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ORIGINAL ARTICLE

Optimizing the weld factors affecting ultrasonic welding of thermoplastics

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Abstract

This work presents the optimization of weld factors for ultrasonic welding of similar thermoplastics acrylo-nitrile butadiene styrene (ABS) to ABS (ABS/ABS) and polypropylene (PP) to PP (PP/PP) using Taguchi experimental design (L-8). Energy director (ED) fabricated using injection molding is the protruding part for getting ultrasonic vibrations concentrated at the joint interface. Dimensions of ED were increased, as compared to literature, to investigate its effect on joint quality. In addition to enhanced ED dimensions, it was essential to consider the other weld factors properly leading to parametric optimization of these factors for selected thermoplastics. For both ABS and PP, highest lap shear strength (LSS) was achieved while using triangular (TRI) ED instead of SEMI (semi-circular) ED. In the case of ABS, applied pressure, amplitude, and hold time are found to be the significant factors for maximizing LSS; however, amplitude and weld time are found to be more contributing parameters for weld strength in the case of PP. Significant improvement in the weld strength (LSS) has been achieved after conducting the validation experiments for both ABS and PP, i.e., 31.21 MPa (104% of original ABS shear strength) and 22.36 MPa (319% of original PP shear strength) respectively. Substantial enhancement in LSS has been acquired as compared to previous studies. This improvement was only possible with introducing the new joint design for ultrasonic welding that is an innovative design idea. Furthermore, these huge improvements in LSS were never reported for any other welding process utilizing thermoplastics in literature. Although ABS and PP are ductile, various causes of fracture brittleness are also microscopically studied for both materials.

Keywords Energy director (ED) · lap shear strength (LSS) · polypropylene (PP) · acrylo-nitrile butadiene sytrene (ABS) · thermoplastics · heat affected zone (HAZ)

1 Introduction

Ultrasonic welding of thermoplastics have been widely accepted by the industries in past decades [1–4]. Ultrasonic welding is still known as an efficient process with zero polymer degradation. Ultrasonic welding has a wide range of applications, e.g., automotive, packaging, textile, appliances, etc. Typical products involve lens cleaning, highlighter, napkin, solar panel, MP3 Player, pacifier, Mobile phones, headlights, airbags, etc. [5].

An alternate way of joining thermoplastics is the adhesive bonding. If parts to be bonded are big enough, then adhesive bonding becomes difficult to achieve. Therefore, adhesive bonding may pose difficulty in terms of handling, extensive preparation of surfaces, lengthy curing periods, and introducing heat at the bonding interface of materials.

Fusion bonding may be achieved employing various plastic welding techniques. These welding techniques are categorized based on the way of providing heating sources at the expected bond location. A well-known class of fusion bonding is friction welding including spin, vibration, stir, and ultrasonic welding processes [6–15]. In order to overcome the drawbacks of adhesive bonding especially heating complexities, alternate heating and curing procedures may be utilized via various welding processes, e.g., vibration welding, microwave welding, induction welding, resistance welding, and ultrasonic welding [16, 17]. As far as polymeric systems are concerned to be welded ultrasonically, amorphous and semi-crystalline thermoplastics are thought to be better raw materials for ultrasonic welding than that of crystalline thermoplastics. However, energy directors (EDs) are usually fabricated using injection or compression molding processes on one

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mating thermoplastic specimen to localize the ultrasonic vibrations at bonding zone. But thermosets are found hard to be welded ultrasonically [18–21].

Development of plastics and its composites has opened new doors for extensive research. Ultrasonic welding is believed to be an attractive thermoplastic joining process. A significant number of people use the ultrasonically welded products every day in the USA [22]. Yousef pour et al. [23] provided a review of various joining techniques for thermoplastics. They have pronounced various fusion bonding techniques along with relevant equipment, production methodologies, technical factors' effects on welded joint, and their applications. Nonhof and Luiten [24] have suggested four steps to perform ultrasonic welding. These steps have given rise to various phenomena during ultrasonic welding of plastics. Various claims were also tested about amorphous and semi-crystalline thermoplastics. Prakasan et al. [25] attempted to simulate the ultrasonic welding of thermoplastics. They have described the viscoelastic heating as the main heating mechanism while welding thermoplastics ultrasonically. Simulated results agree with the measured temperatures during ultrasonic welding. TRI ED is found to have high temperature regions and high ultimate tensile strengths (UTS) as compared to other EDs. Although they [25] have provided the researchers with excellent approaches for ultrasonic welding of thermoplastics, number of experiments seems to be short which should be extended in terms of its depth and breadth. Villegas and Bersee [26] studied the effects of orientation and configuration of various energy directors. This work has presented a good effort in finding the effect of triangular ED on weld quality, but this is limited to only TRI ED and one material type, i.e., polyetherimide. Tsujino et al. [27, 28] studied the welding characteristics from ultrasonic welding systems by using various frequency levels, e.g., 20, 40 and 67 KHz. Weld strength achieves its larger value by using 67 KHz welding equipment differing from those of 20 and 40 KHz. Again, effects of other weld factors (such as amplitude, ED, pressure etc.) have not been considered in this research on weld strength. Moreover, plastic welding has been done using different ultrasonic welding systems but thickness of specimens seems to be very small, i.e., less than 1 mm. Also, energy director has not been used for welding thermoplastics. Hence, proper considerations of all weld factors are required to have better understanding of UWP for plastics.

Wu et al. [29] employed an ultrasonic welding technique for welding plastics with various geometries. Certain welding time has also been proposed with high level of normal pressure to achieve higher weld strengths. In this work, a procedure is developed for welding thermoplastics, i.e., polycarbonate with placing 0.5 mm thin sheet at the joint interface. However, using ED at joint interface can definitely result in better weld quality. Shu et al. [30] explained the ultrasonic spin welding of thermoplastics using various weld factors. Analysis of variance shows that hardening time is the most dominant weld factor that affects the welding quality. This work has only analyzed the spin welding considering relevant weld factors. It can also be extended to weld thermoplastics ultrasonically. Wu et al. [31] used the design of experiments to get a proper understanding of ultrasonic welding and vibration welding of thermoplastic polyolefin (TPO). For both welding processes, amplitude of vibrations has been observed to be the dominant factor for affecting the weld strength. Maximum weld strength obtained by utilizing ultrasonic welding is 40% of the base material strength, whereas 66% for vibration welding. Although the current work presents a good comparison of two welding processes, this work is limited to only thermoplastic polyolefin (TPO). In other words, weld strength from ultrasonic welding might appear greater than that from vibration welding if two thermoplastic materials were used. A. V. Aaken and C. Hopmann [32] conducted a scientific examination to address influence of moisture on interaction between ultrasonic welding process and material properties. They used polyamide which is highly hygroscopic, in their study. Although authors have highlighted an excellent direction towards examining ultrasonic welding of plastics, only one weld parameter (welding time) was considered to adapt to moisture content during ultrasonic welding in this work.

Liu et al. [33–35] studied, in their other work, optimization of joint strength of ultrasonically welded thermoplastics and its composite. Triangular ED has been found to join samples with highest strength for virgin polypropylene and 10% glass-fiber-filled polypropylene composites, whereas a semi-circular energy director has been found to acquire highest strength for 30% glass-fiber-filled composites. In their work, SEMI ED has been observed to impart the highest weld strength. Rani et al. [36] implemented fractional factorial design to ultrasonic welding of thermoplastics, i.e., acrylo-nitrile butadiene styrene (ABS) and high-density polyethylene (HDPE). They have found that welding time and welding pressure significantly affect the joint strength. Although Liu and Rani [33–36] have worked on optimizing weld strength from utilizing thermoplastics, they have used the similar Philips's sample geometry. Therefore, optimization of weld strength may be achieved with improved and new sample geometry. Yew Khoy Chuah et al. [37] studied the improvement in speed and quality of weld using different EDs, e.g., triangular, rectangular, and semi-circular ED. The most efficient ED among these three EDs was found to be semi-circular, followed by rectangular and triangular respectively.

Much of the current literature pays particular attention to few ultrasonic weld factors and almost little attention to sample design. Empirical investigation into different sample design, changes in ED dimensions, and considerations of all probable weld factors is necessary to find the effect of these factors on bond strength as this may result in significant improvement in the bond strength. Moreover, an enhancement in

ED dimensions may have great impact on improving joint strength leading to optimization of ultrasonic weld factors for enhanced ED dimensions. In fact, this work presents an in-depth study into enhancing weld strength substantially which has not been dealt thoroughly by researchers as a function of ED dimensions. In this research, ABS and polypropylene (PP) have been welded ultrasonically with an improved joint design, since this combination of amorphous and semi-crystalline thermoplastics and joint design were never studied before. Therefore, the present work aims to investigate this gap in terms of unique material combination, improved joint design, and holistic set of weld factors for considerable enhancement of weld strength as compared to those which have already been established in literature.

2 Experimental work

In this research, optimization of weld strength is acquired resulting from ultrasonic welding of thermoplastics, i.e., ABS and PP. ABS is an amorphous thermoplastic and PP is a semi-crystalline type of thermoplastic. In this study, ABS and PP samples to be welded were molded from granules (small grains/pieces/pellets) of ABS and PP correspondingly using piston injection molder with certain set of parameters, as mentioned in Table 1. Piston Injection molder is a desktop injection molding system also named as “HAAKE Minijet Piston Injection Molding System” supplied by Thermo Scientific. This molding system is extensively used to manufacture a wide variety of test specimens with limited size of molded part. Thermoplastic materials are heated in a small cylinder with the help of heaters. Molten thermoplastic is finally injected from cylinder into the molds using piston that is actuated pneumatically. The piston injection molding system is controlled using a touch control panel governing accurately the molding conditions of Table 1.

An ASTM Standard D3641-97(08.02), addressing on a standard practice for injection molding test specimens of thermoplastics materials, was followed during sample preparation.

Although conditions of injection molding (cylinder temperature, injection pressure, post pressure, and melting time) were set according to the values in Table 1 for ABS; contrarily, no fixed value of these conditions could be used for PP, as suggested in ASTM Standard D3641-97(08.02) owing to complex effect of sequence of applying pressures, temperatures, and time settings on different thermoplastics. Another possible explanation of using the range (min-max) of injection molding conditions for PP is the effect of Melt Flow Index (MFI) on molding PP. Value of MFI for PP is 14.81 g/min which is higher than that of ABS, i.e., 0.92 g/min [38]. The higher the MFI value for a thermoplastic material, the lower will the viscosity of that material be. Since viscosity of PP is lower than that of ABS, molten PP material was often resulted in larger flashes (thin fin of material formed at the mold’s parting line during an injection molding process) and short fillings of mold. Due to these resultant flashes and short fillings of mold, many samples were wasted in an effort to ensure the degree of quality of samples. These flashes were also required to be trimmed with a cutter/knife for each molded part. These unnecessary flashes and short fillings are caused by the higher fluidity (i.e., lower viscosity) of PP. Therefore, a range of injection molding conditions was determined first empirically and used for molding PP in an attempt to have tight control over short filling of mold and flashes.

Optimum performance of ultrasonic welding may be achieved by considering all factors and their levels resulting in optimized LSS. Optimum performance parameters may be determined by S/N ratio. In this study, the criterion for S/N ratio is defined as “bigger the best” implying lap shear strength should be optimized for its maximum value.

In this research, two geometries of EDs were designed and utilized, as shown in Figs. 1, 2, 3, and 4. The dimensioning and tolerancing, as can be seen in the Figs. 1, 2, 3, and 4, follow the rules stated in the American Society of Mechanical Engineers’ standard known as ASME Y14.5-2009. Figure 1 is the zoomed view of EDs to highlight the enhanced dimensions of EDs separately which are considered to be the most influential part of ultrasonic welding of thermoplastics. Likewise, Figs. 2 and 3 are the sketches showing the multiview illustrations of upper specimen to be welded ultrasonically containing EDs (samples with EDs) as well, as shown in Fig. 4 in detail. Moreover, Fig. 4 depicts the orientation of both samples with ED and without ED (i.e., flat or lower specimen). Ultrasonic welding experiments for both ABS and PP were accomplished by using this orientation, as illustrated in Fig. 4.

As a result of geometries of energy directors and orientation of samples used, lap shear joint was obtained eventually. Moreover, five samples were tested for ABS and four samples were tested for PP against each experimental run as per L-8 matrix of experiments, as shown in Tables 2, 4, and 5. Average

Table 1 Injection molding conditions for sampling

Material	Cylinder Temperature (°C)	Injection pressure (bar)	Post pressure (bar)	Melting time (min)
ABS	200	660	500	3–5
PP (Min-Max)	200–230	200–550	150–500	4–7

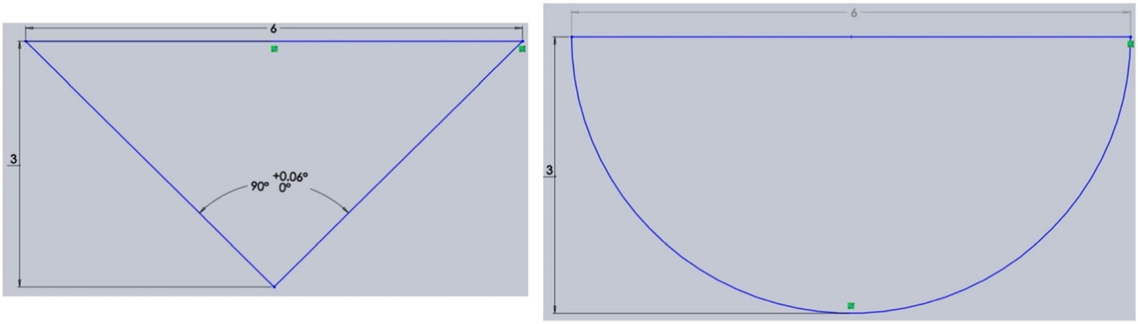


Fig. 1 Geometries of EDs (all dimensions are in mm)

values are reported herein and results of test replications were within 10% of each other.

Where A, B, C, D, and E represent factors, as shown in columns of Table 2, and their levels, as can be seen in rows of Table 2 under factors, for both materials, as shown separately in Table 3.

In order to optimize the lap shear strength (LSS) of a joint, a good understanding of the ultrasonic welding process conditions including effect of process factors is necessary. Owing to this, a series of experiments utilizing various combinations of process factors were performed in this work. Table 3 shows the careful selection of crucial process factors and their levels. For ABS (see Table 3), two levels of welding time are selected, i.e., 0.9 and 0.8 s, as verified from literature [25]. Amplitudes 21.0 and 18.9 μm have been identified as its respective two levels. Two levels of holding time, i.e., 0.2 s and 0.4 s, are chosen. Two levels of pressures, i.e., 21 and 25 MPa, have been decided to be combined with other factors. As mentioned earlier, two EDs, i.e., SEMI and TRI, were used in this study.

As far as PP was concerned, factors' levels selection strategy for pressures and EDs was kept same whereas it was altered for other essential factors. For instance, it was decided to increase the hold time for PP, i.e., 3.0 and 4.0 s. Similarly, weld time was also increased up to 1.5 s, as shown in Table 3 and guided by literature [39], due to requirement of high welding time in joining PP. Amplitude was also lowered to 16.8 from 18.9 for first level only, as can be seen in Table 3. These alterations in factors' levels were justified after conducting few trial experimental runs in order to understand the effect of factors' levels on under-weld and over-weld situations. Moreover, few levels of factors for both ABS and PP were different, e.g., weld time, hold time, and amplitude. This difference was also considered necessary as a result of various findings from ultrasonic welding trial experiments. Furthermore, ABS is an amorphous thermoplastic (i.e., having random molecular structure) which requires less ultrasonic energy for getting sufficient LSS to be optimized, as can be seen in the last column of Table 4. Contrariwise, PP is a semi-crystalline thermoplastic (i.e., having orderly molecular structure e.g. crystals) which requires more ultrasonic energy in order to avoid under-weld situations (if levels of weld time, hold time, and amplitude are kept same, i.e., similar to what have been justified for ABS). As a matter of fact, ultrasonic energy is a strong function of weld factors' levels. In other words, increasing the values of weld time, amplitude, pressure, and hold time will increase the ultrasonic energy. This kind of difference between factors' levels may also be seen in literature when using amorphous and semi-crystalline thermoplastics [37, 39].

For various weld conditions, LSS of ultrasonic bond was tested by Hounsfield Tensometer and H5KS Tensile Tester. Shear clamps were also designed by considering the configuration of the welded joint and a special care was taken of coincidence of line of action of shear force in tension with

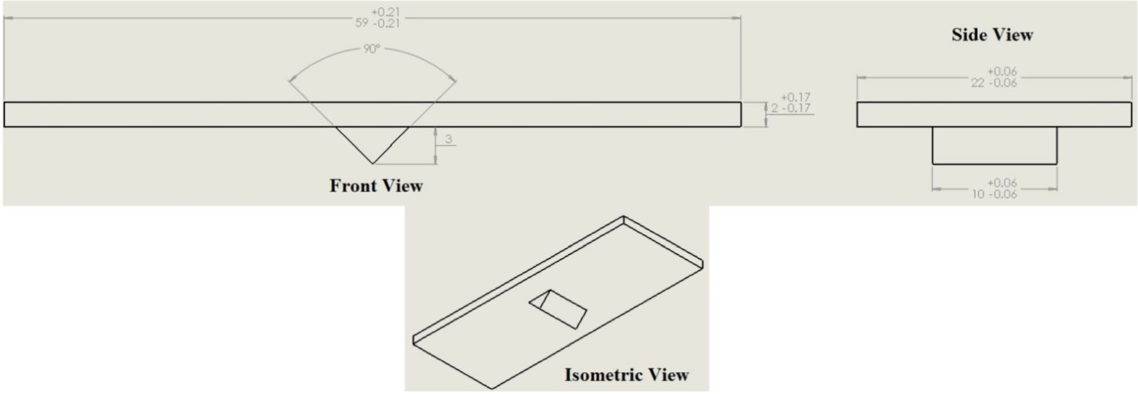


Fig. 2 Sample with TRI ED (all dimensions are in mm)

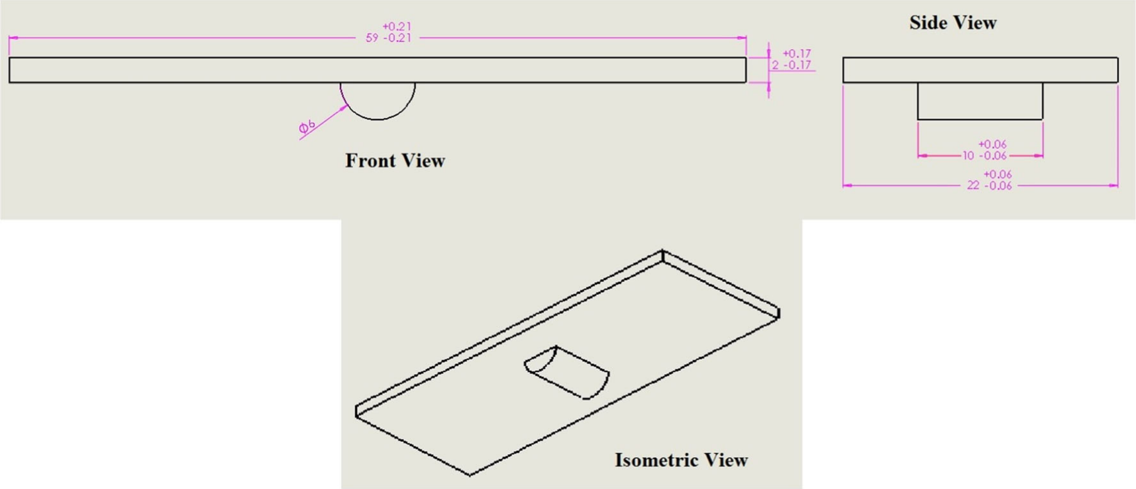


Fig. 3 Sample with SEMI ED (all dimensions are in mm)

centerline of the joint interface. Each joint bonded ultrasonically was clamped and sheared either by motorized shear tester (as utilized for majority of welded samples) or by H5KS tester at a constant shear strain rate of 3.24 mmT^{-1} throughout where T is in minutes.

3 Results and discussion

S/N ratios were calculated for eight sets of experiments for both ABS and PP, as shown in Tables 4 and 5 respectively.

A software known as "QUALITEK-4" was used for performing average and S/N analyses in this work. QUALITEK-4 has the ability to perform various analyses based on different design of arrays. It liaises well with ANOVA analysis by using directly not only averages but also S/N ratios. Although the usage of software does not contribute a lot towards general uniqueness of this study, this software was never used for ANOVA and S/N ratio analyses in literature. Of the prospective of newness for this software, this may be considered as another novel aspect of this research.

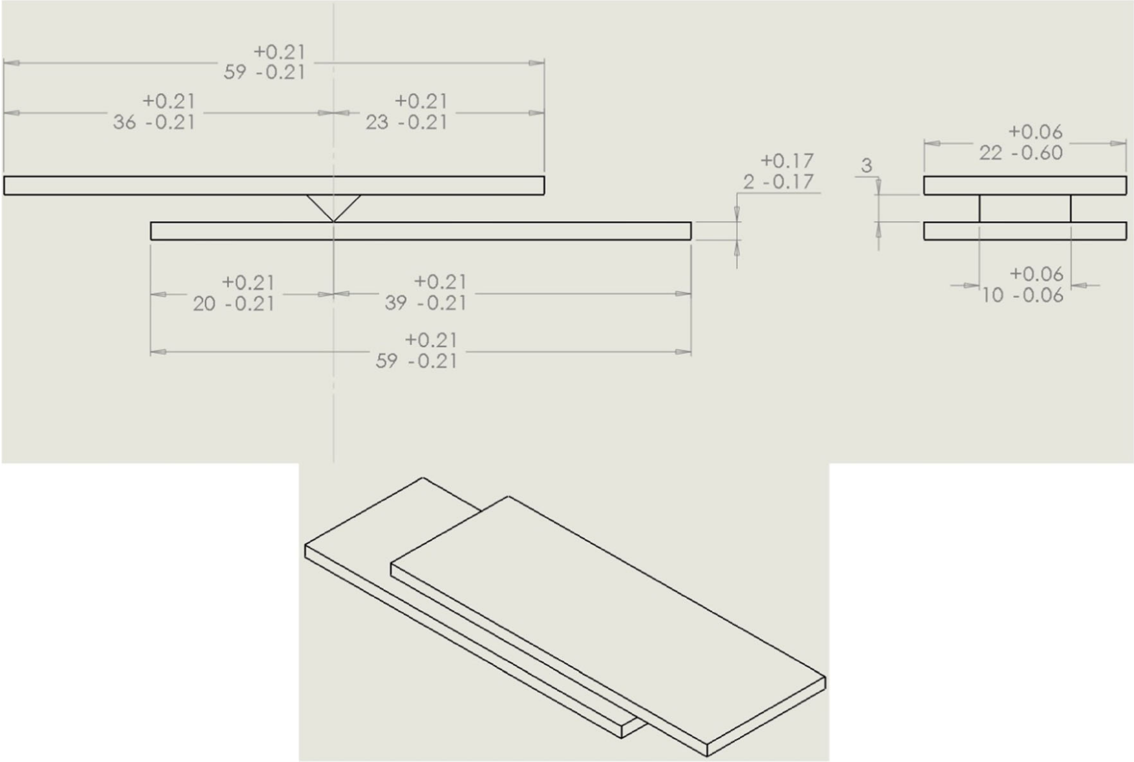


Fig. 4 Orientation of samples (front, side, and isometric views) (all dimensions are in mm)

Table 2 L-8 experimental array

Runs	A	B	C	D	E
1	1	1	1	1	1
2	1	1	2	2	2
3	1	2	1	2	2
4	1	2	2	1	1
5	2	1	1	1	2
6	2	1	2	2	1
7	2	2	1	2	1
8	2	2	2	1	2

Therefore, optimal conditions were identified from Table 6 which also show the average effects of factors for ABS and PP respectively. These optimum conditions were also selected for the validation test based on the highest average effect of factors' level for both ABS and PP. As an instance for ABS, level 2 of each weld factor (in italics) was selected to be an optimal condition for validation test except the geometry of ED for which level 1 (in italics) was selected, as mentioned in Tables 3 and 6. In other words, A2/B2/C2/D1/E2 and A2/B2/C1/D1/E2 were identified as the combination of optimal conditions for validation test for ABS and PP respectively. Moreover, A2/B2/C2/D1/E2 corresponds to weld time of 0.9 s, amplitude of 21 (μm), hold time of 0.4 s, TRI ED for geometry of ED, and pressure of 25 MPa for ABS. Similarly, A2/B2/C1/D1/E2 corresponds to weld time of 1.5 s, amplitude of 21 (μm), hold time of 3 s, TRI ED for geometry of ED, and pressure of 25 MPa for PP.

However, Fig. 5 shows the graphical representation of average effects of each factor based on S/N ratios for ABS. Moreover, Fig. 6 can help us select the optimum performance levels of weld factors for PP.

For ABS, role of ED geometry appeared to be highly significant with a *p* value 0.01, as shown in Table 7. After the ED geometry, amplitude was found to be next significant and then hold time, as can be seen from Table 7, for their *p* values less than 0.05.

Table 3 Factors and levels for both ABS and PP

Factors	Thermoplastic materials			
	ABS		PP	
	Level 1	Level 2	Level 1	Level 2
A. Weld time (s)	0.8	0.9	1.4	1.5
B. Amplitude (μm)	18.9	21	16.8	21
C. Hold time (s)	0.2	0.4	3	4
D. Geometry of ED	TRI	SEMI	TRI	SEMI
E. Pressure (MPa)	21	25	21	25

As far as PP is concerned, no weld factor was found significant for *p* value criterion less than 0.05, as can be looked at right side columns of Table 7.

Likewise, percent contributions (PCRs) were also determined from Table 7. For ABS, ED geometry was significant with the highest PCR of 80.50% towards achieving the highest LSS while amplitude and hold time were significant with moderate and low PCRs of 11.51% and 4.70% respectively. A likely reason of acquiring maximum PCR for EDs is owing to the considered view of manufacturing an energy director, as an essential ingredient of welding plastics ultrasonically, on one of the samples to be welded. Moreover, it is inevitable to expect not only maximum statistical contribution (i.e., PCR) but also the maximum physical contribution of ED towards weld strength, since ED is the only ultrasonic weld factor directing the whole ultrasonic energy locally at a very small weld zone. Ultrasonic energy is a collective impact of almost all the weld factors, e.g., pressure, weld time, and amplitude. In other words, the utilization of ultrasonic weld factors seems to be unbeneficial and purposeless in the absence of energy director because the ultrasonic energy will be lost haphazardly without being concentrated solely for welding thermoplastics. Of the two EDs used in this work, TRI ED has been found to be the most significant as compared to SEMI ED. This is due to the reason that TRI ED converges the ultrasonic energy better than that of SEMI ED due to TRI ED's v-shape geometry which is different from SEMI ED's u-shape geometry. Since TRI ED was found to be the optimal level of ED, the physical reasoning for TRI ED is held true for both materials ABS and PP. An in-depth discussion on the influence of EDs will be incorporated in this study on coming pages.

For PP, the highest percent contribution towards LLS was noted for amplitude and the lowest for weld time with 50.67% and 3.29% respectively. Firstly, the amplitude of ultrasonic vibrations implies the peak or maximum possible value of ultrasonic vibration. Since ultrasonic energy consists mainly of ultrasonic sinusoidal mechanical waves, attenuation of ultrasonic energy is a strong function of viscoelastic properties (e.g., loss modulus) of material into which this energy (having peak value/amplitude of ultrasonic vibrations) is damped and dissipated in terms of heat. Hence the greater the amplitude, the higher will be the dissipation of heat As mentioned in Table 8, PP has lower value of loss modulus than that of ABS. Higher loss modulus is required to dissipate ultrasonic energy into heat, which is also called viscoelastic heating source, providing substantial amount of heat to weld plastics. Although storage modulus of PP is higher than that of ABS, most of the ultrasonic waves are returned back after impinging into the PP material without being dissipated as heat. In other words, amplitude of ultrasonic energy is the crucial weld factor required to weld PP with the highest LSS and needing to be set maximum as much as possible as few ultrasonic vibrations

Table 4 Results for ABS

Runs	Weld time (s)	Amplitude (μm)	Hold time (s)	ED geometry	Pressure (MPa)	Average LSS (MPa)	Welding energy (J)
1	0.8	18.9	0.2	TRI	21	11.48	378
2	0.8	18.9	0.4	SEMI	25	5.20	453.6
3	0.8	21	0.2	SEMI	25	5.79	504
4	0.8	21	0.4	TRI	21	22.97	420
5	0.9	18.9	0.2	TRI	25	12.93	510.3
6	0.9	18.9	0.4	SEMI	21	5.47	425.25
7	0.9	21	0.2	SEMI	21	6.08	472.5
8	0.9	21	0.4	TRI	25	31.45	567

may return back without generating heat. Based on this physical interpretation of amplitude and its relation to LSS, proper consideration must be given to amplitude of ultrasonic vibrations to weld PP successfully; otherwise, welding of PP is either difficult leading to lower LSS or is never achieved with zero LSS. Moreover, higher value of amplitude will be desired to convert the ultrasonic energy into viscoelastic heating that is why amplitude of 21 μm was found to be the optimal level of amplitude for welding PP.

3.1 Influence of weld factors on LSS for ABS

3.1.1 ED influence on LSS

ED geometry was found to be significant and having the highest percent contribution for ABS. Moreover, TRI ED was found to be optimal level of ED geometry. A possible reason for significance of TRI ED is its smallest volume as compared to volume of SEMI ED which implies larger concentration of ultrasonic energy in case of TRI ED. Due to this reason, larger portion of a TRI ED has been melted quickly as compared to SEMI ED.

As ABS is an amorphous thermoplastic, it is having glass transition temperature (103 °C). As temperature goes above its glass transition temperature, the viscosity of the ABS drops down and molten ABS starts flowing. It is that point where the role of other weld factors especially pressure comes in. On increasing the pressure to its high level for TRI ED, molten material has been pressed severely to spread evenly at the expected bond area resulting in higher LSS. This is why, high pressure is thought of a major reason for optimizing the LSS in case of TRI ED for ABS. On the other hand, SEMI ED has larger volume than that of TRI ED resulting in lack of concentration of ultrasonic energy and supply of greater volume of molten material at the weld interface. It has been empirically observed that molten SEMI ED comes out of the weld interface which reduces the bond strength.

3.1.2 Amplitude influence on LSS

Next significant factor for ABS was amplitude having higher percent contribution after ED geometry. A likely explanation for amplitude's significance and PCR is that an ultrasonic vibration consists of frequency, amplitude, and time period. The purpose of amplitude of ultrasonic vibrations is to vibrate the molecules which make a polymer. During the molecular vibration, the molecules rub themselves against each other originating the frictional heat. The higher the amplitude of vibration, the more will be the frictional heat. This frictional heat helps the thermoplastics achieve its melting point quickly. It is known very well for an ultrasonic vibration that frequency and time period remain constant (20 KHz and 50 μs respectively). In this work, it was then only peak-to-peak amplitude that was varied at constant interval of 2.1 μm. For an

Table 5 Results for PP

Runs	Weld time (s)	Amplitude (μm)	Hold time (s)	ED geometry	Pressure (MPa)	Average LSS (MPa)	Welding energy (J)
1	1.4	16.8	3	TRI	21	4.66	588
2	1.4	16.8	4	SEMI	25	1.44	705.6
3	1.4	21	3	SEMI	25	22.42	882
4	1.4	21	4	TRI	21	22.00	735
5	1.5	16.8	3	TRI	25	21.97	756
6	1.5	16.8	4	SEMI	21	2.43	630
7	1.5	21	3	SEMI	21	22.46	787.5
8	1.5	21	4	TRI	25	22.62	945

Table 6 Selection of highest factors' levels in italics for both ABS and PP

Factors	Thermoplastic materials			
	ABS		PP	
	Level 1	Level 2	Level 1	Level 2
A. Weld time (s)	19.05	*20.30*	13.66	*21.86*
B. Amplitude (μm)	17.68	*21.67*	8.53	*26.99*
C. Hold time (s)	18.38	*20.97*	*20.03*	15.48
D. Geometry of ED	*24.91*	14.44	*20.00*	15.51
E. Pressure (MPa)	19.15	*20.20*	14.90	*20.61*

optimized value of LSS, a proper and stable supply of molten material is required at expected interface of weld. This is owing to the presence of high level of amplitudes that a sufficient supply of molten material is initiated by utilizing the collapse of ED. This stable or uniform availability of molten material is further spread evenly under the action of pressure hence resulting in proper heat affected zone HAZ and optimized LSS. Therefore, a tight control over the supply of molten material (ABS or PP) from both EDs (SEMI or TRI) can be ensured by employing high levels of amplitudes.

3.1.3 Hold time influence on LSS

Last significant weld factor was hold time. Hold time is a time that is set after turning the ultrasonic vibration OFF, i.e., after getting thermoplastics welded or welding time. A probable explanation for the significance of hold time is to ensure maximum crushing of softened ED without forcing molten ED to leave weld interface during a set time. Moreover, hold time should be kept smaller in order to keep the molten material available at weld zone and prevent this molten material from leaving the weld zone which results in lowering LSS. Therefore, fraction of second of hold time was used in current work for ABS in order to maximize the LSS.

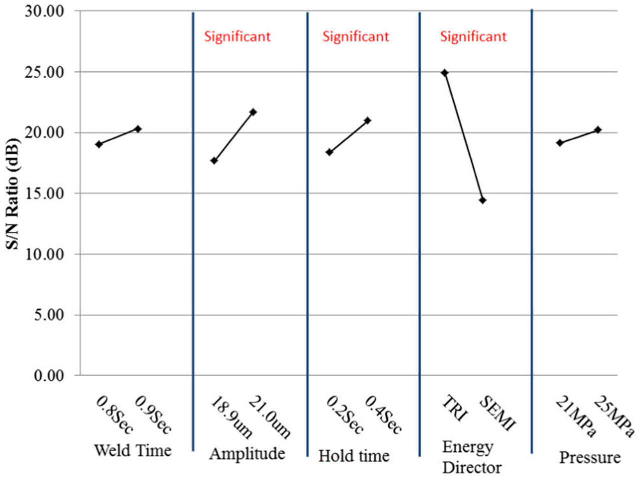


Fig. 5 Optimum performance levels of factors for ABS

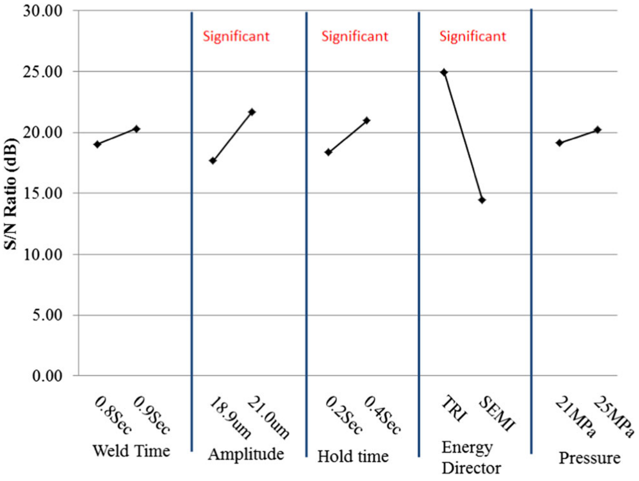


Fig. 6 Optimum performance levels of factors for PP

3.2 Influence of weld factors on LSS for PP based on percent contribution (PCR)

3.2.1 Amplitude influence on LSS based on its PCR

From Table 7, no weld factor was found significant for PP but percent contribution of amplitude was found to be the highest towards LSS. The possible reason for highest contribution of amplitude can be understood from Eq. 1. According to Eq. 1, heat developed due to welding energy and has direct proportionality with square of the amplitude at molecular level. This heat is again directly related to the phase change of PP from glassy to rubbery. This phase shift is essential for attaining better spread of PP material at the bond zone. That is why, the amplitude of vibrations was found to be more contributing factor than other weld factors for PP. Likewise, the presence of angular velocity in Eq. 1 [25] is addressing the importance of welding time (having high contribution after amplitude) and frequency of ultrasonic vibrations in generating the heated regions at weld interface. In this research, frequency of vibrations was kept/set to be 20 KHz.

$$Q_{avg} = \omega\, \epsilon_A{}^2\, E^{II}/2 \quad (1)$$

where, ω = angular velocity
ϵ_A = strain amplitude
E^{II} = loss modulus
ω = 2?f and f = 20 KHz

Moreover, high level of amplitude was found to be optimal for both materials. One of the likely reasons that mean LSS is comparable for both materials, as shown in Tables 5 and 6 at high level of amplitude is, when an ultrasonic vibration is propagated. For instance, attenuation of amplitude through PP is higher due to higher storage modulus of PP, as shown

Table 7 ANOVA (main values only) for both ABS and PP

Factors	Thermoplastic materials			
	ABS		PP	
	p value (0.05)	PCR	*p* value (0.05)	PCR
A. Weld time (s)	0.17	0.92	0.35	3.29
B. Amplitude (μm)	0.02	11.51	0.11	50.67
C. Hold time (s)	0.04	4.70	0.58	0.00
D. Geometry of ED	0.01	80.50	0.58	0.00
E. Pressure (MPa)	0.21	0.59	0.50	0.00
Error	–	1.78	–	46.04
Total	–	100%	–	100%

ANOVA at 95% Confidence Level

in Table 8. Hence, lower LSS is obtained with PP as compared to ABS. Moreover, amplitude attenuation and decay rate of ultrasonic oscillations are also affected by the ratio of energy stored to energy dissipated which is higher for PP, i.e., 12.09, as shown in Table 8.

3.2.2 Weld time influence on LSS based on its PCR

In order to understand fully the impact of significant and highly contributing weld factors, behavior of thermoplastic may be modeled with the help of a dashpot and a spring. One basic model is shown in Fig. 7.

Spring may be resembled to shear rigidity and dashpot to viscosity of polymeric system. Also, time-dependent behavior of Voigt model may well be equated to time-dependent electrical behaviors of different amalgamations of capacitance and resistance or resistance and inductance. When capacities and resistances are related to springs and dashpots respectively, it makes, somehow, a physical sense for storage and dissipative components of a polymer [41].

Polypropylene (PP) is a semi-crystalline thermoplastic, and it has definitely sharp melting point to be equal to 165 °C. In order to melt ED made of virgin PP, sufficient amount of ultrasonic energy is needed to be supplied while PP specimens are welded ultrasonically. This energy is necessary due to the sharp melting point of PP.

As far as weld time is concerned, it was found to have second higher percent contribution towards LSS for PP. One second of weld time means the supply of 20,000 cycles of ultrasonic vibrations to the samples. Slight variation in LSS may be observed if low level of weld time is used because of using two different geometries of ED. TRI ED has been completely collapsed and melted to a greater extent at high level of weld time as compared to SEMI ED. Bond spread and bond formation are also found better using triangular geometry of ED at high level of weld time because bigger heat affected zone is acquired.

Moreover, higher weld time implies that more cycles of vibrations will be imposed on the samples to be welded. Furthermore, PP has lower loss modulus and heat distortion temperature which mean that ED will severely be crushed if high level of weld time will be utilized. Loss modulus is related to the energy dissipated as heat when ultrasonic vibrations are applied to the specimens. Loss modulus is also called as out-of-phase component of complex modulus. Moreover, heat distortion temperature (HDT) is defined as the distortion rate of a material at a particular temperature. Hence, optimal

Table 8 Complex moduli for both materials [40]

Complex moduli (GPa)	Frequency (KHz)	ABS	PP
Storage modulus (GPa)	20	2.75	3.87
Loss modulus (GPa)	20	0.42	0.32
Storage modulus/loss modulus	20	6.55	12.09

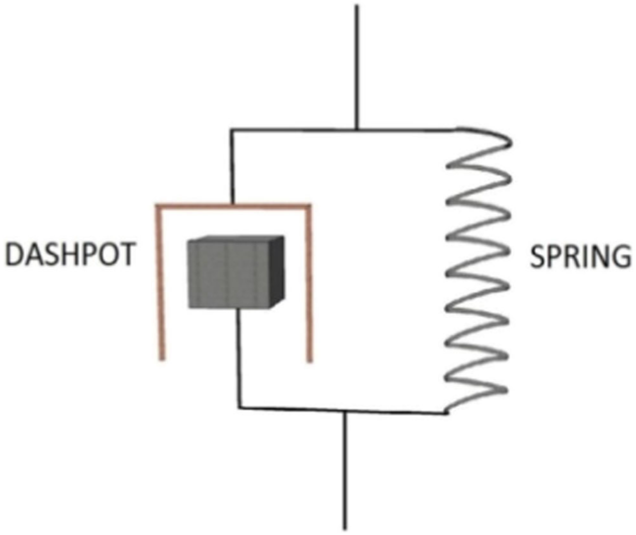


Fig. 7 Voigt model (spring and dashpot in parallel)

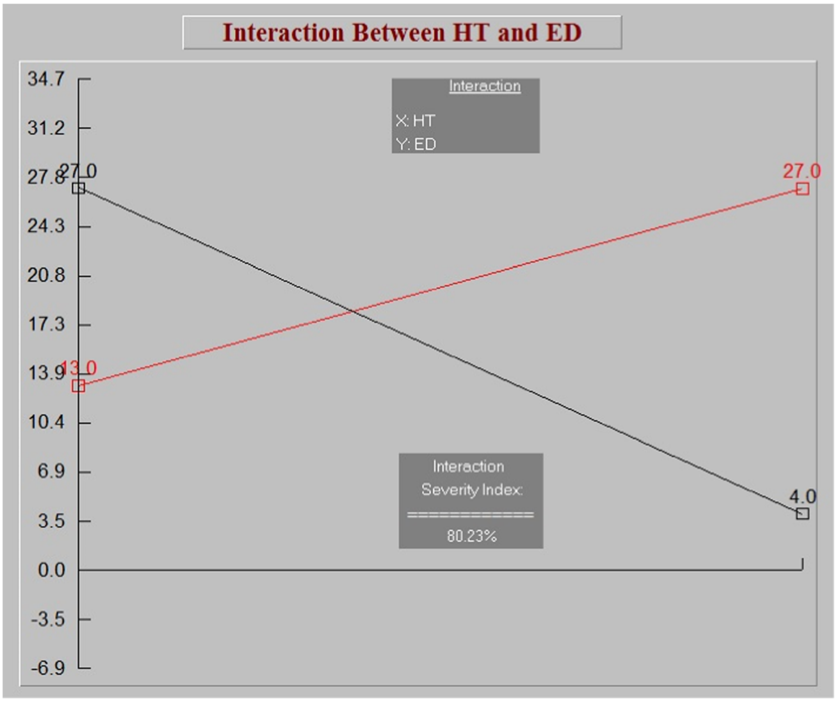


Fig. 8 Interaction between hold time (HT) and energy director (ED)

LSS can absolutely be attained with high level of welding time.

Furthermore, after getting ED melted, the very next point of interest is the recrystallization of molten PP upon cooling. The recrystallization of PP is not an easy parameter to explain as there are plenty chances of interaction of individual molecules with neighboring molecules thereby resulting in momentary entanglement. Also, it is almost impossible to evaluate the degree of entanglements, i.e., complete or partial after welding process.

Upon evaluating the LSS, the dominant failure mode changes from chain pull-out to chain scission. Inter-diffusion of polymer systems, i.e., ABS and PP during ultrasonic welding, is the major phenomenon after achieving the softening temperature. This inter-diffusion of plastics mostly results in entanglements. Entanglements are called the topological

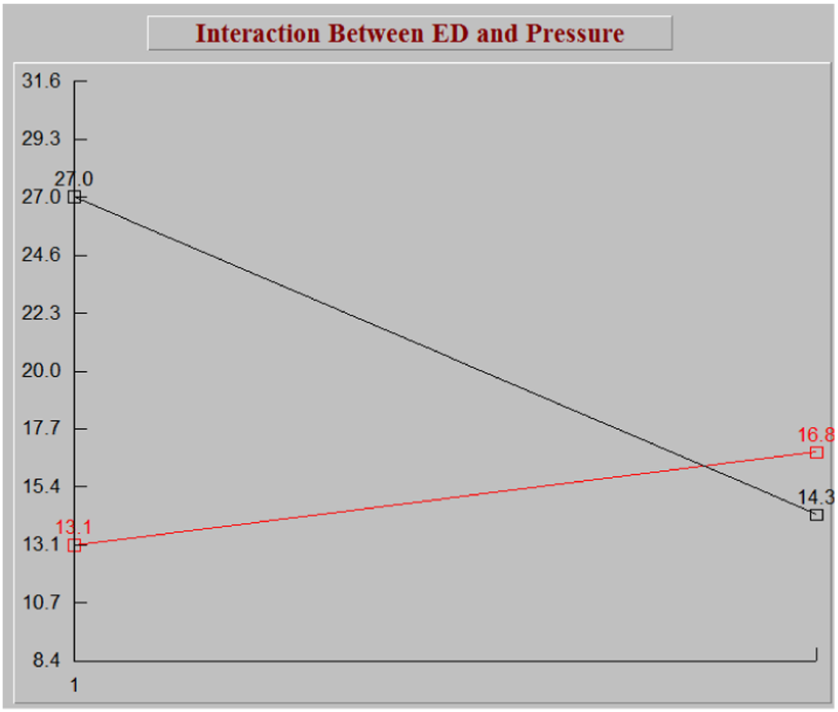
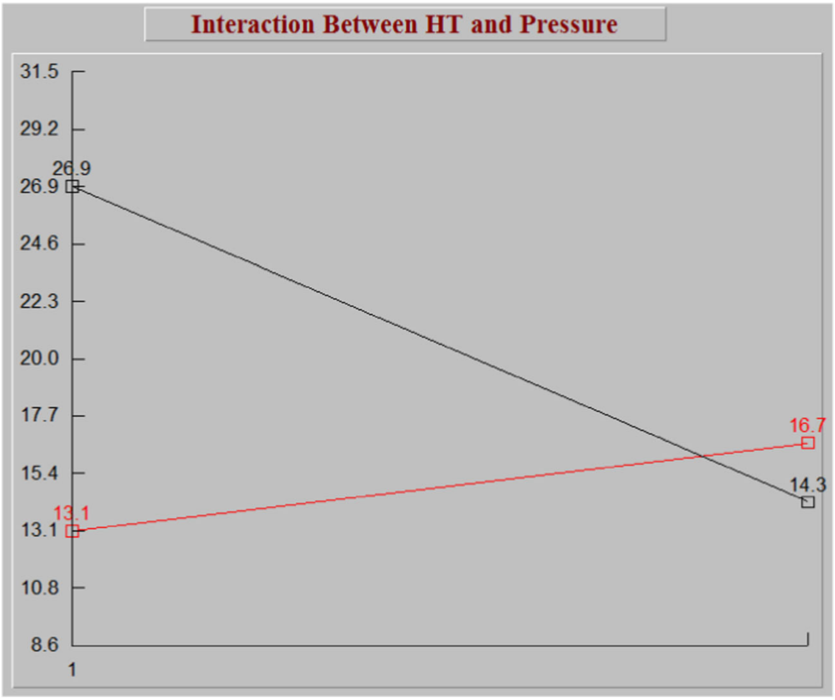


Fig. 9 Interaction between energy director (ED) and pressure

Fig. 10 Interaction between hold time (HT) and pressure



constraints (TCs) governing the viscoelastic and plastic changes. These interfacial entanglements usually strengthen the bond strength and avoid chain pull-out mode of failure [42]. Therefore, slight variations in the weld strength may be observed.

3.2.3 Investigation into interactions between weld factors for PP

Interactions between weld factors were also investigated in order to find out the cause of error 46.04% for PP ANOVA. Since amplitude and weld time were explained earlier for their maximum PCRs towards achieving LSS and for their direct influence on LSS; three combinations of interactions among ED, hold time, and pressure were required to be discussed for their zero PCR towards LSS and high contribution towards error. Therefore, Fig. 8 shows the presence of interaction between hold time (HT) and energy director (ED). Severity Index (SI) of this interaction is 80.23%. Hence any level of hold time may affect the independent effect of energy director on LSS. In other words, there are a lot of chances of having the combined effect from both hold time and energy director on the average LSS. Therefore, LSS is heavily affected by interaction effect of both hold time and energy director. Similarly, Figs. 9 and 10 indicate the severe interactions (SI = 59% approximately) between ED and pressure and hold time and pressure respectively.

3.2.4 Validation experiments

At this stage, the result predicted is required to be validated via a validation experiment by using the optimum conditions. For validation experiment, five samples were welded, tested, and analyzed by utilizing optimal levels of welding factors for ABS, as can be seen in Table 9. Average LSS value of 31.21 MPa is acquired which is more than the original ABS shear strength, i.e., 30 MPa [43]. Hence, significant improvement up to 104% (i.e., joint/weld efficiency) in weld strength has been achieved for ABS when comparing LSS with shear strength of original ABS which was not established anywhere

Table 9 Validation experiment (ABS)

Runs	Weld time (s)	Amplitude (µm)	Hold time (s)	ED geometry	Pressure (MPa)	LSS (MPa)	Average LSS (MPa)	S/N ratio (dB)	Welding energy (J)
1	0.9	21	0.4	TRI	25	31.77	31.21	30.00	567.00
2	0.9	21	0.4	TRI	25	30.10			
3	0.9	21	0.4	TRI	25	31.04			
4	0.9	21	0.4	TRI	25	30.88			
5	0.9	21	0.4	TRI	25	32.30			

Table 10 Validation experiment (PP)

Runs	Weld time (s)	Amplitude (µm)	Hold time (s)	ED geometry	Pressure (MPa)	LSS (MPa)	Average LSS (MPa)	S/N ratio (dB)	Welding energy (J)
1	1.5	21	3	TRI	25	22.17	22.36	27.08	945
2	1.5	21	3	TRI	25	22.25			
3	1.5	21	3	TRI	25	22.05			
4	1.5	21	3	TRI	25	23.00			

in literature. For example, Yew Khoy Chuah et al. [37] found this strength improvement up to 18% from ultrasonic welding for ABS which is much lower as compared to what has been found in this study. Likewise, R. V. Eswaran et al. [40] derived empirically the joint strength for ABS using ultrasonic welding to be equal to 56.67% which is still less than that of one obtained in this research. Prakasan et al. [25] attempted again to find out the value of joint strength for ABS using ultrasonic welding to be equal to 50%. T. Azdast et al. [44] have found friction stir-welded (FSW) joint strength to be equal to 33.34% which is also less than that of acquired in current work. Sadeghian et al. [45] have found joint efficiencies to be 99.1% and 94% for friction stir-welded ABS with cylindrical and conical pin profiles respectively which are still less than that of the one attained in this study. The joint efficiency from the FSW ABS was found to be 88.76% with threaded pin profile by Bagheri et al. [44]. With double-shoulder tool with simple pin, FSW ABS joint efficiency was found to be less that is equal to 45.6% and this efficiency was increased up to 60.6% when using double-shoulder tool with convex pin by Pirizadeh et al. [46]. Mendes et al. [47] have found this joint efficiency slightly increased up to 67% for FSW ABS joint with stationary shoulder and conical threaded pin.

Another validation experiment was also conducted for optimal levels of weld factors using PP, as shown in Table 10. Average LSS value of 22.36 MPa is found that is also much higher than the actual shear strength of original PP [48], i.e., 7 MPa. This is an excellent indication of achieving the bond strength more than the parent material strength up to 319% that was not obtained in past studies. In other words, it is really hard to find such a study on considerable enhancement in bond strength from previous literature. For instance, Wu et al. [31] reported the improvement in strength up to 26.67% for PP using ultrasonic welding. Although Wu et al. [31] reported this strength improvement up to 39.34% using vibration welding, the substantial improvement in weld strength was found really higher in this study with ultrasonic welding. TSUJINO et al. [49] have found weld strength for PP joints to be 71.42% using ultrasonic welding with frequency 40 KHz that is more than that used in current research. R. V. Eswaran et al. [40] have measured the joint strength to be equal to 85.71% for PP; however, this value is still much less than the one obtained in this work. Kiss et al. [50] have empirically found the joint efficiency to be 50% for FSW PP joint with traditional milling tool and huge plate thickness to be equal to 15 mm.

3.3 Microscopic analysis of weld quality (LSS) for ABS and PP

Microscopic study of fractured surfaces reveals the crucial reasons which may cause failure upon testing the weld strength. Since failure of various polymers directly depends on the macro and micro structure of polymeric material, loading, loading rate, and temperature; state of stress is also exposed to find the causes of crack commencement and its advancement to eventually failure.

Deformation occurs through viscoplastic flow processes in thermoplastic polymers. Hence, thermoplastics are considered ductile due to their non-crystalline structure [51]. Thermoset plastics are usually brittle. Material structure, loading situations, and thermal conditions affect the way ductile fracture (fracture with plastic deformation) and brittle fracture (fracture with little or no plastic deformation) occurs. Viscoplastic deformation is strongly dependent on temperature and strain rate. That is why strain rate

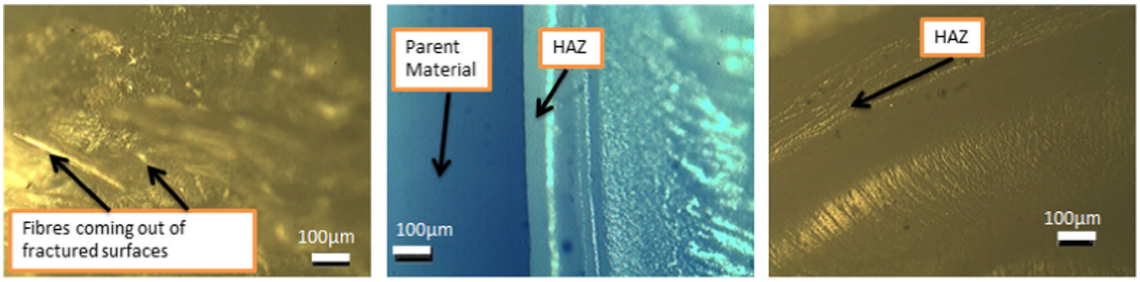


Fig. 11 Micro-fibrils and heat-affected zone (HAZ) for ABS (experimental run 8)

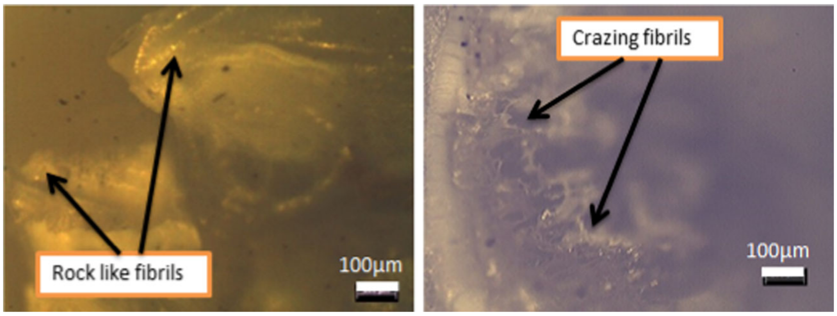


Fig. 12 Rock like fibrils for ABS (experimental run 2)

was kept constant at room temperature for all welding runs and weld strength tests in this work.

Although both ABS and PP are ductile, shear tests for measuring weld strength show that welded joints from both ABS and PP give brittle fracture. However, LSS for ABS is much higher than that of PP showing that elastic region for ABS is much higher than that for PP before the occurrence of bond failure without or little plastic deformation. Moreover, microscopic examination reveals that the causes of brittle type of failure in both ABS and PP are the possibility of presence of rock like fibrils, crazing fibrils, etc., as shown in Figs. 11, 12, 13, and 14.

Application of loads results in plastic flow of polymers leading to formation of crazes at micro level, as shown in Fig. 14. Crazes are crack predecessors. Formation of cavities/micro-voids in polymers is one cause of plastic deformation, as shown in Fig. 13. Despite merging into a crack, the micro-voids are stabilized by fibrils which comprise polymer. This section of voids and fibrils is jointly called as a craze, as shown in Fig. 14. The crack generation phenomenon may be used to reveal how shear occurs at the weld zone during shear testing. Current microscopic examination also helps us clarify the existence of brittle type of failure along with huge improvement in LSS for both ABS and PP.

4 Conclusion

An L-8 orthogonal array of experimental matrix is used based on Taguchi method in this study. ABS and PP were used with former as an amorphous thermoplastic and later as a semi-crystalline thermoplastic. New improved designs of specimens were employed by ultrasonic welding resulting in an improved strength of lap joint on large scale.

- ED geometry and amplitude were found to be more significant and then hold time for ABS whereas for PP, amplitude and weld time were found to be more contributing factors in achieving maximum LSS. However, no weld factor was found to be significant in case of PP.
- TRI ED was noted to be the optimal contributor in delivering highest LSS for both ABS and PP.
- Reasons for obtaining better results for ABS/ABS as compared to PP/PP were also deliberated in terms of complex moduli.
- Based on validation experiments performed for both ABS and PP with optimal level settings, significant improvement in LSS was achieved considerably above the actual shear strength value for both joints ABS/ABS and PP/PP.

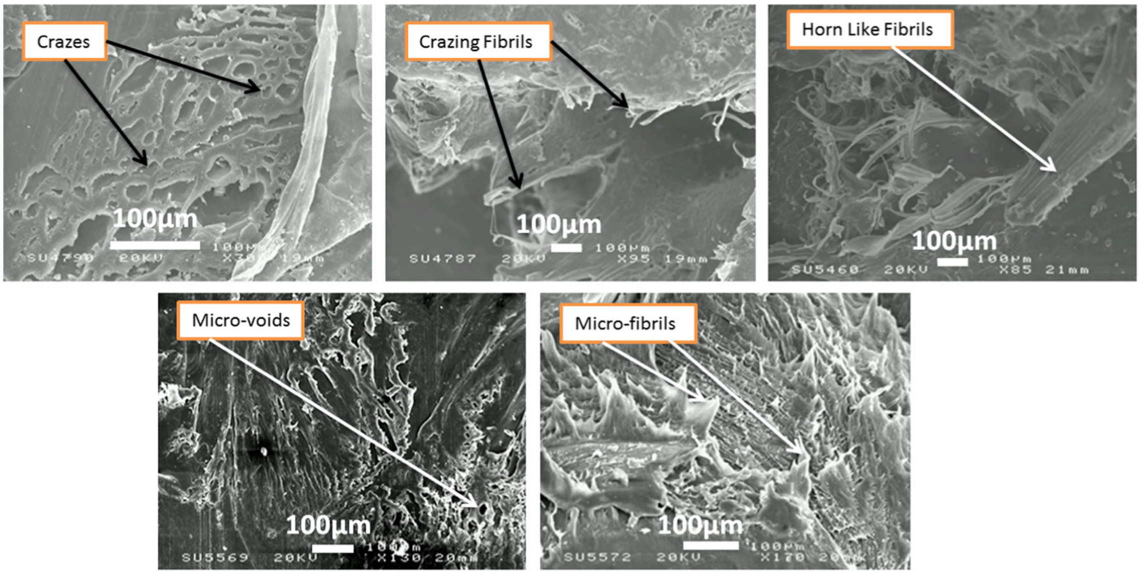


Fig. 13 Micro-fibrils, horn like, and micro-voids for PP (experimental run 8)

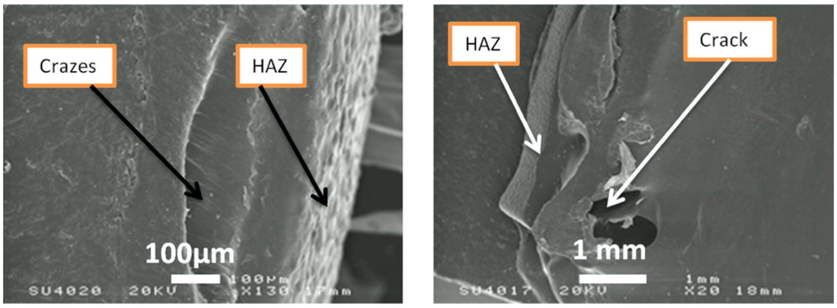


Fig. 14 Micro-voids, heat-affected zone (HAZ), crazes, and cracks for PP (experimental run 3)

This improvement in LSS has never been obtained in previous studies for both thermoplastics.

- Overall, ABS was found to be better than PP in imparting maximum LSS.
- Of microscopic examination, rock-like, horn-like, and crazing fibrils leading to micro-voids, crazes, and cracks have been revealed to be the main causes of brittle fracture for ductile thermoplastics (ABS and PP) which may be thought of providing an interesting explanation of findings in this research.
- Further progress in this research may be recommended in terms of using other industrial thermoplastic materials utilizing same framework of experimentation.

Acknowledgments It is hereby admitted that experimentation in this work has been completed using Lea Lab of The University of Sheffield UK.

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