COMPARISON OF ULTRASONIC WELDING AND VIBRATION WELDING OF THERMOPLASTIC POLYOLEFIN

C.-Y. Wu, A. Benatar and A. Mokhtarzadeh

ABSTRACT

Thermoplastic polyolefin (TPO) is widely used in automotive interior applications including instrument panel, doors, and centre console. Ultrasonic welding and vibration welding are two common joining techniques used in the industry. The goal of this study was to use design of experiments (DOE) to evaluate the ultrasonic welding and vibration welding of a TPO. This study included ultrasonic energy director welding using American Welding Society (AWS) standard test samples and vibration welding of two AWS Tee samples in butt joint geometry. The weld strength was compared to bulk material tensile strength of moulded AWS I-beams. Ultrasonic welding results indicated that amplitude was the most dominant factor in affecting the welding strength and both time and weld pressure had minimum impact on weld strength. The maximum achievable weld strength using ultrasonic welding was 40 % of the base material strength. Vibration welding results indicated that amplitude was the most dominant factor in affecting the weld strength and high weld pressure resulted in lower weld strength. The maximum achievable weld strength using vibration welding was 66 % of the base material strength.

IIW-Thesaurus keywords: Experiment design; Friction welding; Process variants; Ultrasonic welding; Vibration; Thermoplastics.

1 Introduction

The use of thermoplastic polyolefins (TPO) in automotive interior and exterior applications has been increasing dramatically. The applications include bumper fascia, instrument panel, and door panels. The major advantages of using TPO are long-term durability and cold weather resistance. Some good examples of these applications can be found on the instrument panels on 2000 Ford Focus and the 2000 Pontiac Bonneville [1], as well as, the door panel of Mercedes-Benz E class, Porsche 986/996 and Honda Civic [2].

Many automotive components have complex geometries and cannot be injection moulded efficiently. Therefore, there is a need to mould the components separately and join them together using a welding process [3]. There are many welding methods that can be used to join polypropylene (PP) or TPO such as hot plate [4], vibration [5], ultrasonic [6], infrared [7] and laser [8]. Previous studies indicated that vibration welding of TPO T-joint produced acceptable weld strength and the joint strength was not affected dramatically by the welding parameters such as amplitude, weld time and pressure [5]. The joint strength is more sensitive to the composition of the materials rather than to the welding parameters [4]. Ultrasonic welding of TPO was reported to produce good weld strength [6] but the weld strength is reduced by paint over spray. Weld break force of ultrasonic welded and vibration welded TPO were also reported [6], but the processes could not be compared because different joint configurations resulting in stress concentrations and different joint areas were used for each case. Therefore, the main objective of this study is to optimize ultrasonic and vibration welding of TPO using design of experiments (DOE) and to compare the weld strength between the two processes as well as with the bulk material strength of TPO.

2 Experimental procedures

2.1 Sample preparation

TPO pellets were injection moulded into three different American Welding Society (AWS G1.2) standard test geometries for this study [9]. The first sample was a reference I-beam sample to evaluate the bulk material strength. The second sample was a T-sample used for both ultrasonic and vibration welding. The third sample was an ultrasonic welding sample with large size energy director. Figures 1-3 show the geometry of the samples as specified in the AWS standard. For the energy director

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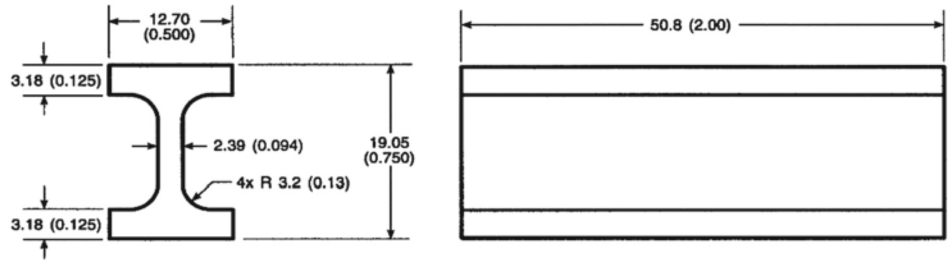

Notes:
1. All dimensions mm (in.)
2. Tolerances: x.x ... ±0.2 (0.008)
x.xx ... ±0.05 (0.002)

Figure 1 – Standard AWS reference I-Beam sample geometry

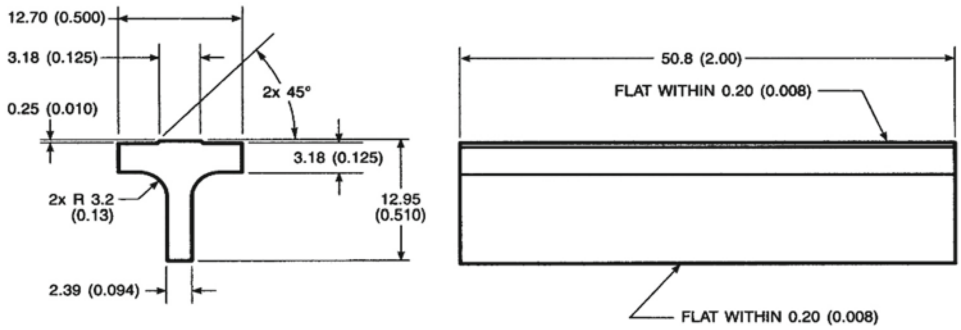

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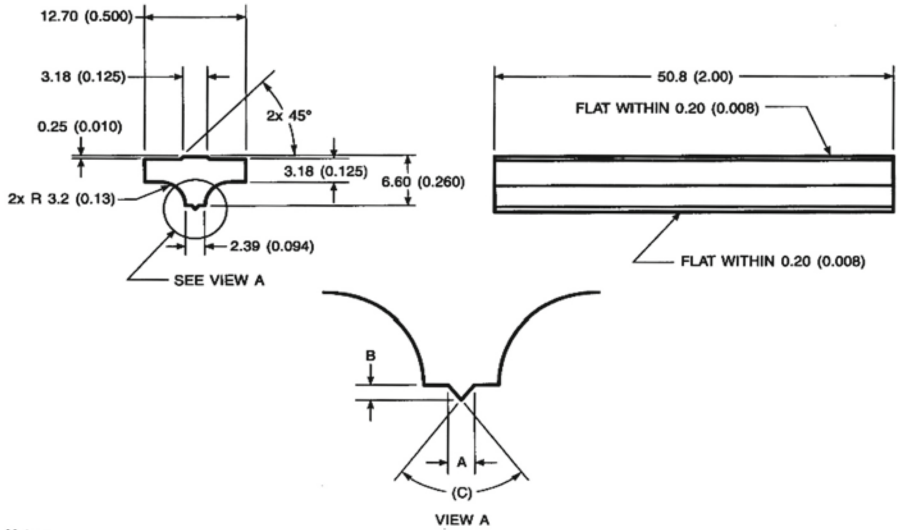
Figure 2 – Standard AWS T-sample geometry



Notes:
1. All dimensions mm (in.)
2. Tolerances: x.x ... ±0.2 (0.008)
x.xx ... ±0.05 (0.002)

Profile	A	B	Ref. C
Small Energy Director	0.61 (0.024)	0.30 (0.012)	90°
Large Energy Director	0.81 (0.032)	0.51 (0.020)	77°

Figure 3 – Standard AWS ultrasonic welding energy director sample (large energy director used for this work)

samples, the large energy director configuration was used with a height of 0.51 mm and included angle of 77° (see Figure 3). The thicknesses of the web of the Tee and reference sample were measured at five locations for three samples and it typically varied from 2.43 mm to 2.47 mm with an average of 2.45 mm. Therefore, the nominal length and web thickness were set at 50.92 mm and 2.45 mm, respectively. During ultrasonic welding, the energy director sample was placed on the top (in contact with the ultrasonic horn), and was welded to a T-sample to form an I-beam. The height of the ultrasonic welded sample was approximately 19.55 mm.

During vibration welding, two T-samples were welded together to form an I-beam. The height of the vibration welded sample was approximately 25 mm. The welded samples were then tested and compared to the moulded I-beam samples.

The AWS G1.2 standard [9] specifies the equations to be used to calculate the nominal weld failure stress. For ultrasonic welding with energy director butt joints, the nominal failure stress (σ) is found by the following relation:

$$\sigma = \frac{\text{Failure Load}}{\text{Web Cross Sectional Area}} \quad (1)$$

Similarly, Equation (1) was also used to calculate the weld strengths for the vibration butt welding of the Tees and for the bulk I-Beam samples.

2.2 Ultrasonic welding

Ultrasonic welding was done at 20 kHz using a Branson ultrasonic welder that included a 920MA power supply with 921aes actuator. Figure 4 shows the welding fixture and horn that were used to weld the AWS G1.2 standard test samples. Ultrasonic welding was done using the time mode with five samples being welded for each set of welding parameters. Initial screening was performed by varying the amplitude of vibration from 20.5 to 40.1 µm peak-to-peak (P-P), the weld time from 0.2 to 1.0 s, and the pressure from 4 to 12 MPa. For all the welds, the trigger force was set at 440 N and the hold time was fixed at 2 s. The minimum conditions for just producing a reasonable weld

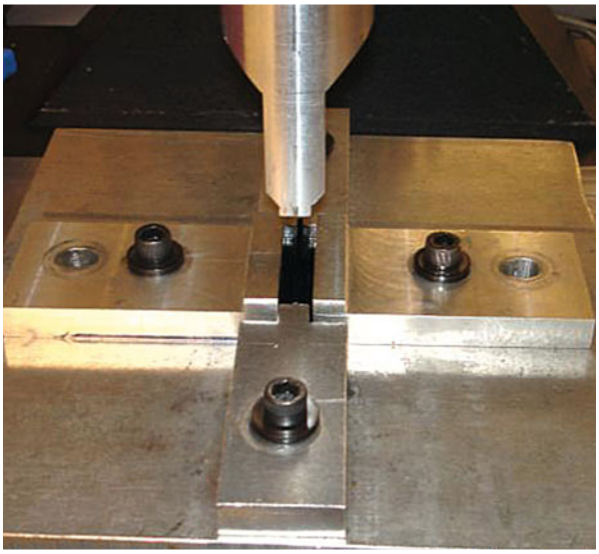


Figure 4 – Welding fixture and horns for AWS G1.2 test samples

Table 1 – Range of parameters for ultrasonic welding DOE

Parameter	Minimum	Maximum
Amplitude [µm p-p]	24.1	40.1
Time [s]	0.4	0.8
Pressure [MPa]	4.8	9.6

and the maximum conditions for producing a significant amount of flash were selected for the range of DOE variables. Figure 5 a) shows the just welded and Figure 5 b) the maximum flash samples. Table 1 lists the DOE matrix used for the ultrasonic welding study. Three factor and two level full factorial design of experiments was used, resulting in eight welding parameter combinations. In addition to that, a centre point was also added using the average value of each parameter.

2.3 Vibration welding

Vibration welding was done using a Branson Mini-Vibration welder. Figure 6 shows the welding fixture that was constructed to enable the application of low welding pressures through the use of two small air cylinders. Vibration welding was done using the time mode with five samples being welded for each set of welding parameters. Initial screening was performed by varying the amplitude of vibration from 0.5 to 1.25 mm peak-to-peak (P-P), the weld time from 1 to 6 s, and the pressure from about 0.5 to 3 MPa. For all the welds, the hold time was fixed at 6 s. The minimum conditions for just producing a reasonable weld and the maximum conditions for producing a significant amount of flash were selected for the range

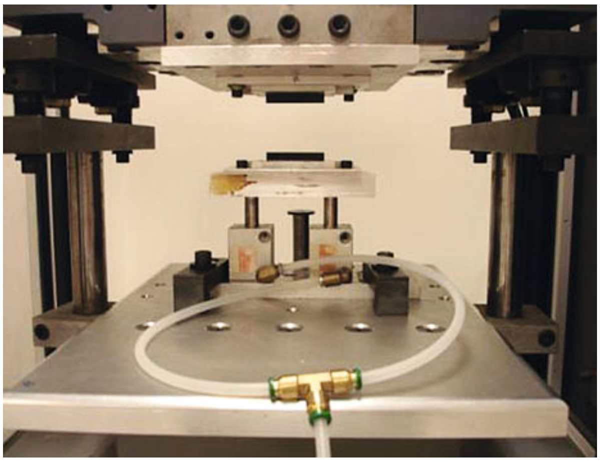
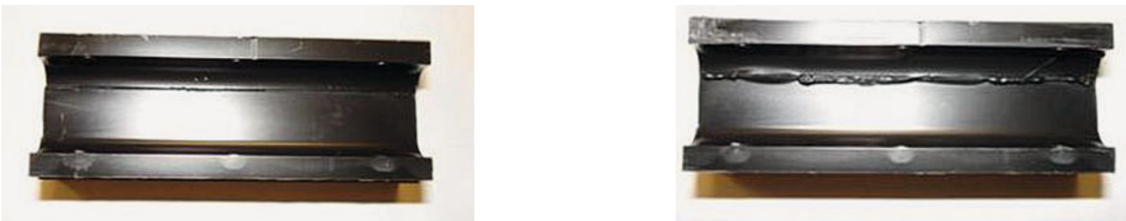


Figure 6 – Welding fixture for vibration welding



a) Just welded sample

b) Maximum flash sample

Figure 5 – Photos of ultrasonic welding

a) Just welded sample   b) Maximum flash sample

Figure 7 – Photos of vibration welding

Table 2 – Range of parameters for vibration welding DOE

Parameter	Minimum	Maximum
Amplitude [mm p-p]	0.75	1.25
Time [s]	2	4
Pressure [MPa]	1	2

of DOE variables. Figure 7 shows the just welded and the maximum flash condition samples. Table 2 lists the range of parameters that were used in the DOE. Three factor and two level full factorial design of experiments was used resulting in eight welding parameter combinations. In addition to that, a centre point was also added using the average value of each parameter. It is noted that the vibration welded samples were taller than the ultrasonic welded samples because the T-samples were taller than the energy director samples.

2.4 Mechanical testing

The strengths of the reference samples and the welded samples were measured at room temperature in tension using an Instron 4468 testing machine at a crosshead speed of 5.08 mm/min, as specified in the AWS G1.2 standard. Figure 8 shows the test fixture that was used. Ten reference I-beam samples were tested to determine the average and standard deviation of the bulk material failure stress. Similarly, for each welding condition, five samples were tested and the failure stress was determined using Equation (1). The average weld strength and standard deviation were then calculated for each welding condition.

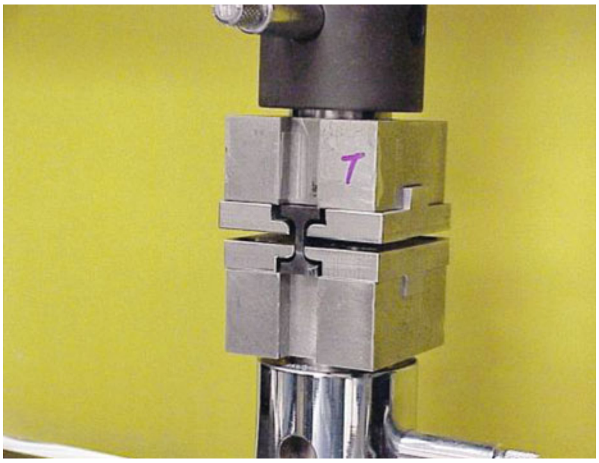


Figure 8 – Pull test fixture

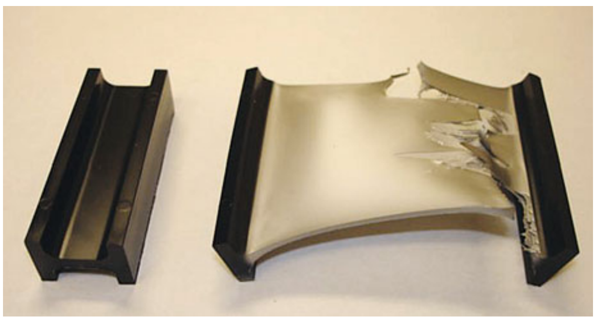
3 Results and discussions

3.1 Tensile strength of reference samples

The reference samples were used to measure the tensile strength of the bulk material. For this TPO the tensile strength was found to be 21.0 ± 0.1 MPa. All the samples underwent significant elongation prior to failure, as shown in Figure 9.

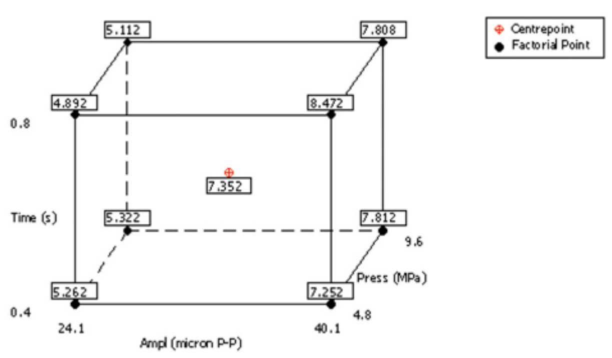
3.2 Weld strength for ultrasonic welding

Figure 10 shows a strength cube plot of the ultrasonic welding results where each data point is the average of five samples. It shows that the maximum weld strength of 8.47 ± 0.66 MPa was achieved using a peak-to-peak amplitude of 40.1 µm, a weld time of 0.8 s, and a pressure of 4.8 MPa. In this case, the weld strength was only 40 % of the bulk material strength. It was observed that all the welded samples failed at the weld interface with no elongation during tensile testing. This is very typical for ultrasonically welded samples due to the squeeze flow induced molecular orientation parallel to the weld interface. In general, ultrasonic welding using high amplitude of vibration produced stronger joints, but it resulted in extensive surface marking (surface damage) on the top part, as shown in Figure 11. The surface marking was created by extended contact between ultrasonic welding tool and soft plastic surface. In automotive applications, surfaces that are visible to the consumer are referred to as "Class A" surface and they are required to be of high quality and good surface finish. The extensive marking that was observed indicates that ultrasonic welding is not



a) Untested   b) Elongated

Figure 9 – Untested TPO reference sample compared to elongated reference sample



Each data point is the average of five samples.

Figure 10 – Strength cube plot with average weld strength [MPa] for ultrasonic welding

Figure 11 – Surface marking on top of ultrasonic welded sample

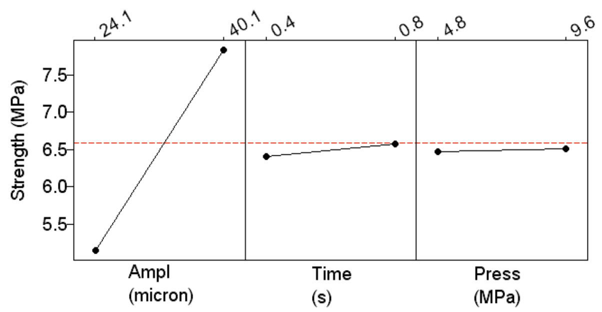


Figure 12 – Main effect plot for ultrasonic welding

suitable to weld TPO in cases where a Class A surface finish is required and in fact, currently, no ultrasonic welding applications are used on TPO Class A surfaces.

Figure 12 shows the main effect plot for ultrasonic welding. The results indicated that higher vibration amplitude produced a stronger joint. Weld time and pressure had little to no effect on weld strength.

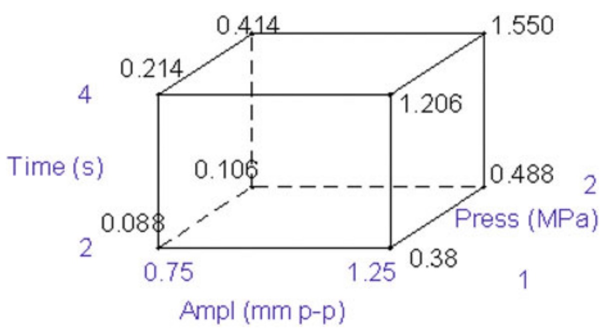
3.3 Weld strength for vibration welding

Stokes [10] divided vibration welding into four different phases based on the penetration or downward displacement of the part as material at the interface melts and squeezes out. Therefore, penetration is also commonly referred to as meltdown. Stokes [10] described vibration welding using four phases:

1. solid friction, where there is little or no penetration,
2. transition, where the interface begins to melt resulting in viscous deformation and heating of the melt along with some squeeze flow, thereby increasing the penetration,
3. steady state, where the amount of melt produced due to viscous heating is balanced with the amount of melt squeezed out and penetration increases at a constant rate, and
4. cooling, where the vibration is stopped resulting in slightly more penetration as some of the melt is squeezed out while cooling and solidifying.

Figure 13 shows a cube plot for the vibration welding penetration or meltdown. The penetration was obtained by measuring the difference in sample thickness before and after welding. As would be expected, the maximum penetration was 1.55 mm using high vibration amplitude, high welding pressure and long weld time. Figure 14 shows the penetration main effect plot for vibration welding. As expected, all high settings produced more penetration. Amplitude was found to have the most significant effect on penetration for the range of parameters studied.

Figure 15 shows a cube plot of the vibration welding strength, where each data point is the average of five test samples. It shows that the maximum weld strength of 13.94 ± 0.19 MPa was achieved using a peak-to-peak amplitude of 1.25 mm, a weld time of 4 s, and a pressure of 1 MPa. In this case, the weld strength was 66 % of the



Each data point is the average of five samples.

Figure 13 – Cube plot for vibration welding penetration [mm]

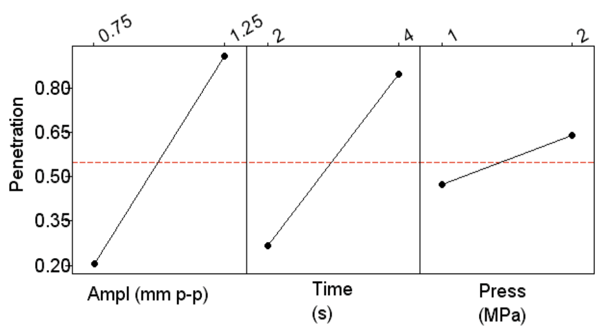


Figure 14 – Main effect plot for vibration welding penetration

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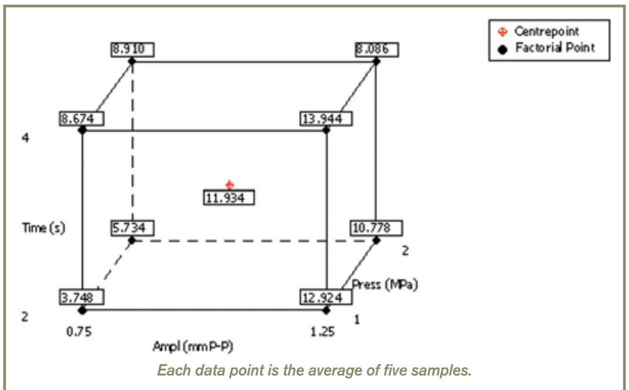

Figure 15 – Cube plot with average weld strength [MPa] for vibration welding

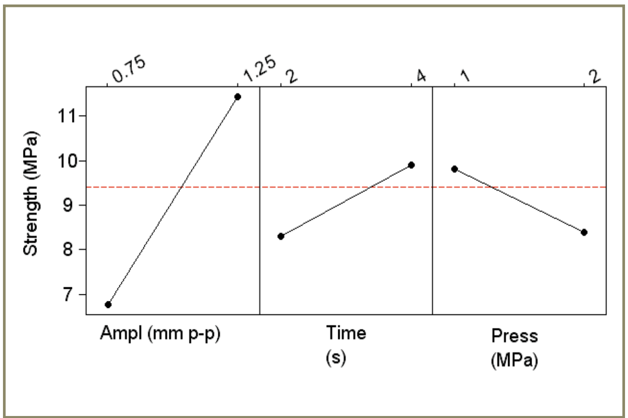

Figure 16 – Main effect plot for vibration welding strength

bulk material strength, which is similar to results found by others for vibration welding of TPO [4, 5]. As is typical of welded joints, it was observed that all the samples failed at the weld interface with no elongation during tensile testing; due to the squeeze flow induced molecular orientation parallel to the weld interface. Therefore, using low weld pressures with high amplitude of vibration, and long weld time resulted in increase in weld strength. It was also observed that the standard deviation for the vibration welds was significantly lower than that of ultrasonic welds. Ultrasonic welding is known to have higher variations in weld strength than other welding processes [11].

Figure 16 shows the main effect plot for vibration welding strength. It shows that amplitude was the most dominant factor on weld strength and higher amplitude resulted in higher weld strength. Increasing weld time also improved the weld strength. However, increasing pressure decreased the weld strength. Therefore, high amplitude and low pressure should be considered for vibration welding of TPO. Longer weld time produced a stronger joint, but the amount of weld flash also increased. Therefore, weld time should be selected to accommodate the flash and desired weld strength.

3.4 Comparison of ultrasonic and vibration welding of TPO

For ultrasonic welding of TPO the maximum weld strength was 8.47 ± 0.66 MPa while for vibration welding it was 13.94 ± 0.19 MPa, which was 40 % and 66 % of the bulk strength of TPO, respectively. During ultrasonic welding, the energy director was primarily melted and squeezed under high pressure to fill the gap between the parts. While this resulted in faster cycle time, it also resulted in less melting of the part surfaces compared to vibration welding, and in higher molecular orientation parallel to the weld, resulting in lower tensile strength for the weld. For vibration welding, using high amplitude of vibration, long weld time, and low weld pressure resulted in longer cycle time but also in more melt and less molecular orientation than ultrasonic welding, and therefore in stronger welds than ultrasonic welding.

4 Conclusions

The goal of this study was to use design of experiments (DOE) to investigate ultrasonic and vibration welding of a TPO and compare their weld strengths to the bulk strength. The study included moulding of AWS standard test samples and performing DOE studies for 20 kHz ultrasonic energy director joints and for vibration welding of two AWS Tees to form a butt joint. The weld strength was compared to the bulk tensile strength of moulded TPO AWS I-beams. It was found that the reference samples had bulk strengths of 21.0 ± 0.1 MPa and they exhibited very ductile fracture with extensive elongation. The welded samples for both ultrasonic and vibration welding exhibited brittle fracture. For ultrasonic welding, the optimum welding conditions had a peak-to-peak amplitude of vibration of 40.1 μm, a weld time of 0.8 s, and a pressure of 4.8 MPa, resulting in a weld strength of 8.47 ± 0.66 MPa, which was 40 % of the bulk strength. For vibration welding the optimum welding conditions had a peak-to-peak amplitude of vibration of 1.25 mm, a weld time of 4 s and a pressure of 1 MPa, resulting in a weld strength of 13.94 ± 0.19 MPa, which was 66 % of the bulk material strength. Therefore, both ultrasonic welding and vibration welding can be used to weld TPO, but the total weld area may need to be increased to provide sufficient load transfer as the bulk.

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