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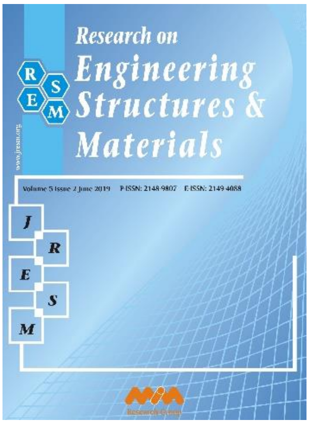

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Research Article

Effects of ultra-high frequency induction system on the carbon fiber reinforced thermoplastic composites

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Abstract

Because of their exceptional features, advanced composites with polymer matrix attract increasing interest in engineering applications recently. Compared to their weight ratio due to the high endurance and hardness values applications of polymer matrixed composites of lightweight, low density, and high performance are popular in military and civil aerospace, automotive, wind power and many other industries. Nowadays, induction heating of the carbon fiber reinforced thermoplastic composites is one of the most important worldwide studies. Due to the importance of accelerating the rate of production from approximately 180-240 minutes to a few minutes, in this study, the weldability of the carbon fiber reinforced thermoplastic composites was investigated.

1. Introduction

Thermoplastics are composed of linear molecule rings which are tied to each other with weak Van der Waals bonds. Thermoplastic materials soften over a critical glass transition temperature and viscosity decreases as the temperature raises. These materials become solid again when they are cooled. As an advantage, they can be stored in a solid state in room temperature. Thermoplastics have high rigidity and impact strength. Thermoplastic resins are preferred to increase the tensile and bending strength of the materials. [1]

Carbon fibers are reinforcing materials with the highest specific modulus and specific strength. [2] Combined with epoxy matrixes carbon fibers exhibit extraordinary strength and rigidity. They are not affected by humidity and their frictional resistance is very high. Their wear resistance and fatigue strength are quite good. Because of these properties, they are widely preferred in military and civil airframes. Having expensive production methods, they are used in high valued applications of the aircraft industry, sports equipment or medical equipment.

The reasons of the interest on carbon fiber reinforced thermoplastic composites are the production processes advantages as short autoclave times, low storage costs and ability to be thermoformed again alongside of their mechanic properties as good impact behavior, damage tolerance, high-temperature resistance, etc. [3-7]

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Although it is generally mentioned with metals because of their electrical and magnetic properties, effects of induction heating on polymer materials and composites are also has been examined in the last decade. [8-20]

Welding of polymer composites to polymer composites is characterized by heating the components over melting temperature, combining them and cooling under pressure.

Induction heating is based on the effects of induced eddy currents and magnetic polarisation. When an alternative voltage is applied to a conductive coil an alternative current is generated. When a magnetically susceptible and electrically conductive material gets close to the coil's magnetic field, eddy currents are induced. Eddy currents encounter with the material's resistance and energy is lost by transforming into heat form. [21]

In welding of thermoplastics, a metal mesh between the contact interface or carbon fiber fabric is used along with other methods, but because this study is about induction welding we just focused on it. Other induction welding parameters are generator power, weld time, pressure and cooling time. [22]

In the first phase of this study, induction welding capability of 4 different compositions of carbon fiber reinforced thermoplastic composites is examined. It is observed from the experiments that cross-ply stacks (0°/90°) plates or unidirectional (UD) stacks plates of which fibers of interfaces are perpendicular to each other can be welded by ultra-high frequency induction system while UD stacks plates with fibers on the interfaces are in the same direction cannot. In the second phase, how the induction coil is heating the carbon fiber reinforced thermoplastic materials and the heating gradient on the surface and across cross-sectional area were observed.

2. Materials and Methods

In this study, carbon fiber reinforced thermoplastic (poly ether ether ketone - PEEK) composite plates, which have 56% carbon fiber ratio in weight, are used. In the first phase, the plates are produced by hot press method and have 14 plies with each ply thickness of 142 μm of prepregs. These are domestically produced by Mir Unique Solutions Inc. The features of the samples are in Table 1. The plates are 20 mm in width, 20 mm in length and 2 mm in thickness. Two of the plates with the same composition are oriented on top of each other and pressed under a standard 1,2 MPa pressure during the welding.

A 2.8kW and 900 kHz ultra-high frequency induction system is used in atmospheric conditions. The cylindrical single turn induction coil has 2 mm diameter as shown in Figure 1. The coupling distance is 4 mm. The weld times and temperatures are given in Table 2.

The temperatures of the composites were measured with an infrared pyrometer (± 5 °C) during the process. At the end of the heating process, the samples were left to cool naturally to room temperature.

In the second phase, the plates are produced in autoclave up to 385°C temperature under an increasing pressure process up to 0,8 Mpa. These too are domestically produced by Mir Unique Solutions Inc. The orientations of the carbon fibers are unidirectional, cross-ply stacks (0°/90°) and 5 satin harness (HS) plates. The plates made of multiplies are 20 mm in width, 40 mm in length and 2 mm in thickness except for the 5 satin harness plies plates due to having 16 plies where the others have 14. Single plies of the compositions are also tested where cross-ply stacks and 5 satin harness orientations have 2 plies naturally.

Table 1. The features of the samples

Sample no.	Description of sample	Contents of sample	The production method of sample
S1	Two (0°/90°) cross-ply stack plates	PEEK matrice and carbon fiber	Hot (400°C) pressed for 15 mins and cold pressed for 15 mins under 5 MPa
S2	Two (0°/90°) cross-ply stack plates	PEEK matrice and carbon fiber	Hot (400°C) pressed for 15 mins and cold pressed for 15 mins under 5 MPa
S3	Two (0°) unidirectional (UD) plates on a hot plate	PEEK matrice and carbon fiber	Hot (400°C) pressed for 15 mins and cold pressed for 15 mins under 5 MPa
S4	Two (0°) UD plates	PEEK matrice and carbon fiber	Hot (400°C) pressed for 15 mins and cold pressed for 15 mins under 5 MPa
S5	Two (0°/90°) cross-ply stack plates	PEEK matrice and carbon fiber	Hot (400°C) pressed for 15 mins and cold pressed for 15 mins under 5 MPa
S6	Two (0°/90°) cross-ply stack plates	PEEK matrice and carbon fiber	Hot (400°C) pressed for 15 mins and cold pressed for 15 mins under 5 MPa
S7	Two (0°) UD plates, the fiber directions are perpendicular in the contact interface	PEEK matrice and carbon fiber	Hot (400°C) pressed for 15 mins and cold pressed for 15 mins under 5 MPa
S8	Two (0°) UD plates, the fiber directions are perpendicular in the contact interface	PEEK matrice and carbon fiber	Hot (400°C) pressed for 15 mins and cold pressed for 15 mins under 5 MPa
S9	Two (0°) UD plates	PEEK matrice and carbon fiber	Hot (400°C) pressed for 15 mins and cold pressed for 15 mins under 5 MPa

Due to the melting temperature of PEEK matrice (343°C) [23], the samples were heated in 350, 400, and 450°C for 2 minutes. During the heating process, the temperature of the samples' reverse sides was measured by another infrared thermometer on the projection of the coil.

Table 2. Welding parameters of samples

Sample no.	Welding temperature (°C)	Welding dwell time (minute)
S1	280	5
S2	310	3
S3	400	5
S4	310	5
S5	280	3
S6	310	5
S7	400	3
S8	310	3
S9	280	5

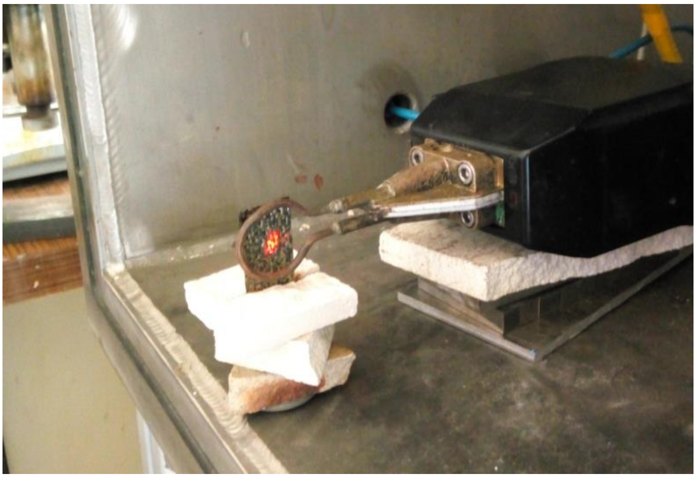

Fig. 1 The cylindrical single turn induction coil.

3. Result and Discussion

The weldability results for carbon fiber reinforced thermoplastic composites are presented in Table 3.

Empirical values are applied in weld times because when the heating generation will be uniform in the cross-sectional area cannot be assessed in this phase of the study due to the lack of thermal camera. The pictures of all of the samples in the study are shown in Figure 2.

The samples in Figure 2 are welded because the orientation of the plies of carbon fibers are perpendicular to each other that eddy currents were induced in closed loops. These eddy currents caused to heat generation.

In the rest of the samples, welding didn't occur because of the unidirectional orientation of carbon fibers to each other. Although hot plate was used under S3, heat generation was not enough to exceed the melting temperature that weld didn't happen due to the too long coupling distance with the hot plate. When the coupling distance is arranged in the field of the coil it is assessed that hot plate will be useful to weld. In some of these samples, variable regions have delamination's or deformations are observed. Because the defining of parameters is not studied in this phase, especially with interfaces they are not examined.

Table 3. The weldability results

Sample no	Welding orientation	**Result** (*Because of calcification problems of the material, results are checked by eyesight only.*)
S1	Two (0°/90°) cross-ply stack plates	Welded
S2	Two (0°/90°) cross-ply stack plates	Welded
S3	Two (0°) unidirectional (UD) plates on a hot plate	In line with the theory, eddy current could not be generated and although hot plate was used heat generation and welding did not happen.
S4	Two (0°) UD plates	In line with the theory, eddy current could not be generated, thus heating and welding did not happen.
S5	Two (0°/90°) cross-ply stack plates	Welded
S6	Two (0°/90°) cross-ply stack plates	Welded
S7	Two (0°) UD plates, the fiber directions are perpendicular in the contact interface	Welded
S8	Two (0°) UD plates, the fiber directions are perpendicular in the contact interface	Welded
S9	Two (0°) UD plates	In line with the theory, eddy current could not be generated, thus heating and welding did not happen.

In the second phase, 35 samples are used but because the IR thermometer is not precise and the single turn coil couldn't generate a uniform heat distribution, correct and precise measurements couldn't be done. So the results were not satisfactory and are not given here.

In order to achieve more uniform heating pattern, a new coil design is needed. Thus a new coil was designed as in Figure 3. The new coil has 3 mm in diameter due to the restrictions of the sample dimensions and the design.

The coupling distance was arranged as 3 mm at the beginning but desired heating values were not achieved because of not enough power of the generator that it was decreased to 2 mm. The reason for this is assessed as the new coil has a thicker (3 mm) diameter and the induction system is designed for a coil with 2 mm diameter. So the power of the system was not enough for the new coil.

The setting point of the pyrometer is shown in Figure 4. The temperatures below the samples were measured on two points. These two points are as in Figure 5.

In the first four samples, it is seen that measured values of single 5 HS stack plates are very close to the set temperatures by the pyrometer.

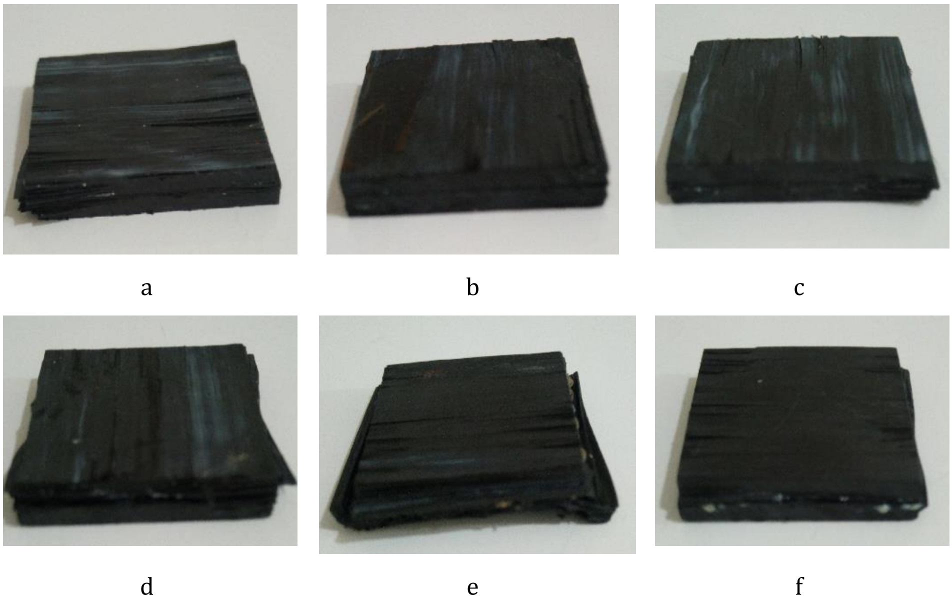

Fig. 2. The pictures of the induction welded samples: a) S1, b) S2, c) S5, d) S6, e) S7, f) S8

In 5 and 6th samples, 8 5 HS woven plies stack plates' measured temperatures, especially of the 1st temperature point, are significantly low. Although it is assessed that the reason is the increasing coupling distance by the thickness of the plates, 7 and 8th samples do not support the assessment. This situation might be a subject of further studies with more precise measurement equipment and more samples.

Fig. 3 The new coil design

Fig. 4 Setting point of the pyrometer.

In the 9, 10, 11 and 12th samples, measured temperatures of cross-ply stack (0/90) of 14 plies decrease slightly due to the explanation of 5 and 6th samples.

As a result of the study, it is observed that setting the pyrometer at 350°C does not provide exceeding the melting temperature of PEEK matrices of the samples and it is not a good parameter. Thus, 400°C will be used in successive studies.

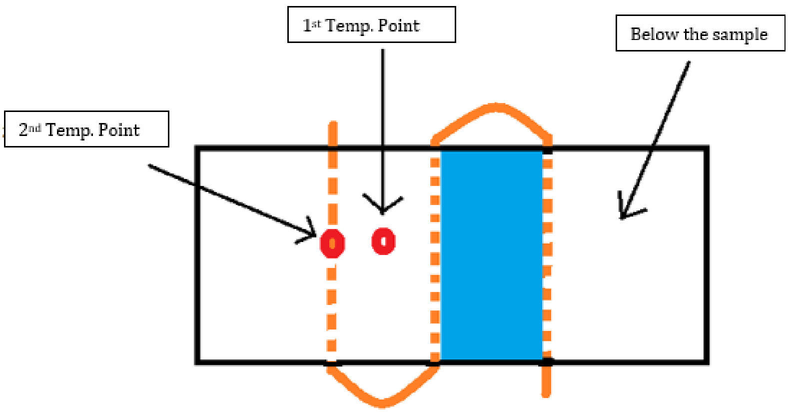

Fig. 5 The measurement points by IR thermometer.

Table 4. Heating gradient results.

Sample no	Set Temp. (°C)	1st and 2nd Temp. Point by IR Thermometer (°C)	Sample Architecture
1	400	365-400	Single 5 HS stack
2	400	345-400	Single 5 HS stack
3	350	310-325	Single 5 HS stack
4	350	310-345	Single 5 HS stack
5	400	310-330	8 5 HS woven plies stack
6	400	315-330	8 5 HS woven plies stack
7	350	295-345	8 5 HS woven plies stack
8	350	320-350	8 5 HS woven plies stack
9	400	355-375	Cross ply stack (0/90) of 14 plies
10	400	295-345	Cross ply stack (0/90) of 14 plies
11	350	330-345	Cross ply stack (0/90) of 14 plies
12	350	310-320	Cross ply stack (0/90) of 14 plies

4. Conclusion

In line with the theory, welding has occurred in the samples 1, 2, 5, 6, 7 and 8 while in the samples 4 and 9, due to no eddy current generation in (0°) UD plates heating and welding didn't happen in contact interfaces. In sample 3, to overcome the mentioned problem, the hot plate was placed under the plates but the heat generated in the interface didn't reach the melting temperature that welding didn't happen.

Defining the parameters will be the subject of future phases of the study. In the second phase, the architecture and orientations of the plates were considered and heating gradients of (0°) UD, (0°/90°) cross-ply stacks and 5 satin harness plates with single and multiplies were revealed. According to the conclusions of the study; the thermoplastic composites with % 56 wt. carbon fiber reinforcement were heated successfully due to the response of carbon fibers to induction currents.

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