# PARAMETRIC STUDIES ON THERMOPLASTIC COMPOSITE WELDING FOR AEROSPACE APPLICATIONS

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## ABSTRACT
The major limitations of thermoset polymers are their inability to be re-melted or recycled, shorter shelf-life, higher storage costs, and longer curing times thereby opening up opportunities for using thermoplastic based composites. Industries have turned their focus to thermoplastic composite materials because of their benefits such as Superior processability, Form freedom, Excellent mechanical performance at elevated temperatures, Excellent toughness, Very low moisture absorption, Outstanding chemical and solvent resistance, Indefinite shelf life at ambient temperature storage, and Excellent FST performance. Due to these benefits many airframe manufacturers and research institutes are initiated more research work on these high-performance thermoplastic composites. Using low melt PAEK (Poly Aryl Ether Ketone) polymer with carbon fiber (T700) prepreg the present experimental investigation was carried out to optimize process parameters for the autoclave consolidation and ultrasonic welding process for aerospace standard. Autoclave consolidated laminates were subjected to ultrasonic C Scan for the anomalies present in the laminates and qualified. Further, the manual hand-held ultrasonic gun was used for the fabrication of single lap joints (SLJ) specimens and similar configuration SLJ were fabricated by co-consolidation process using autoclave vacuum bag technique. These specimens were subjected to non-destructive evaluation of ultrasonic ‘C’ scan. Subsequently these laminates were cut into specimens as per the ASTM standards and single lap shear strength was computed and presented here.

## INTRODUCTION
Thermoplastic composite materials are replacing traditional engineering materials and are demanded in areas with high production rates. This may continue only if composites are supplied at lower costs without any compromise to the quality. The high costs are mainly due to raw material and processing cost and inefficient processing methods. As the use of thermoplastic composites are fairly new and still under extensive research are going on the processing methods based on the thermoplastic raw materials. The processing of thermoplastic composites depends on reaching very high temperatures, which is generally above the normal processing temperatures of thermoset composite materials. The autoclave processing method with vacuum bagging techniques are well developed for the production of thermoset composite components, the same

autoclave consolidation has been adapted to the high-temperature processing of thermoplastics also [1]. Every new raw material needs to optimize for its consolidation cycle using autoclave before going for part manufacturing.

The understanding of the processing of a material is very important as this enables the user to understand the various capabilities of the material and how the material processing can be modified to reduce the part production time. Challenges arise in welding, screwing and riveting – the classical joining methods found in automotive production. The matrix of fiber composite materials is a bonded composite. Punching these materials by screwing or riveting damages the laminar structure, which is vital to the material's strength and stability. In addition, the punched hole must be sealed using a complex process to prevent delamination of the material. When joining CFRP to metal, there is also a high risk of corrosion. [2]

Using the thermoset composites over several years have brought in various techniques of joining that have been standardized for the use in aerospace industries. The same needs to be carried out for the thermoplastic composite materials. Joining of thermoplastic composites is an important step in the manufacturing of aerospace thermoplastic composite structures. In general, joining of thermoplastic composites can be categorized into mechanical fastening, adhesive bonding, solvent bonding, co-consolidation, and fusion bonding or welding. Fusion bonding or welding has great potential for the joining, assembly, and repair of thermoplastic composite components and also offers many advantages over other joining techniques. The process of fusion-bonding involves heating and melting the polymer on the bond surfaces of the components and then pressing these surfaces together for polymer solidification and consolidation. [10]

Many researches have experimented the use of ultrasonic welding for thermoplastic composites and have shown good results and this technique shows potential of reducing the processing time of the joining of composite parts by a very large difference when compared to conventional methods. Ultrasonic welding parameters discussed by various researchers are illustrated in Table 1.

Table 1. Summary of selected researches on ultrasonic welding of thermoplastic composites to thermoplastic composites

| Year | Author | Material | Factor Studied | LSS (MPa) | Parameters |
|---|---|---|---|---|---|
| 2001 | Liu et al., [3] | GF/PP | Effect of ED, weld time and weld pressure | 13.77 | Weld time: 0.25 s, 0.3 s, 0.33 s<br>Weld Pressure: 2.5, 3, 3.5 bar |
| 2002 | Liu et al., [4] | GF/Nylon 6 | Effect of ED, weld time and weld pressure | 17.11 | Weld time: 0.25 s, 0.32 s, 0.4 s<br>Weld Pressure: 2, 3, 4 bar |
| 2010 | Villegas et al., [5] | CF/PEI | Weld Strengths | 32–36 | Weld time: 3.5 s<br>Weld Pressure: 4 bar |
| 2014 | Villegas et al., [6] | CF/PEI | Effect of weld pressure | 37.3 | Weld time: displacement mode<br>Weld Force: 300 N and 1500 N |
| 2015 | Villegas et al., [7] | CF/PPS | Effect of ED | 37.1 | Weld time: displacement mode<br>Weld Force: 1000 N |
| 2016 | Senders et al., [8] | CF/PPS | Effect of ED | 36.5 | Weld time: displacement mode<br>Weld Force: 1000 N |
| 2019 | Goto et al., [9] | CF/PA6 | Effect of energy | 40 | Flat ED (0.3 mm)<br>Weld Force: 940 N |

From the literature it was found that the energy director material and matrix materials are same for almost all the cases. In the present project an attempt is made with different matrix materials as energy director for all ultrasonic welding experiments. This paper discusses the experimental work that has been carried out on Carbon-LM PAEK prepreg material with PPS film as energy director for ultrasonic welding trails and autoclave consolidation without any ED for single lap joints.

## RAW MATERIALS & AUTOCLAVE OPTIMIZATION PROCESS

Carbon T700 with LM-PAEK high-end thermoplastic composite material that has been specifically engineered with a low melt viscosity and low melt temperatures when compared to the other thermoplastic materials were used for the present research, which was sourced from Toray. Carbon Fibers impregnated with semi crystalline engineered PAEK resin at a ratio of 66 % fiber and resin content of 34 %. The typical neat resin properties given as follows.

a) Density of 1.30 g/cm$^3$,

b) Glass transition temperature ($T_g$) at 147°C,

c) Melt temperature ($T_m$) 305°C,

d) Processing temperature ($T_p$) with a range of 320-380°C.

Processing of the raw material by autoclave consolidation was carried out by varying the process parameters like vacuum, pressure and temperatures. Mainly application of external pressure during conslodation process was altered with respect to the various temperature during the processing cycle. Based on multiple trials and its corresponding ultrasonic ‘C’ scans a finalized cure cycle was arrived for subsequent laminates. The autoclave set up is shown in Figure 1 and Figure 2.

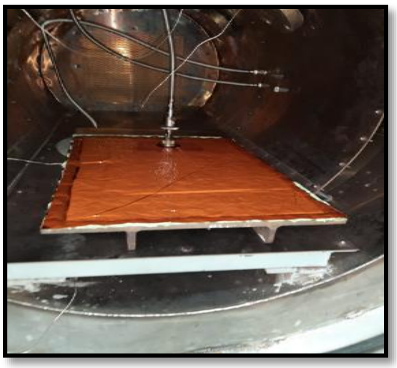

Figure 1. Test plate with TPC laminate inside vacuum bag

Figure 2. Autoclave ready for processing

Multiple trials were performed with changes in the pressure and temperatures at different intervals of the curing process in the autoclaves. The following process cycles were followed for the autoclave optimization process.

**Process Cycle 1**: Heated to 330°C ± 3°C with full vacuum and 7 bar external pressure. Dwelled 20 mins at 330° C. Cooling was done with external pressure and full vacuum till 60°C

**Process Cycle 2**: Heated to 340°C ± 3°C with full vacuum and 3.5 bar external pressure. Increased the pressure to 6 bar after reaching 340°C and dwelled at 20 mins. Cooling was done with external pressure and full vacuum till 60°C

**Process Cycle 3**: Heated to 365°C ± 3°C with full vacuum and 6 bar external pressure and dwelled for 20 mins. Cooling was done with external pressure and full vacuum till 60°C

**Process Cycle 4**: Heated to 365°C ± 3°C with full vacuum and 3.5 bar external pressure. Increased the pressure to 6 bar after reaching 365°C and dwelled at 20 mins. Cooling was done with external pressure and full vacuum till 60°C

Based on the NDT C-Scan results the fourth process cycle was acceptable. Process cycle 4 was finalized for processing of laminates and prepared the co-consolidation single lap joint laminate. Figure 3 shows the results of the ultrasonic ‘C’ scan carried out on the laminates produced using different process cycles. Cure number 5 was carried out with the same process cycle as in cure number 4 and the results showed acceptable levels of consolidation and the same was concluded for the autoclave processing.

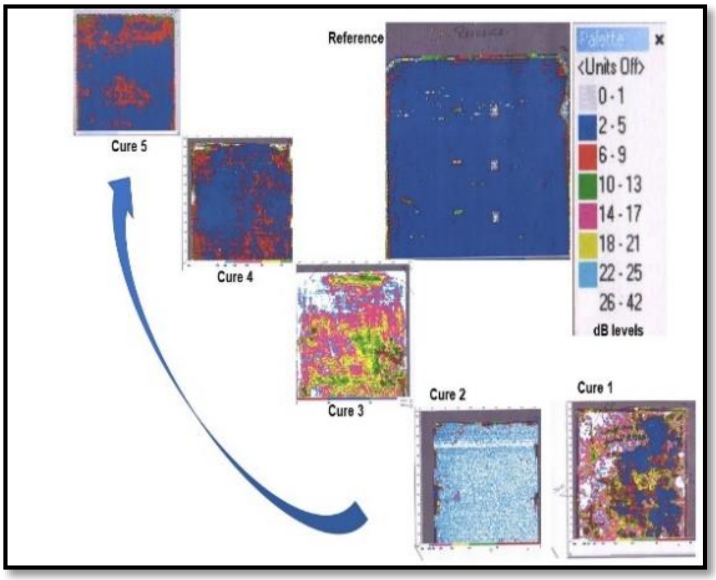


Figure 3. C-Scan results of Autoclave processing method

## SINGLE LAP JOINTS BY CO-CONSOLIDATION AND ULTRASONIC WELDING OF TPC

Co-consolidation of SLJ was carried out by preparing two laminates of the quasi isotropic sequence [0, +45, -45, 90]$_s$ and the required overlap width is marked on either side of the laminates. The laminates were aligned carefully and held in place with the high temperature flash breaker tape to make sure the laminates don't displace from the marked locations. Further, the laminates are to be supported externally by supporting caul plates on either sides and maintained the laminate from bending. Finally, once the laminate was ready for processing the entire setup is placed on to a metallic steel plate. The vacuum bag was prepared with the help of high temperature general sealant tape, breather material, additional flash breaker tapes vacuum valves and the vacuum bagging film etc. The laminates were sufficiently debulked & bagged and processed in an autoclave as per the optimized processing cycle. The SLJ laminate was obtained and shown in Figure 4.

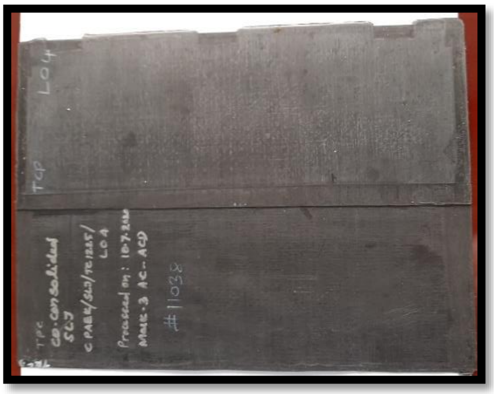

Figure 4. Co-consolidated laminate

Ultrasonic welding is categorized as the friction welding type used for joining of thermoplastic. It utilizes ultrasonic waves at 20 KHz frequency with other vibration characteristics such as amplitude etc. A static force or weld pressure is also introduced at the same time with ultrasonic waves causing the material to join owing to intermolecular friction in plastics. The fixture was designed to hold the laminate in place to enable the joining of the entire length of the SLJ laminate along the overlap region. The fixture was designed to constrain the movement of laminates to ensure the laminates are fixed firmly during the welding process. The fixture is shown in Figure 5 with the laminate assembly.

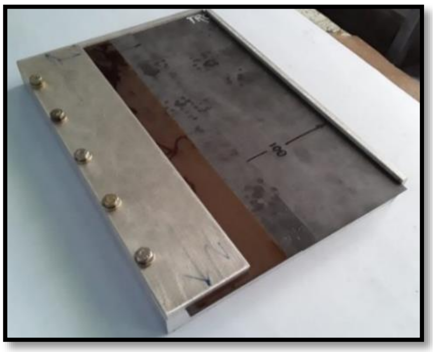

Figure 5. Fixture with Laminates assembled

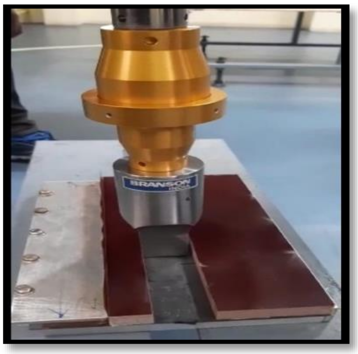


Figure 6. Manual ultrasonic welding gun

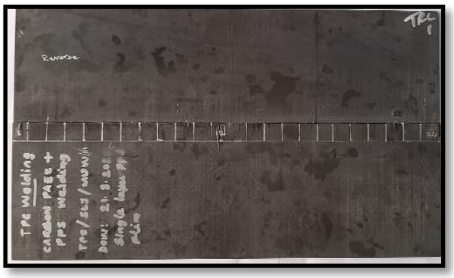

Figure 7. Ultrasonic Welded SLJ laminate-1

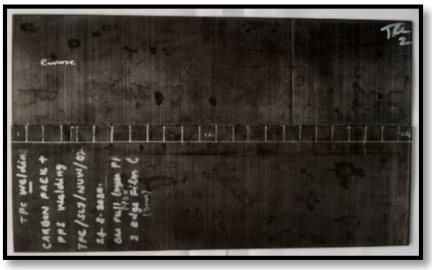

Figure 8. Ultrasonic Welded SLJ laminate -2

Further overlapping laminate placed on top was held by an aluminum plate locked by five bolts, to ensure the laminates don't dislodge due to the compressive force of the ultrasonic horn during the welding process. The joining was carried out on the TPC laminate carefully aligning the laminates on to the fixture and securing it with the constraining supports given. The fixture allows the top laminate to be placed such way that the overhang on the bottom laminate was set to 12.5 mm as required by the ASTM standard.

The parameters for the ultrasonic welding process were finalized based on the fact that the thermoplastic material is capable of melting and solidifying multiple times on application of temperature. The literature suggested that the ultrasonic welding requires the use of energy directors that is prepared from the neat resin in different shapes such as triangular, flat and rectangular shapes of same matrix material of substrate. However, this experiment was performed with a focus on directly subjecting the laminate to the ultrasonic vibration and determine the possibility of joining without the use of energy directors as shown in Figure 6. It was found that the PAEK material was melting partially but was not bonding together. Hence, it was decided to use a thermoplastic film as the energy director but little low melting temperature thermoplastic film of PPS. The welding parameters used for the manual ultrasonic welding trial-1 & trial 2 of the laminate was as shown in Table 2 :

Table 2. Ultrasonic Welding process parameters

| Item no | Description | ED material | Size & Shape of ED | Vibration time in Seconds | Pressure hold time in seconds |
|---|---|---|---|---|---|
| 1 | Trail- 1 (MUW-1) | PPS | 13 mm strip | 20 | 20 |
| 2 | Trail -2 (MUW-2) | PPS | 3 mm strip 3 pieces | 30 | 20 |

## NON-DESTRUCTIVE & DESTRUCTIVE MECHANICAL TESTING

Qualification of the joints were performed by ultrasonic NDE and mechanical testing; NDT method the true definition according to BS EN 1330-4:2000 is the 'Image of the results of an ultrasonic examination showing a cross-section of the test object parallel to the scanning surface.' However, the C-scan does not have to be a single cross-section but often shows a combination of measurements obtained through the whole thickness.

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Here, ultrasonic 'C' scan method is used to inspect the laminate and the joint region any defects like porosity and voids. The 'C' scan result of co-consolidated SLJ laminate was shown in Figure 9. It is found that the interface region has not been bonded well. There was a poor bonding at the joint region, however this was co-consolidated without any energy director at the interface. The ultrasonic welded 'C' scan images are shown in Figure 10. The quality of the welding is not good and 'C' scan results found that most of the places are very higher dB level and dynamic range. This shows that few welding parameters needs to be modified and ED also could be changed however, these specimens will be subjected to mechanical testing to find out its lap shear strength.

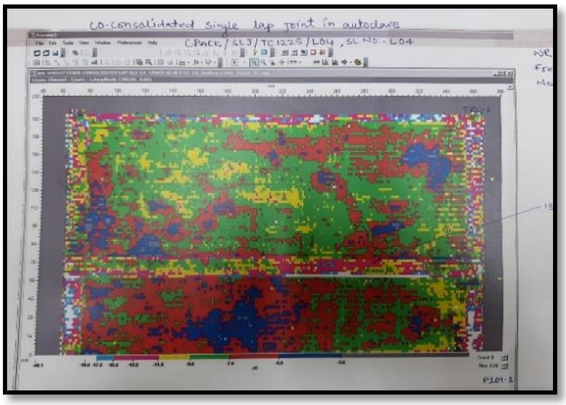

Figure 9. C-Scan result of co-consolidated Specimen

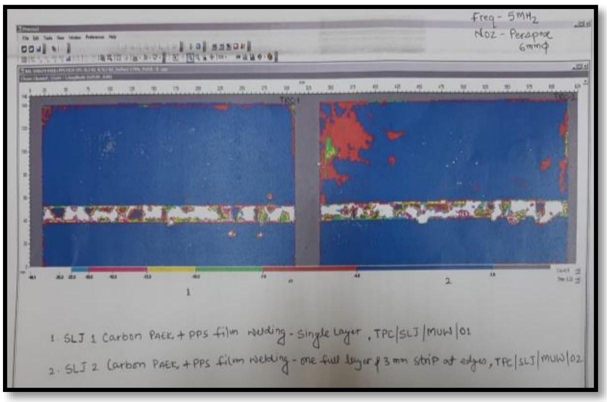

Figure 10. C-Scan result of MUW-1 Specimen (left) & MUW-2 Specimen (right)

Lap shear specimen has been prepared from the SLJ laminates and end tabs were bonded. Instron model 5984 Universal testing machine. Since the specimens are fixed with end tabs to maintain the same thickness on both ends of the specimen there is no offset in the loading. The rate of loading was 1.22 mm/min through cross slide of the equipment.

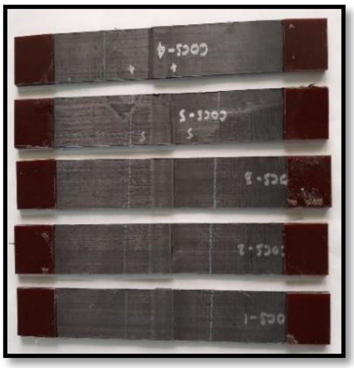

Figure 11. Co-consolidated specimens with end tabs

Figure 12. MUW-1 Specimens cut to dimensions

Figure 13. MUW-2 Specimens cut to dimensions

The prepared specimens are shown in Figures 11 to 13. The axial tensile load was applied to the specimen till failure of the specimens

Once the specimen fails the corresponding load was considered for computation of the lap shear strengths. The lap shear strength was calculated as the failure load or the maximum loaded of the specimen whole divided by the bond area. ($l_0$) multiplied by the width of the overlap (w) the same has been shown below.

$$LSS = \frac{F_{max}}{l_0 \times w}$$

$F_{max}$ = Failure load of the specimen
$l_0$ = Over lap length -------------- ①
w = width of the specimen

Using the equation 1, the lap shear strength was computed for all the specimens. The comparison of the lap shear strength of these specimens were illustrated in the Figure 14

## RESULTS AND DISCUSSIONS

The co-consolidated specimen shows maximum load bearing capacity and has shown an average lap shear strength of 36.02 MPa. However, one specimen strength was up to 41.24 MPa. It shows that the maximum potential of the joint. It is expected that if laminate 'C' scan quality is good, then the average lap shear strength may increase further. The specimens joined with the help of ultrasonic welding with the PPS interface and the with a minimum holding time of 20 seconds during heating and cooling has shown the average lap shear strength of 8.76 MPa. With an increase in the holding time to 30 seconds with an application of pressure for 20 seconds the specimens have shown an average lap shear strength of 16.14 MPa. The increase in the holding time and application of pressure has affected the joining process with an increase in almost twice when compared to the 20 seconds holding time. Ultrasonic welding shows that the pressure application after heating through ultrasonic vibration plays a crucial role in the fusion bonding process. In the present experiment, hand-held ultrasonic gun was used, hence it was difficult to control the magnitude of the pressure. It is proposed to have a device which can control the pressure during welding.

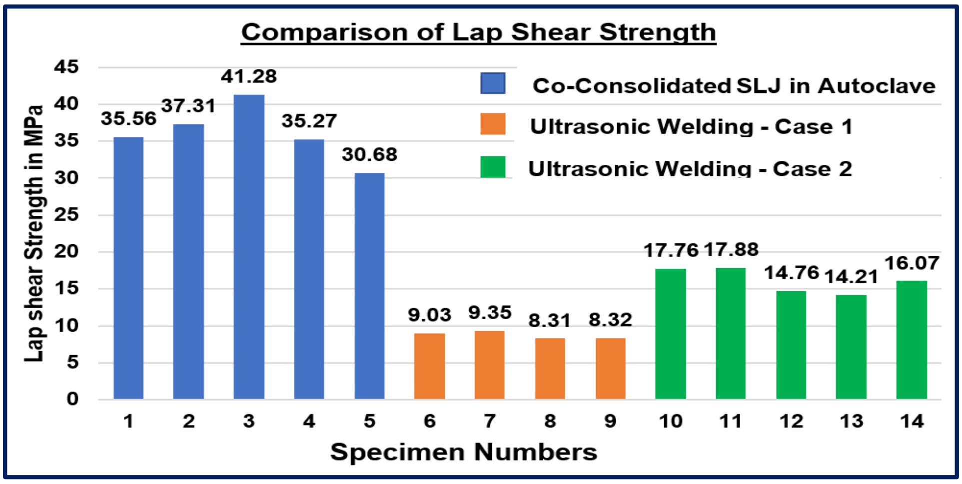


Figure 14. Comparison of Single Lap Shear Strength of three joining methods

In comparison of the lap shear strengths as shown in Figure 14 it is clear that the SLJ specimens joined by co-consolidation method has shown the maximum bond strength. In spite of little poor consolidations as seen in the c scan reports the lap shear strength was high. This shows the co-consolidated method was very effective in joining of thermoplastics. The ultrasonic method of joining can be improved by reducing the porosity and voids as seen in the ultrasonic c scans by selecting suitable parameters and optimize the joining process to obtain the required consolidation levels. Some of the possible reasons of the poor consolidation could be the poor interaction between the PPS and PAEK polymer chains. Further studies on interaction between dissimilar polymer chains can help understand the best suited energy director for the use in the joining techniques.

## CONCLUSIONS

The above presented work on the optimization process of the PAEK thermoplastic composite for autoclave consolidation and the optimized cure cycle can be used for any monolithic parts. The SLJ specimen joined using co-consolidation method processed by autoclave vacuum bagging technique showed prominently higher values in the bond strength when compared to ultrasonic welding process. It is clear from the experimental work that the welding time was less than a minute, however the co-consolidated specimen requires a much higher time along with the use of various consumables that can be avoided with the use of an optimized ultrasonic welding process. The current welding process to be studied further with changes in the interface material to a much more suitable polymer resin. The C-scans show significantly very high voids with poor consolidations between the two different resin systems. Further a suitable fixture to be designed for applications of higher-pressure during welding process, immediately after ultrasonic vibration on the specimens. The energy director may be redesigned to get maximum lap shear strengths.

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