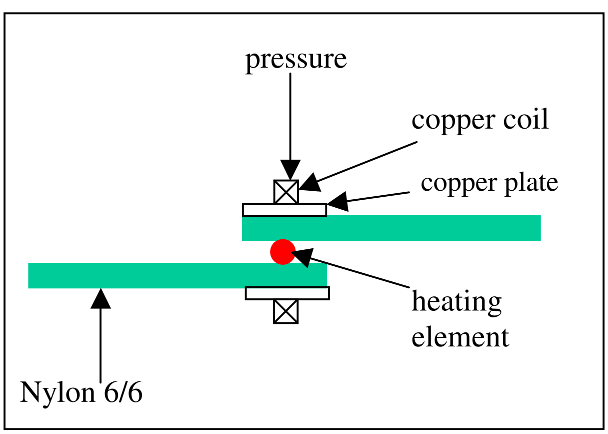

Figure 1 Experimental setup

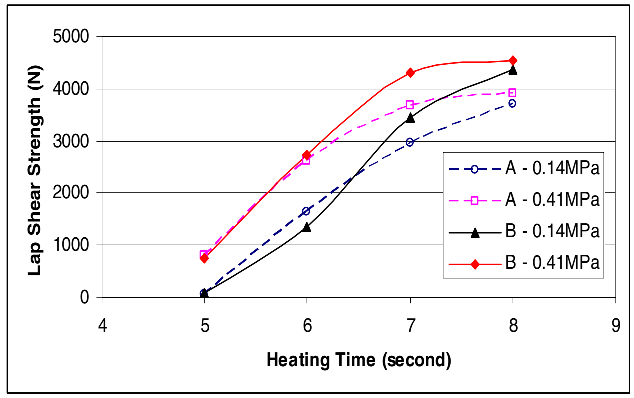

Figure 2 Effect of weld pressure and weld time on weld strength - induction welding

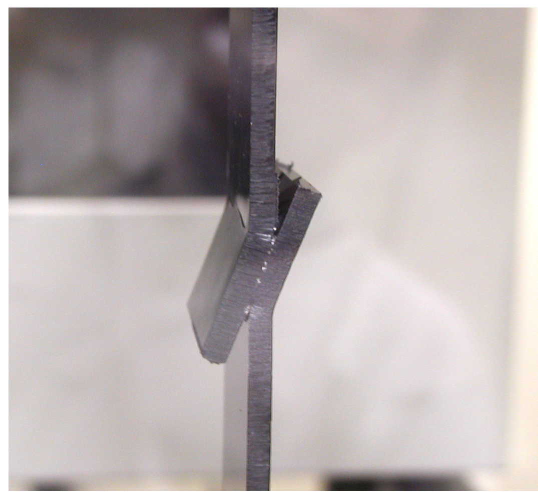

Figure 3 Bending during tensile testing of induction welded sample

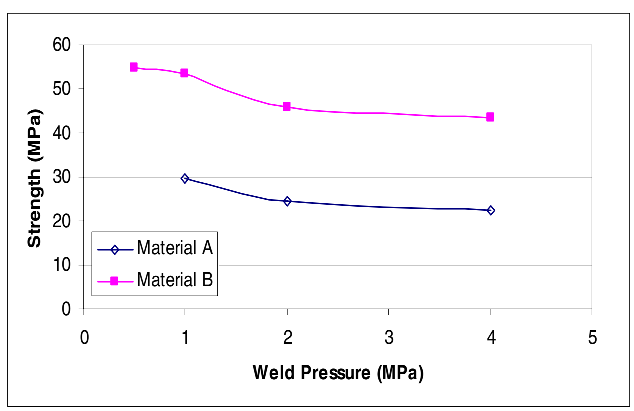

Figure 4 Effect of weld pressure – vibration welding Bulk material strength for material A and material B is 56 MPa and 61 MPa, respectively

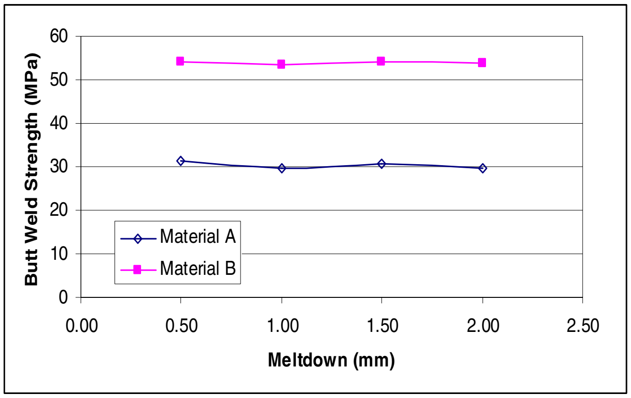

Figure 5 Effect of meltdown – vibration welding

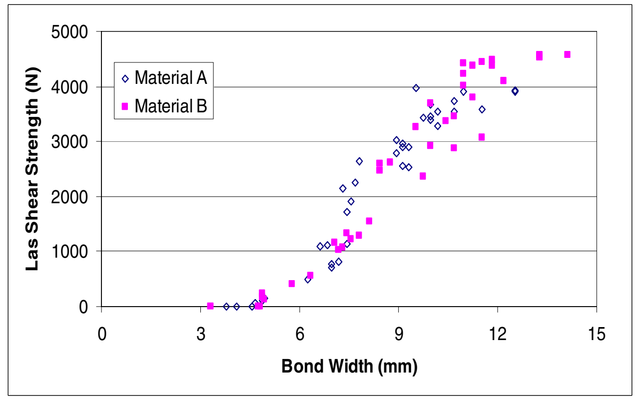

Figure 8 Effect of bond width on lap shear strength

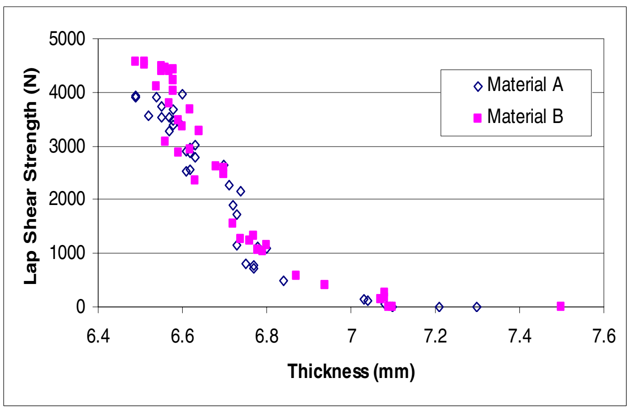

Figure 6 Effect of sample thickness on lap shear strength

Figure 9 Fracture surface of high strength welds

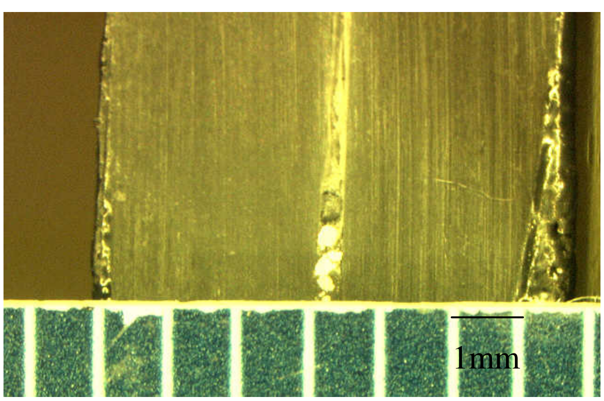

Figure 7 Cross section of the joint

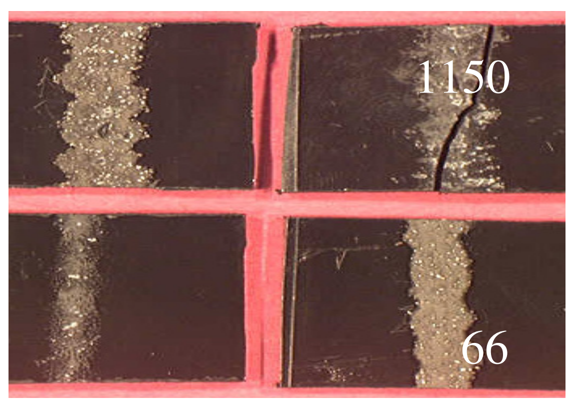

Figure 10 Fracture surface of low strength welds