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INVESTIGATION OF PROCESS PARAMETERS ON FUSION BONDING FOR THERMOPLASTIC COMPOSITES

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ABSTRACT

The objective of this study is to determine the optimum process parameters of the resistance welding of PPS thermoplastic composite laminates. Stainless steel mesh is used as a heating element. A lap-shear joint type is used and mechanically tested. The optimum process parameters are determined by changing the current and time under a constant pressure. The experimental set-up consists of three main parts include a DC power supply, metal clamps to apply the current, and a pressure tool which locates and applies forces to laminates. Results reveal that optimum parameters for resistance welding of PPS material 25 A and 60 s under constant pressure value of 0.2 MPa. Clamping force, insulation, and good connections are also critical for good fusion bonding.

INTRODUCTION

Lightweight structures, superior mechanical properties, and competitive prices are extremely important in aerospace industry. The use of thermoset composites instead of metals has provided good advantages. However, there are some disadvantages of thermoset composites such as long processing times, inability to recycle potentials due to their crosslinking structure, high thermal conductivity, and hardness which is not preferable in regions where they are exposed to vibration and relatively shorter life. Therefore, new materials have been investigated in order to eliminate those disadvantages. Recently, thermoplastic composites have got great attention due to their several advantages over thermoset composites. Some of the most important advantages are unlimited shelf time, faster manufacturing, and great recyclability potentials.

Increases in the use of thermoplastic composites in aerospace industries have made composite joining processes very important. The joining processes used in composite structures include mechanical fastening, fusion bonding, co-consolidation and adhesive bonding. It is well-known that traditional joining methods of mechanical fastening and adhesive bonding are difficult, labor intensive, and high cost [Yousefpour et al., 2004]. A cost comparison was made by The Boeing Company that indicated labor savings for fusion bonding at composite wing structures are greater than 61% compared to mechanical fastening

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[Wedgewood and Hardy, 1996]. Mechanical fastening methods have several disadvantages. These are stress concentrations, galvanic corrosion, delamination during drilling operation, increase in total weight, process time, and labor costs [Stavrov, Bersee, 2004]. Adhesive bonding process has similar issues with mechanical fastening. Good surface preparation is mandatory for a good bonding result. This process also has long cure cycles and usually requires autoclave. These drawbacks make adhesive bonding technique undesired for thermoplastic composites joining.

Due to thermoplastics chemical properties, fusion bonding has great potential for joining operation of thermoplastic reinforced composite materials. In the process, properties of thermoplastic matrices are used. Bonding is achieved by heating above transition temperature or the crystalline melting point of thermoplastic polymers at the interface under a required pressure. Main fusion bonding types are listed as friction, ultrasonic, induction and resistance welding.

The objective of this study is to investigate the optimum process parameters of resistance welding which is a sub-topic of fusion bonding for thermoplastic composites. A schematic representation of the resistance welding experimental set-up is shown in Figure 1.

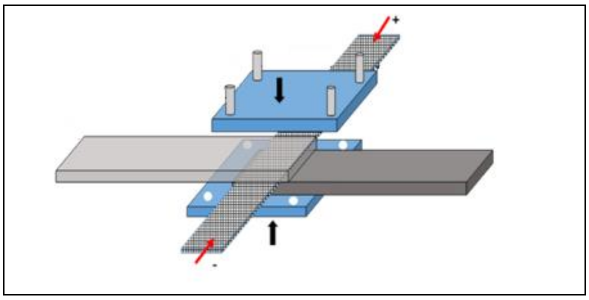

Figure 1: Experimental set-up of resistance welding

In this process, there are several parameters that should be considered for the resistance welding to optimize the mechanical properties of the welded joints. The most effective resistance welding process parameters are welding pressure, power input, welding time, heating element type, and the clamping pressure.

Welding pressure is one of the most important parameters to produce high quality joints. This parameter is required to be performed under control. The process mentioned above for resistance welding is also called as constant displacement method. Main advantage of this method is controllability of the final joint thickness and it requires usage of simply tools. On the other hand, it is not available to control the actual pressure in the bond during the process. [Stavrov and Bersee, 2005]. Yuan et al. investigated the effects of hold pressure during the resistance welding of carbon-fiber-reinforced polyetherimide (PEI) laminates. [Yuan et al.,2001]. The heating element was a metal mesh sandwiched glass fiber reinforced PEI. The experiments were carried out with a current of 30 A for 32 s. Different holding pressures between 0.2 – 2 MPa were applied. Results reveal that the deconsolidation defects were reduced by increasing holding pressure. In addition, the flexural strength and modulus were also increased by increased holding pressure. Optimum welding pressure is obtained between 0.4 and 1.2 MPa. Power level directly affects to applied pressure parameter [Hou and Friedrich, 1992].

Another important parameter for the resistance welding is the power which is applied to the sandwiched heating element. Power level is inversely proportional to heat loss. As a result of heating only interface of laminates, the amount of heat loss on laminates is much greater at lower power levels. Another parameter for minimizing the heat loss, longer welding time is required for melting the resin at the interface [Hou et al., 1999].

Properties of heating element is also critical for the resistance welding. Comparative studies between the metal mesh heating elements and carbon fiber heating elements for welding of carbon fiber/PEEK laminates were performed. Results indicate that the metal mesh heating elements improved the heating efficiency more than the carbon fiber heating elements. However, they have some issues in terms of shear stress concentration, weight penalty, and radar signature [Ageorges et al., 2001].

Polypheneylenesulfide (PPS) is a thermoplastic polymer that have a high melting point (285 °C), and relatively low density (1.35 g/cm^3) [Yamamato and Takashima, 2002]. These properties make PPS a superior candidate for aerospace applications. There have been a few studies on the resistance welding of PPS composites. One of the studies investigated on welding of the glass fabric reinforced PPS with a stainless-steel mesh as the heating element in a lap-shear joint configuration [Shi et al., 2015]. This study shows both experimental and numerical results. According to this study, measured temperatures from specimens were obtained close to numerical results. It is found that most important parameters of welding temperature are input power and welding speed. Welding temperature is directly proportional to the input power. By increasing the voltage "input power", higher welding temperature can be achieved. On the other hand, welding temperature is inversely proportional to welding speed. Results show that relation between the welding temperature and welding voltage is more sensitive.

METHOD

Low-cost tooling requirement, fast manufacturing and less energy consumption are the main advantages of resistance welding. For these reasons, process parameters are quite important in order to get a good bonding. In this study, experimental methods were used to obtain optimum process parameters.

Working principle of resistance welding is generating necessary heat through heating element and melting the thermoplastic matrix. Requirement for melting the thermoplastic matrix is reaching the temperature at the bond line. Temperature value is T_g for amorphous, T_m for semi-crystalline polymers. During all stages of process, pressure should be applied.

Experimental Method

An experimental set-up was developed for the resistance welding process shown in Figure 2. A pneumatic system and piston mechanism apply the pressure on welding area. A load cell under the welding area measures the force.

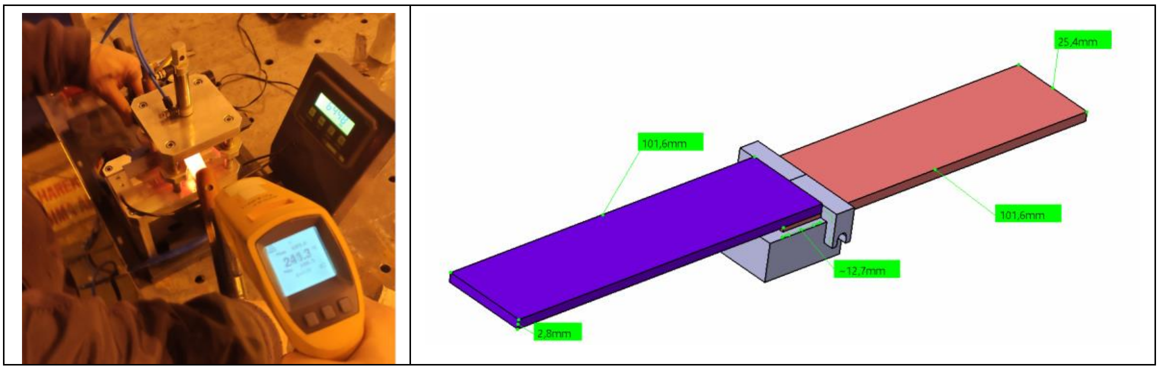

Figure 2: Resistance welding fixture

Welding fixture tool consists of a pneumatic load system, a monitor that displays the applied force and a detail that locates the specimens. Welding machine that used for resistance welding is Tig 4300 AC/DC. Welding process was done at DC configuration. Temperature was measured by J type thermocouple. Beamex MC 2 model was used to connect thermocouple and monitoring temperature values. The equipment used in the experiment is shown in Figure 3.

Figure 3: Welding machine and temperature calibrator

Materials

Thermoplastic prepreg Toray-Cetex TC1100 PPS/T300JB Carbon 200gsm Woven Fabric Reinforced Laminate 43% RC were supplied from Toray Industries Inc., Japan. The laminate has a density of 1.55 g/cm^3, tensile strength 0° of 753 MPa and tensile modulus 0° of 55.9GPa. The glass transition temperature, melting temperature, and the processing temperature of the neat resin are 90 °C, 280 °C and 300-330 °C, respectively. Stainless steel metal mesh with a mesh size of 61 μm and diameter of 0.04 mm is used as the heating element and supplied from TEKPUN Steel Mesh Industry Inc., Istanbul, Turkey.
Laminates were cut to desired sizes by waterjet machine. Due to waterjet technology, it was not required to grind edges of samples. Also, this technique does not require surface preparation. Those two parameters were shortened the process times.

Process

Optimization parameters are current, time, and pressure. By considering these parameters, a welding fixture was developed. Supplemental parts are, a DC power supply and metal clamps to apply current on heating element.

A heating element is located between two specimens to be welded. Electrical current is applied to heating element from both sides. Interface of thermoplastic materials heats up, molecule diffusion at the interface occurs. During welding process, pressure should be applied over the interface area to promote molecular diffusion. Thermoplastic matrix starts to melt when the temperature rises. After cooling time, resistance welding operation is completed. Energy dissipated from the resistor which is heating element in resistance welding is proportional to the resistance, current, and elapsed time.

$$E = I^2 R t \qquad (1)$$

R is the resistance value of the heating element. This value is calculated from equation given below. Here γ, is the specific resistance of the material [Ω], *L* length of heating element [m] and *w* is the width of the heating element [m].

$$R = \gamma \frac{L}{w} [\Omega] \tag{2}$$

Three different current parameters were done by three different durations. Test samples are shown in Table 1. Pressure value was set as 0.2 MPa for all experiments.

Table 1: Parameters of test samples

Material	Current (A)	Time (s)
PPS	20 A	30 s
PPS	20 A	50 s
PPS	20 A	75 s
PPS	22 A	30 s
PPS	22 A	50 s
PPS	22 A	75 s
PPS	25 A	30 s
PPS	25 A	50 s
PPS	25 A	75 s

Mechanical Tests

Single lap shear test was performed according to EN2243-1 standard. The equipment was INSTRON 5985. The apparent lap shear strength (LSS) of the joints was calculated by dividing the maximum load to the total overlap area.

$$\boldsymbol{\tau} = \frac{F_{max}}{LXb} \left[\frac{N}{mm^2}\right] \tag{3}$$

The morphology of the fracture of the welded specimens after lap shear test was investigated via scanning electron microscopy (SEM) with QUANTA 400F Field Emission SEM.

RESULTS AND DISCUSSION

Increases of the current, the pressure and the heating time have certainly affected the shear strength of joints. In order to understand the effects of welding parameters on the welding performance, single lap shear tests were performed. Higher shear strength values provide better mechanical properties for joints. When the amplitude of the current is low such as 12A and duration is short such as 30s for this experiment, it was shown that heat generated due to resistance was not sufficient for bond materials to bond. Welded joints were deformed without applying a force.

Experiments were carried out with values of among 20, 22 and 25 amperes. Welding was performed for 30, 50, and 75 seconds at each current value. Lap shear test results were given in Table 2.

Table 2: Lap shear test results

	Specimen note	Width	Length	Maximum Load	Tensile stress at Maximum Load	Avg Tensile stress at Maximum Load
		[mm]	[mm]	[N]	[MPa]	[MPa]
1	**20A 30s**	25.42	12.75	3,494.30	10.78	**11.45**
2		25.32	12.66	3,621.13	11.30	
3		25.38	12.71	3,956.67	12.27	
4	**20A 50s**	25.44	12.72	3,808.76	11.77	**14.12**
5		25.38	12.75	4,625.18	14.29	
6		25.46	12.67	5,253.80	16.29	
7	**20A 75s**	25.43	12.69	5,323.60	16.50	**14.52**
8		25.46	12.76	4,425.38	13.62	
9		25.37	12.71	4,338.44	13.45	
10	**22A 30s**	25.41	12.70	3,351.09	10.38	**11.05**
11		25.36	12.66	3,625.19	11.29	
12		25.44	12.73	3,718.18	11.48	
13	**22A 50s**	25.36	12.75	5,423.09	16.77	**15.95**
14		25.36	12.63	5,416.47	16.91	
15		25.44	12.68	4,570.39	14.17	
16	**22A 75s**	25.48	12.80	6,116.20	18.75	**17.05**
17		25.38	12.63	5,116.86	15.96	
18		25.46	12.77	5,344.69	16.44	
19	**25A 30s**	25.42	12.65	3,602.25	11.20	**11.77**
20		25.36	12.72	3,756.89	11.65	
21		25.39	12.66	4,002.52	12.45	
22	**25A 50s**	25.44	12.73	6,210.05	19.18	**18.43**
23		25.46	12.74	6,114.87	18.85	
24		25.30	12.60	5,501.98	17.26	
25	**25A 75s**	25.50	12.75	6,135.48	18.87	**19.32**
26		25.32	12.62	6,169.58	19.31	
27		25.45	12.78	6,429.86	19.77	

It was observed that both increment of current and time, increases the lap shear strength. For all current values, 30 seconds duration was not enough to get higher lap shear strength results.

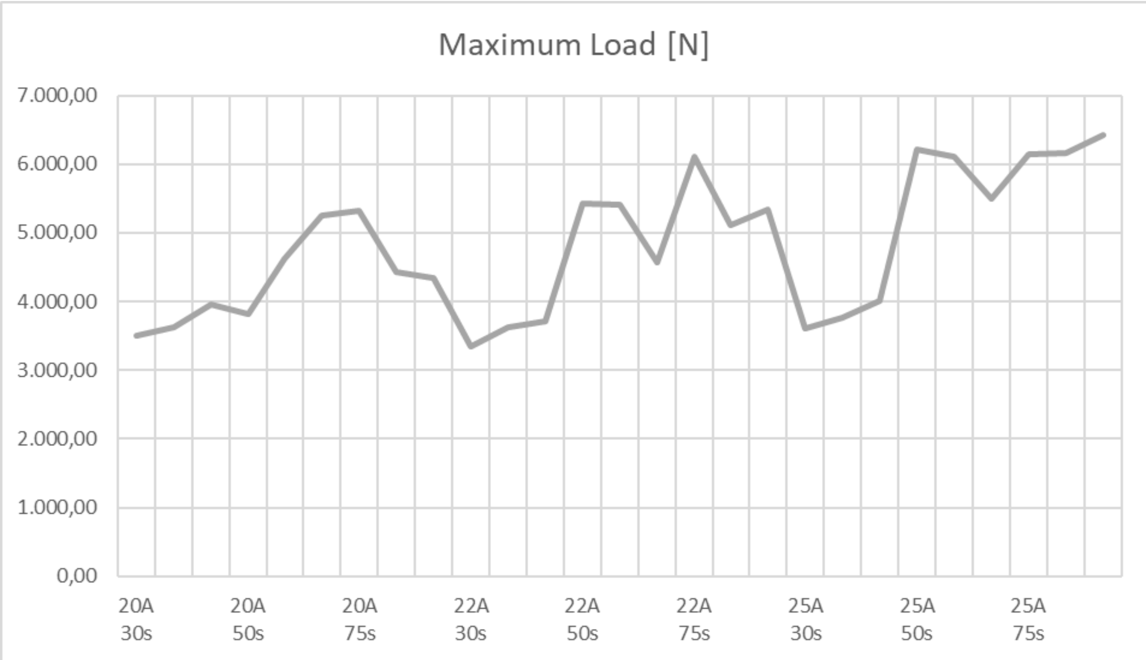

Figure 4: Overall lap shear test results

Another important finding from the results was minor strength difference between 50 and 75 seconds of each current value. Thus, SEM results were analyzed for 25A 50s and 25A 75 s.

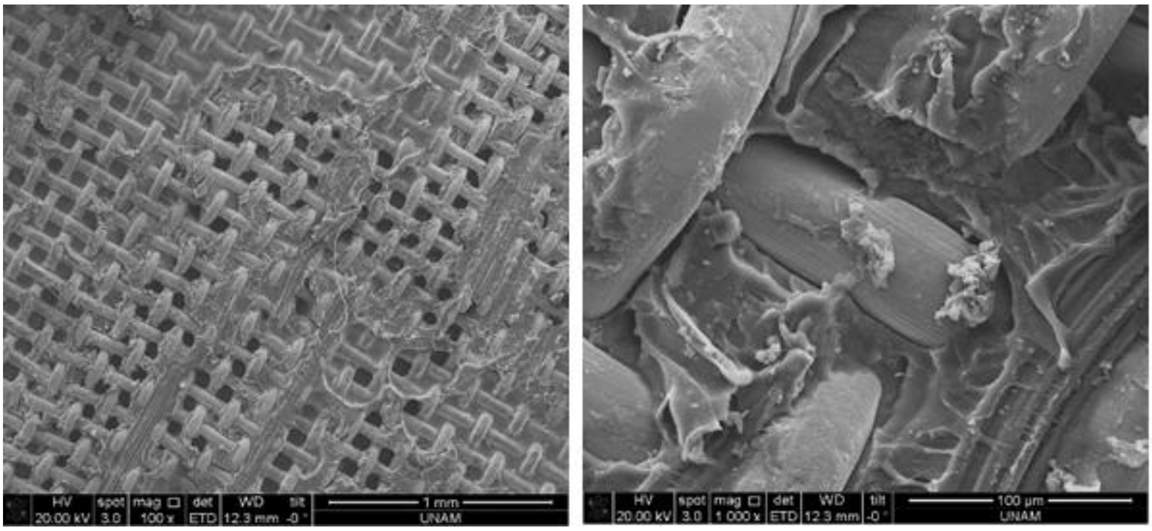

Figure 5: SEM results for 25A 50s

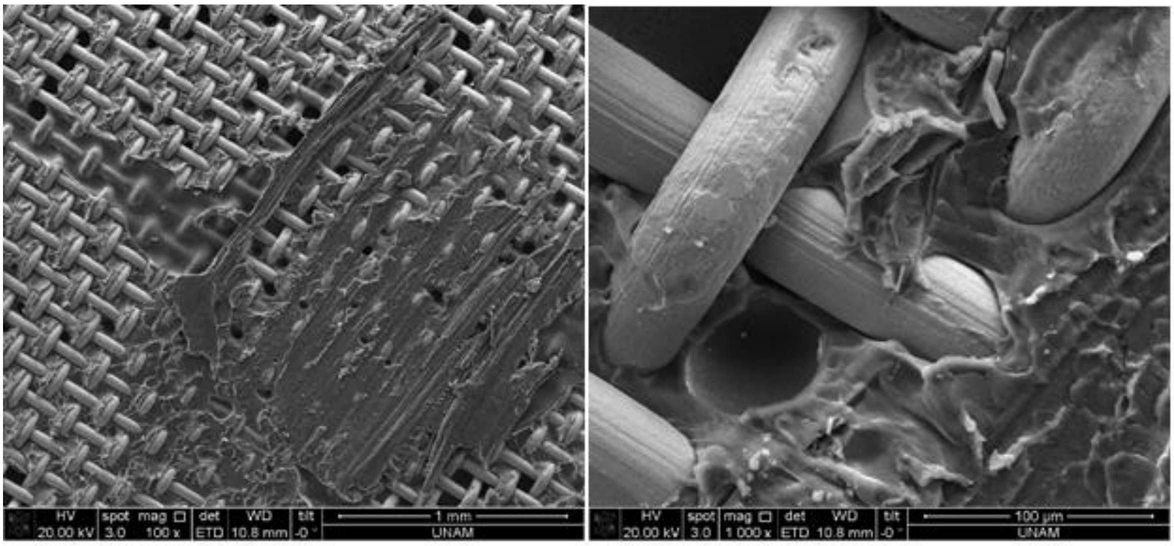

Figure 6: SEM results for 25A 75s

For 75s duration, it was observed that there were breaks in the matrix structure in some adhesion areas. It causes negative effect for lap shear strength values. This means lap shear strength value was increased after 50 seconds until breaks in the matrix occurred. 25A and 60 seconds experiments was done in order to find optimum duration. Lap shear results for 25A 60s were given in Table 3.

Table 3: Lap shear results for 25A 60s

Specimen note	Width	Length	Maximum Load	Tensile Stress at Maximum Load	Avg Tensile Stress at Maximum Load
	[mm]	[mm]	[N]	[MPa]	[MPa]
25A 60s	25.46	12.73	6,119.45	18.88	**19.51**
	25.44	12.74	6,268.94	19.34	
	25.41	12.72	6,564.76	20.31	

At high current amplitudes, required heat was generated and good bonding was achieved at the interface. It was observed that integration between stainless steel mesh with the composite laminates were almost flawless. Thus the strength was improved significantly. The molten polymer fills the gaps between the metal mesh and two composite parts. To produce necessary amount of heat for melting laminates, current should flow through the joint. For this purpose, the welding time was increased. By increasing the welding time, the average single lap shear strength of the specimens was increased. Increasing the current to 28A causes decomposition of molten material from the interface and this causes a decrease in shear strength. Certain level of heat is required for the consolidation of laminates. At lower current levels, higher strength joints are produced. It was shown that strength of the joints decreases with the increasing current. At higher current levels, laminates become overheated and this results undesirable fiber motions. Overheating causes squeeze flow of laminates and this results negatively on strength of joint.

In order to make the resistance welding successful, the system must be well insulated. During the experiments, it was observed that the welding process failed in cases where the insulation was not adequate. Insulating materials are used to prevent energy leakage from the system.

The pressure force applied on the samples during the welding process is another factor that directly affects the mechanical properties of welded joints. For this purpose, a pneumatic system was used to apply and control the pressure over the laminates. Constant pressure method was used in the experiments. In cases where the pressure was incapable, it was observed that the welding quality was insufficient.

Another important parameter is clamping pressure of power supply and mesh element connection. This parameter is kept constant after optimization by trying different pliers. At the beginning, welding pliers of welding machine was used to clamp heating element. This caused the narrow-section heating material to heat up very quickly and it was observed that the stainless-steel mesh ruptured before the welding process was completed. To eliminate this problem, lighter welding pliers with a smaller holding area were used.

CONCLUSION

Effects of time and current parameters were investigated for the resistance welding of PPS thermoplastic composite laminates. It was shown that when the power level is too low, the heating element could not be heated enough to melt the interface materials and no welding occurred. If the power level is too high, it was shown that only edges of laminates welded due to rupture of heating element exposed to high temperature. Effects of both time and electrical current was researched as input energy. For resistance welding, results were not the same for same energy values. For example, same amount of energy can be given to the system by applying relatively higher current for a shorter time with applying a lower current for a longer period and the results are expected to be different.

Finally, optimum parameters for resistance welding of PPS material were 25 A and 60 s under constant pressure value of 0.2 MPa.

ACKNOWLEDGEMENT

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