Vibration and Ultrasonic Welding Behaviour of Polymers and Polymer Composites- A Review

S.G. Arul selvan*[1], R. Rajasekar[2], M. Kalidass[1], M. Selwin[1]
[1]Department of Mechanical Engineering, M. Kumarasamy College of Engineering, Karur, Tamil Nadu, India.
[2]Department of Mechanical Engineering, Kongu Engineering College, Perundurai, Erode, Tamil Nadu, India.
***Corresponding author: E-Mail: sgarulsgselvansg@gmail.com**

ABSTRACT

This review work reports a detailed analysis of two different welding technologies considering polymers fields. Thermoplastic polymers with or without fillers have attracted both industrial and research attention as they gives a wide range of properties and finds themselves in a various common applications often replacing metals. Often whole replacement is not favoured and since there are situations to join the parts or components. One among the possibility is that these materials could undergo welding. So several welding techniques on the thermoplastic polymer materials are discussed in general and also valuable suggestions has been drawn from the scientific literature work of various authors and are provided.

KEY WORDS: Welding, Thermoplastics, Composites, Polymers.

1. INTRODUCTION

A Polymer is generally a large packed molecule composed of many repeated similar subgroups called monomers. Polymer classification falls into thermosetting and thermoplastic polymers. Despite the advancement in properties in the higher range, thermoplastic polymers are preferred over the thermosetting polymers since they can be reformed into any shape after they are formed. Thermoplastics effectively fix themselves to the fullest advantage involving complex shapes. With the advantages in its fold, a wide range of applications are found in many fields especially automotive applications. Thermoplastics have the advantage of forming into different shapes through moulding. However single component moulding is difficult in certain applications like manifolds for air intake, rocket motor casings and assemblies for lighting which involves complexity in geometrical shapes.

Concentration on these thermoplastic material advantages and difficulties is because some polymers provide similar or near to similar mechanical properties of metals and its alloys with reduced weight and ease of manufacturing. Hence, their applications are comparable to some metallic alloy applications. Moreover, they have been replaced by the thermoplastic polymer materials.

Due to the difficulty in single piece moulding of some complex shapes as mentioned above, joining methods are implied. The joining methods are mechanical joining and adhesive bonding and welding. Mechanical joining and adhesive bonding are commonly used to assemble metallic alloys or some composite components. Yet there are some demerits such as increased stress concentrations due to drilling holes and additional weight with fasteners and special surface preparations while using adhesive bonding. Welding of thermoplastics does not have such difficulties.

Hence, an attempt is made in this work to review the welding techniques such as vibration welding, ultrasonic welding considered for welding various thermoplastics such as Polyethylene, Polypropylene, Polycarbonate, Polymethyl methyl acrylate etc.

Vibration Welding: Vibration welding is one of the common welding techniques employed for welding thermoplastic polymer composites. In vibration welding, the specimen or parts to be welded are primarily clamped into upper and lower fixtures and they are pressed against each other under a predefined pressure based on the application. Of the two parts, one is vibrated at a frequency and amplitude which are predetermined. As a result of this, energy is generated by frictional force and with that energy welding is done. Throughout the entire process, any one of the parts, which is to be joined, is fixed and the other one is given the vibrational movement. Vibration welding takes place in 4 steps.

- Solid friction state, in which there is no melt down but an interface heating.
- Unsteady melt generation, here melting begins and follows an unsteady flow.
- Quasi-stationary melt generation, where the melt flow follows a steady state pattern. Here welding is done and the velocity is constant. This state forms and defines the weld quality.
- Solidification state, where the vibration motion incorporated to one of the parts is stopped and the melt is cooled.

The Process parameters of vibration welding are frequency (f), weld pressure (p_o), vibration time (t_v), melt down (s) and amplitude of vibration (α).

Some of the picturable advantages of vibration welding when compared with other advanced and friction welding processes are better weld quality with no degradation, easier processing, inexpensive cost in tooling and ability to weld a number of components due to its higher production rate. Linear type of vibration welding technique is quite applicable in cases relating to joining of thermoplastic polymer composites. Schematic representation of vibration welding is given in figure.1.

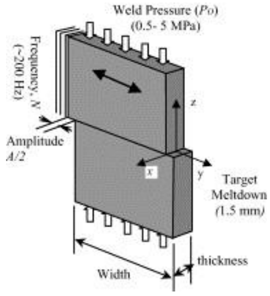

Figure.1. Vibration welding

Pal (2015), studied vibration welding of amorphous Acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polymethyl methyl acrylate (PMMA) and semi crystalline polybutylene terephthalate (PBT). Rectangular blocks of specimen were prepared with dimensions of 115mm*20mm*4mm. welding was performed on the 20mm*4mm edge with 240Hz and 1mm frequency and amplitude respectively under 0.5MPa of pressure. Pure specimens say PC-PC, PMMA-PMMA, ABS-ABS, PBT-PBT and combined semi crystalline and amorphous specimens such as PBT-PC, PBT-PMMA and PBT-ABS were welded and studied. From the studies, the pure specimen had better tensile strength than the mixed specimen.

Differential scanning calorimetry (DSC) analysis results from the study had showed that glass transition temperature of the welded parts had affected the weld quality and not the other properties. Different materials can be welded with care taken so that their glass transition temperature in a close range. With the crystalline structure, PBT had exhibited higher interlayer spacing with the X-ray diffraction analysis. The result of the morphological studies was that quality had been dependent on mechanical interlocking rather than interfacial bonding. Similar polymers had shown higher quality welds. However mechanical properties of welded components were dependent on the surface roughness.

Leyu Lin (2015), exhibited a study on vibration welding of polypropylene with silica (SiO_2) nano particles at 1, 2 and 4 volume percentages. The specimen dimensions were 50*50*4mm^3. The welding parameters used were damping time of 40-450ms, weld pressure of 0.8-4 MPa, 240Hz and 0.7mm frequency and amplitude respectively. Nano filler addition to the semi crystalline polymer had accelerated the crystallinity behaviour and solidification and cooling down of the weld was faster than the pure polypropylene. But the Nano filler content had no or zero effect on the free damping time. SEM images of Weld part morphology of Polypropylene filled with 2 volume % nano particles with a welding pressure of 0.8 MPa with and without quick ramp-down control is shown in figure 2. With different damping times, similar weld strength had been obtained and hence the effect of damping time in this technique relating to the weld strength was nil. This was because, crystallization of welded region of weld melt had occurred only after the complete stoppage of free damping of the vibration head. This was obtained from the temperature measurement study and hence even when forced damping was implied, the weld strength did not alter or change.

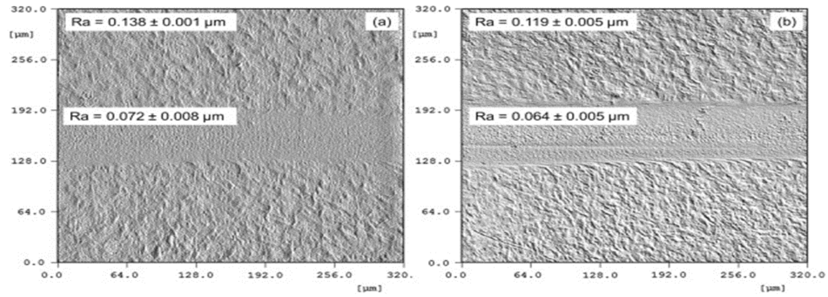

Figure.2. Weld morphology of Polypropylene filled with 2 volume % nanoparticles with a weld pressure of 0.8 MPa with andwithout quick ramp-down control

Leyu Lin (2015), investigated about polypropylene on vibration welding through scanning electron microscope (SEM) study with titanium oxide (TiO_2) nano particles in volume percentages of 0.5, 1 and 4%. Process parameters used in vibration welding of 50*50*4mm^3 specimen were 0.7mm amplitude, 240Hz frequency and varying weld pressure of 0.4 to 4 MPa. The author claimed that increase in the weld pressure had increased the melt down and its rate for both pure polypropylene specimen and polypropylene nano composite specimen leading to production cycle time reduction. Also melt viscosity had decreased with the incorporation of TiO_2 nano particles due to the slip between the TiO_2 nano filler and the polypropylene polymer chain which had formed the reason for he molten film thickness reduction. Nano particle content did affect the tensile strengths of the weld which was also affected by the weld pressure. The SEM results had claimed the presence of agglomeration of the nano particles which had weakened the weld strength. Impact strength had increased with the nanoparticle addition but it did not had any influence on the tensile strength of the polypropylene polymer.

Das (2011, 2012), had given a detailed analysis on vibration welding of PC and noryl composites with poly (caprolactone) and polystyrene as the compatibilizers respectively and cloisite 20A nanoclay as the nano filler to the polymers. Process parameters used were 0.99mm amplitude, 240HZ frequency and 1 MPa weld pressure. Crystallinity was found to be improved through X-ray diffraction analysis in both the PC and noryl nanocomposites when they were compatibilized with poly (caprolactone). Morphology of the specimens viewed through the SEMon the welded joints had shown higher fibrillation in both the PC and noryl nanocomposites with compatibiliser. High resolution transmission electron microscope (HRTEM) results had implied that a better dispersion of the cloisite 20A in the polymer matrix was observed when both the nano composites were compatibilized than the uncompatibilized nano composites.

Das (2011, 2012), had investigated about the effects of vibration welding on the nanoclay filled LLDPE (Linear Low Density Poly Ethylene) with and without the ethylene maleic anhydride copolymer as the compatibiliser. X-ray diffraction analysis data had showed that a better crystallinity i.e. smaller size of the crystallite was observed when compatibilized. SEM study revealed that agglomeration was reduced when the compatibiliser was added. When mechanical properties are concerned, tensile strength was found increased in the presence of the compatibiliser of body part but found decreased in the welded joints when compared to the pure LLDPE specimen. HRTEM study implied that agglomeration was spotted in the specimen with pure LLDPE nano composites but the compatibilized LLDPE nano composites had better dispersion of nano clay.

Ultrasonic Welding: Ultrasonic welding is one among the most commonly used technique for welding the thermoplastic materials. This is because it is the by far swiftest known welding technique available. The time of welding in the ultrasonic welding is normally well within a second i.e. less than 1 second. Ultrasonic welding process utilises high frequency and lower amplitude for welding. Frequency is of the range 20 to 40 KHz and amplitude ranges from 2.5 µm to 0.25mm. Ultrasonic welding is preferred for welding thermoplastic materials in mass production. Weld quality of ultrasonic welding is higher. In this welding technique, the ability to join two components or parts depends on the material properties, frequency of welding, joint design and welding amplitude.

Theoretically Ultrasonic welding process is actually made up of five different but highly coupled sub processes. They are;

- Mechanics and vibrations of the tool parts,
- Visco elastic heating of the thermoplastic material,
- Heat transfer through the thermoplastic,
- Flow and wetting and
- Intermolecular diffusion.

The welding system is composed of power supply, piezoelectric transducer, booster, horn, substrate and a support base. The generated oscillations from the applied electrical power with a high frequency of the order of 20 kHz to the piezoelectric transducer. The oscillations produced by the transducer are very small, so a booster is to be connected to the transducer in order to increase the amplitude of vibration. Thus produced mechanical vibration is then transferred to the metal horn which induces ultrasonic sound waves. This energy is used for welding the components. A high quality and precise weld can be obtained through ultrasonic welding even at a larger relative distance from the site from where the mechanical vibrations are introduced. Ultrasonic welding can provide a very high quality weld with materials having good acoustic properties.

The process parameters used for ultrasonic welding are frequency, amplitude of vibration, welding time and welding pressure. Ultrasonic welding process representation is given in figure.3.

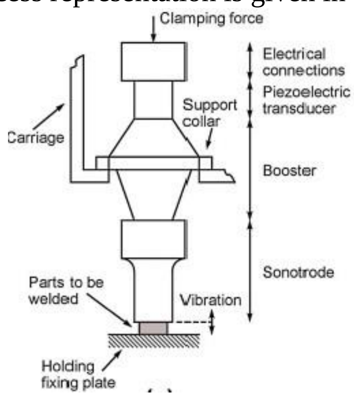

Figure.3. Ultrasonic Welding

Wu (2012), had given a comparison between ultrasonic welding and vibration welding in welding thermoplastic polyolefin. In the study, specimens were welded by both ultrasonic and vibration welding and the weld strength of both the welds were compared with the bulk material strength. An 'I' sample for bulk material testing and 'T' specimen for welding were used. Three parameters used were welding time, frequency, welding pressure and amplitude of vibration. Ultrasonic welding had been performed with 20 kHz frequency, the welding pressure from 4 to 12 MPa, amplitude of 20-40 µm and welding time of 0.2 to 0.8s whereas vibration welding was done with a frequency of 240 Hz, the welding pressure from 0.5 to 3 MPa, amplitude of 0.5 to 1.25mm and welding time of 1 to 6s. The results from the study had shown that 40 % of the strength of the bulk material was achieved with the ultrasonic welding whereas 66 % of the strength of the bulk material was achieved with the vibration welding. The observed results had minted on the fact that ultrasonic welding which when used with vibration of high amplitude produced notable stronger joints, but it had resulted in extensive surface damage on the surface. From the results it was clear that higher amplitude of vibration had produced a stronger joint but at the same time weld time and weld pressure had very little rather nil effect on weld strength while considering ultrasonic welding. In case of vibration welding, amplitude was one of the most prominent factor on strength of the weld. Higher amplitude had resulted in weld strength which was higher enough. Weld strength was also found to be increasing when the welding time was increased in vibration welding. The optimum conditions for ultrasonic welding from the results was 40.1 µm amplitude of vibration, weld time of 0.8 s and 4.8 MPa weld pressure resulting in a weld strength which reached a maximum of 40 % of the bulk strength. The optimum conditions for vibration welding from the results was 1.25mm amplitude of vibration, weld time of 4 s and 1 MPa weld pressure resulting in a weld strength which reached a maximum of 66 % of the bulk strength.

Benatar (1989), had given a detailed study on ultrasonic welding of Poly ether ether ketone (PEEK). In this study the author had used PEEK graphite APC-2 composites for welding. The study had clearly implied that ultrasonic welding which when applied on advanced and latest composites had provide excellent strength in case of joints and the welding was very flexible. Therefore in this study ultrasonic welding of thermoplastic composites and their advanced followers were studied both theoretically and experimentally. In case of theoretical study, the process was further subdivided into five different but coupled sub processes. The experimental work had verified that either the interface impedance or the power and acceleration traces had rose quickly when the melt fronts meet and a good bond or joint was produced. This behaviour of the PEEK had allowed for the development of closed loop control when ultrasonic welding is considered for advanced composites.

Gutnik (2002), had done a work to give some of the characteristics of ultrasonic welding while joining polymers. Joining of polymers generally had denoted thermoplastic polymers because thermosetting polymers cannot be welded. According to the author selection of polymer was an important process. Evaluation of weld ability of the material, elasticity and damping factor should be done. Based on the damping factor the polymers were classified into rigid, semi rigid and soft polymers. Rigid polymers include polymeric materials like polystyrene whose damping factor was in the range less than 35/m. Similarly semi rigid polymers like polypropylene had damping factor of the range of 35/m to 55/m. And soft polymers say polyethylene have a damping factor of above 55/m. Rigid polymers can be welded by both contact and transmission type welding while soft polymers can only be welded by contact type welding. The quality of welding by ultrasonic process was affected by the welding parameters the most. According to the author the welding parameters were classified as primary parameters and auxiliary parameters. The primary parameters include amplitude of mechanical vibrations in micrometres, frequency of the mechanical vibrations in kHz, the time of welding or welding exposure time in sec and static pressure in MPa. The auxiliary parameters include materials, shape, size of working instrument and the base. For the soft polymers the parameters suitable from the study were 10 to 50 µm of amplitude, 20 kHz frequency, and weld pressure well below 3 MPa and weld duration of 1 to 5 seconds. The parameters for the rigid polymers from the study were 10 to 40 µm of amplitude, 20 kHz frequency, weld pressure from 10 to 15 MPa and weld duration of 5 to 7 seconds. It was important to note from the study that ultrasonic welding technique can even be used to join fluoro plastics and poly ethylene terephthelate which cannot be welded by other methods. As a result the author have concluded that ultrasonic welding, despite the high cost, can be used for industrial purposes due to its characteristics.

Villegas (2010), had evaluated the process and performances of ultrasonic welding, resistance and induction welding of thermoplastic composites which were advanced. Polyphenylene composite specimens which are reinforced with 45% of carbon fibre were considered for the static and dynamic analysis for mechanical behaviour and other processes. Welding time, welding pressure, power requirement and energy requirement were the variables used for comparing ultrasonic, resistance and induction welding processes. 25.4 * 101.6 mm^2 rectangular specimens were welded. Optical microscopy and SEM techniques were used to analyse the cross-sections and surfaces which are fractured. The resulted parameters after the welding process had been completed were summarised. 2.2 MPa, 4.4 s, 1980 W and 0.7 kJ of weld pressure, total weld time, power and energy consumption respectively were the process parameters for ultrasonic welding. 0.8 MPa, 85 s, 420 W and 23 kJ of weld pressure, total weld time, power and energy consumption respectively were the process parameters for induction welding. 0.1 MPa, 90s, 90 W and 1.8 kJ of weld pressure, total weld time, power and energy consumption respectively were the process parameters for ultrasonic welding.

Visual or naked eye inspection results of samples which are induction-welded had shown that heating in bulk had caused a rather moderate flow of resin and the outermost surface of that laminate had lost its smoothness which was there initially. In case of ultrasonic welded samples a darker colour of the resin had been spotted next to the edge due to stiff clamping. But the resistance-welded samples had not showed any traces of the welding process. Cross sectional micrographs had confirmed that none of the welded samples had shown a noticeable concentration of voids at the welding interface. Static test results from the paper implied that resistance-welded samples had shown poorly welded areas where as both ultrasonic and induction welded samples had given a good number of lap shear strengths. From the parameters observed from the study it was clear that ultrasonic welding was the fastest of the three welding process and also had least energy consumption. Put together the results induction welding had the undesirable results with the parameters while resistance welding had spotted itself between the two. The fatigue performance analysed was almost similar for all the three types of welded specimens with non-definite fatigue limits ranging around 40%of the corresponding static lap shear strength.

Roopa (2008), had studied about ultrasonic welding of high density polyethylene (HDPE) in the far field region based on several literature studies. Author had used HDPE because of its increasing applications. The challenges that the author faced from the literature study were:

- Without melting of the parts at the horn-part interface of the crystalline materials, due to their well-defined melt temperature, was particularly difficult to get the required energy to the weld zone.
- Semi crystalline polymers welding in far field required more power than, it’s opposite, welding in near field due to the attenuation of the ultrasonic waves.
- Parts with varying or non-uniform cross-section had lower transmissibility and were difficult to handle while welding.

So the author had performed the study to predict the ideal length of the semi crystalline component or part suitable for ultrasonic welding in order to achieve shorter time of welding and improved weld strengths. Ultrasonic welding was done with a frequency of the range 20 kHz with 1500W power requirement, amplitude of 50 µm to 60 µm and weld pressure of 4 MPa. In order to pick the effective range for ultrasonic welding, the horn-joint distance was varied from15 to 50mm because of the holding difficulties during the tensile testing. Theoretical evaluation had pointed out minimum and maximum temperatures at the node and anti-node positions of the ultrasonic waves. But due to the higher energy absorption rates near the horn and vibrating tool interface, temperatures recorded during the experiments was higher. The difference of values between experimental and theoretical phases was due to the scattering of ultrasonic waves in the surrounding atmospheric air whose effects were not considered in the theoretical phase. When the amplitude of vibration was increased from 50 µm to 60 µm, the heating rate had increased which had made the temperature at the interface also to increase from 110ºc to 140ºc. As a result, the ultimate tensile strength of the weld was higher at the anti-node where the temperature was higher and the vice versa. Also the ultimate tensile strength of the weld was higher with higher amplitude. From the theoretical and experimental studies the author had concluded that the crucial part in far field welding of semi crystalline polymers was the amplitude selection and the displacement anti-nodes had the higher strength of the failure welded joints. And also high interface temperatures were obtained at higher amplitudes for a given specimen length.

Zhang (2010), had performed a study on heating process of thermoplastics by ultrasonic welding. According to the author, improvising the accuracy of welding became an important research topic. Welding accuracy was directly influenced by the temperature distribution in the welding zone. Primarily the thought was that the rise in temperature during the ultrasonic welding was generated from the contacting surface interfacial friction. But actually, the main heating effect was from visco elastic heating during ultrasonic welding rather than the interfacial friction experienced by the materials. Due to the small welding zone and faster welding speed with ultrasonic welding, the melting process of the specimen in the welding zone it was hard to observe it using the available techniques. The heating mechanisms of the specimens in temperature ranges both below and above the glass transition temperature Tg of PMMA were studied based on numerical simulation and temperature measuring experiment. Simulation was done using ANSYS. PMMA components were simulated and in order to improve the efficiency of calculation, 2D model was employed. For calculation of visco elastic heat, the 2Dmodel was meshed by Visco88 visco elastic elements. The result of simulation had shown that the maximum sliding velocity was at the corner and it had gradually decreased when scanned away from the corner. Once when the temperature of the corner had reached the glass transition temperature, visco elastic heat had been activated and the heat-affected zone spreads rapidly. Experimental study was performed with PMMA of glass transition temperature of 105º c and the welding was done with frequency of 30 kHz and welding time of 0.3 s and 0.4 s. Temperature during welding was measured using a thermocouple. The results had indicated that not only the distribution of strain and stress but also the interface between the components was to be known prior to the welding process and majority of the visco elastic heat effect was above the glass transition temperature.

Villegas (2010, 2013), had presented the results of study on the effects of different energy directors on the ultrasonic welding of carbon fiber/polyetherimide advanced thermoplastic polymer composites in a near-field setup. The intermolecular friction within the bulk, which resulted due to the application of ultrasonic waves, was applied on the work surfaces to be weld or the joint surface, generated the heat which is required for welding to happen at the interface of the joining members namely “energy directors” (EDs). Energy directors are composed of resin protrusions or man-made/artificially produced asperities on the composite outer surfaces and these EDs had played an important role in the welding process as well as in the quality of the resulted welds. 25.4*101.6 mm samples of continuous carbon fiber-reinforced polyetherimide with the energy directors were used in the study. The basic ED had a triangular shape with a 90◦ angle at it stop, 4 mm base, 2 mm height and 25.4 mm length which was equal to the width of the samples which were to be welded. The parameters used were welding time of 3.5 s, holding time of3.0 s, welding pressure of 4 MPa and the vibration amplitude of 50 μm. The result of visual inspection of the fracture surfaces had provided some valuable information about the weld quality. The two modes of failure primarily experienced in Lab Shear Stress tests were interlinear and interfacial failures. The observed scatter in the size of the welded area which had ranged from 4 % to 9.5 % of the mean value for transverse had been due to the sonotrode design, EDs design and the ultrasonic machine operation mode. Conclusive results from the study were, multiple EDs had significantly reduced the disturbance of the fibres in the outer layers of welded parts and the transverse EDs had provided considerably less scatter in the welded area than the parallel ED configurations. An excessive amount of resin at the welding interface had led to decrease in the weld strength.

Qiu (2010), had proposed a study on the ultrasonic weld properties of heterogeneous polymers between PC and PMMA with a functional gradient interposed sheet (IPS) because of its excellent mechanics properties. A rectangle specimen of $80*10*4mm^3$ was used for ultrasonic welding with parameters say frequency around 28 kHz, amplitude of 30 mm, vibrating time of about 1.0 to 4.0 s, and pressure applied of about 0.1–0.4 MPa. Then specimens had continued elongating where the nominal stress are increased further but increases slowly and ruptured when nominal strain went above 110%. But the IPS which is made of PC and PMMA had shown brittle characters which is not desirable. Welding strengths had been enhanced with the longer welding time until the strengths had reached their largest or highest point at a welding time of3.0 s, after which strengths decreased oppositely. Rupture surfaces of welded joint interfaces at PC under ultrasonic welding stress of 0.3 MPa is shown in figure 4. As a result the amplitude of IPS was lower than the IPS holder but the frequency was the same and the ultrasonic characteristics of IPS was dependent on its material properties. The author had concluded that very long welding time had brought cracking of IPS and air bubbles at the local part of interfaces. Author proposed that higher welding stress might enlarge or widen the welding areas and reduce the air bubbles so as to enhance the strengths. The effective welding conditions for ultrasonic welding of heterogeneous PMMA and PC were shorter welding time and higher welding stresses.

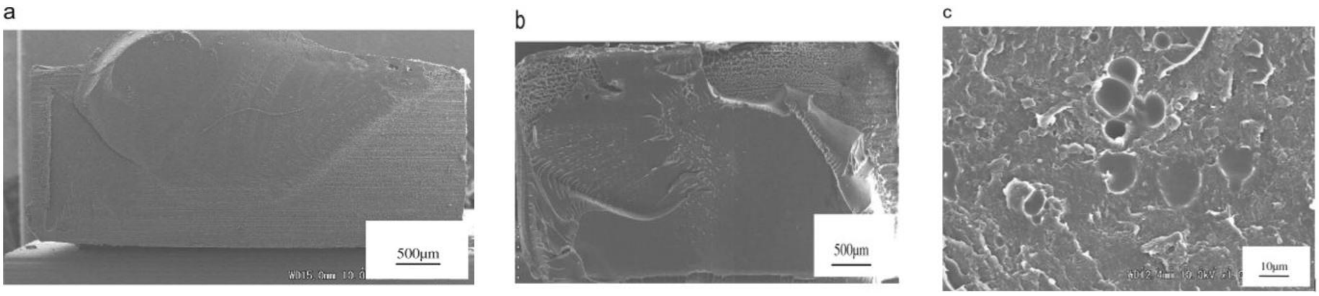

Figure.4. Rupture surfaces of welded interfaces at PC under welding stress of 0.3 MPa (a) 1.5, (b) 3, (c) 4.5 seconds

2. CONCLUSION

From this detailed study it can be concluded that more than one type of welding can be applied to each situation. Almost both the welding technologies presented in this study have many advantages as well as some drawbacks depending on the applications under consideration. General advantages and drawbacks also has to be taken into account while selecting a welding process along with the specific application advantages and drawbacks. A deep study of literature indicated that the most critical factors affecting the welding process and its quality are its process parameters. These parameters differ for each welding and their selection is a critical part which is based on the applications. In several occasions selection of one process parameter affects the other parameters of the same welding technique.

Vibration welding provides a good quality welding for parts which are flat and small for most cases. Agglomeration in case of nanocomposites and fibre delamination are some of the drawbacks of vibration welding but strong welding is achieved with this type of welding compared to the other welding techniques.

Ultrasonic welding provides a defect free welding to a maximum extend and can be used for welding small areas but requires surface preparation, such as adding artificial or man-made asperities with the help ofmoulding. This welding technique is suitable for mass production since it involves a very less operating time but higher installation cost. Fibre delamination and agglomeration in nanocomposites are avoided to some extent with this type of welding technique. This technique can be effectively used for spot welding of thin structures.

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