CHARACTERIZATION AND MODIFICATION OF THE TEMPERATURE DISTRIBUTION DURING CONTINUOUS INDUCTION WELDING

M. Hümbert[a*], P. Mitschang[a]

[a] *Institut für Verbundwerkstoffe GmbH, Kaiserslautern*

Keywords: Induction, welding, temperature distribution.

Abstract

Induction welding is a process, which is particularly suitable for joining carbon fiber reinforced thermoplastics. One critical aspect of this method is the temperature distribution in thickness direction since the fibers throughout the whole laminate are heated. This can lead to deconsolidation and thermal damages. To be able to prevent these unwanted effects, the temperature distribution in thickness direction must be investigated. Before, usually single plate heating experiments have been performed. This paper investigates the temperature gradient in carbon fiber reinforced polyphenylene sulfide laminates when a stack of two laminates is heated and shows that the results from single plate experiments cannot simply be transferred to continuous induction welding.

1 Introduction

For the manufacturing of composite components, thermoplastic polymers offer many advantages, e. g. an unlimited shelf-life or a high toughness. Nowadays, thermoplastic composite components are often produced using pressing processes, which offer short cycle times while being affected by a restricted component size and complexity. Thus, components need to be joined to manufacture larger assemblies. Today, different joining technologies for composite materials are available, but they all have certain disadvantages. Mechanical fastening requires holes which damage the reinforcement and can lead to interlaminar defects. Adhesive bonding overcomes these problems, but often solvents and long curing cycles are necessary. Moreover, nonpolar thermoplastics like polyethylene are difficult to bond. By taking advantage of the fact that thermoplastic polymers can be melted, welding is a good joining alternative. The benefit of this process is that the polymer matrix itself is used to generate the bond. A welding process which is particularly suitable for fiber reinforced thermoplastics is induction welding. In order to optimize the process, this study investigates the temperature distribution in thickness direction.

2 Induction welding of fiber reinforced thermoplastics

Induction welding is based on the ability of electromagnetic (EM) fields to transfer energy without physical contact. When an electrical conductor is placed in an alternating EM field, (generated by an induction coil) eddy currents are induced. According to Joule’s first law, a current flowing through a conductor causes the conductor to heat up. This effect can be used to heat an electrically conductive part, such as a carbon fiber reinforced laminate, which is placed near an induction coil as shown in Figure 1 (right).

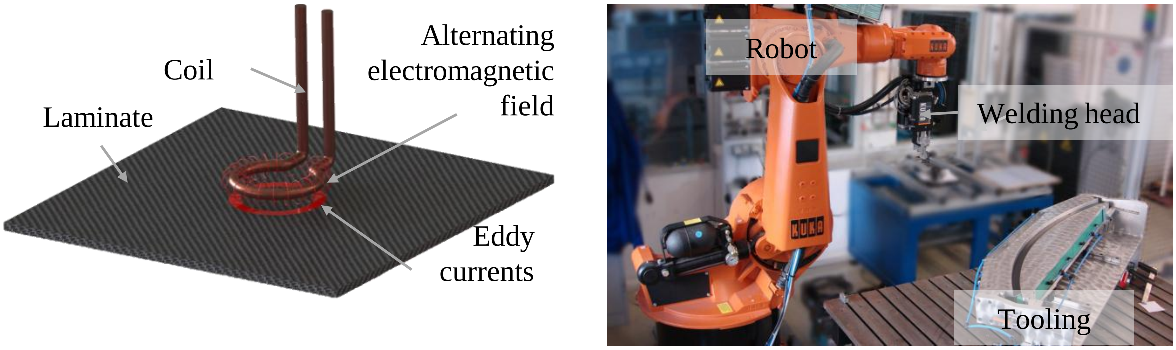

Figure 1: Left: Induction heating of a carbon fiber reinforced laminate; right: continuous induction welding process

In order to use induction heating for welding, the coil must be combined with a consolidation roller. First, the to-be-welded laminate is heated by the coil. Subsequently, the consolidation roller is rolled over the workpieces, applying pressure to the welding area in order to create a strong weld. Composites containing electrically conductive fiber meshes (e.g. carbon fibers weaves or cross plies) can be heated directly, as the fiber meshes form closed-loop circuits [1]. Electrically nonconductive fibers (e.g. glass fibers) need a susceptor in the welding area. The susceptor is made of electrically conductive material [2], e. g. a metallic mesh, or ferromagnetic particles [3]. However, a susceptor is a contaminant that weakens the joint as it can cause high stress concentrations and that tends to corrode when in contact with carbon fibers [3].

The more elegant solution for welding carbon fiber reinforced laminates is to heat the fiber themselves without susceptor. Using this approach, the carbon fibers throughout the whole laminate are heated. Therefore, the heat generation and distribution within the laminate is an especially critical aspect.

3 Heat generation and distribution within the laminate

Several attempts have been made in order to define the dominant heating mechanism for carbon fiber laminates. In general, three different heating principles have been identified. The fibers are heated to joule losses, the fiber junctions heat due to contact resistance, and the polymer between two fibers at their junction is heated by dielectric hysteresis losses [2,4].

The distribution of the heat generated by the above mentioned mechanisms is influenced by many different physical phenomena of which two are mentioned here. One is known as the skin effect and is characterized by the so-called penetration depth δ. The skin effect implies that an alternating current concentrates on the outer layer of a conductor. It is defined by the penetration depth which is the depth below the surface of the conductor at which the current density has fallen to 37 % of its value at the surface [6]:

$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \mu_r \sigma}} \qquad (1)$$

With: δ: penetration depth [m]
ρ: electrical resistivity [Ωm]
μ: magnetic permeability [H/m]
f: frequency [Hz]

The second important effect is that the intensity of the field drops with increasing distance to the coil. It is described by the law of Biot–Savart which defines the magnetic field intensity at any point in the room relative to a conductor [7]:

$$\vec{H} = \frac{I}{4\pi} \oint \frac{d\vec{s} \times \vec{r}}{r^3} \qquad (2)$$

With
$\vec{H}$: magnetic field intensity
I: current
$d\vec{s}$. curve element of the conductor in direction of I
$\vec{r}$: displacement vector from the conductor element to the point
r: distance between the conductor element and the point.

Based on these two phenomena, it is assumed that the top of the laminate (coil side) is heated faster by a stronger electromagnetic field which leads to thermal damages and deconsolidation. In previous investigations [8, 9] this assumption could be confirmed by heating experiments performed on a single laminate. Moser [8] developed a surface cooling consisting of an impinging air jet unit to avoid overheating of the top surface while achieving similar lap shear strength values [9].

In order to achieve a deeper understanding of the heating process, this paper extends these studies to the investigation of the temperature distribution within a stack of two laminates during static heating and continuous welding. One important question to be answered is, whether the findings from single plate static heating can be transferred to a stack of two plates and, moreover, to the continuous heating case. This knowledge can then be used to prevent deconsolidation and overheating during welding.

4 Heating experiments

In order to investigate the temperature distribution during induction welding, heating experiments have been performed. Both, static heating and continuous welding tests were performed. For all experiments, carbon fiber reinforced polyphenylene sulfide (CF-PPS, 5-harnes satin, fiber volume ratio: approx. 50%) was used. The different test cases are listed in Table 1.

Sheet thickness	**Coupling distance**	**Movement**	**Generator power (P_{max}=2.8 kW)**	**Surface cooling**
1.2 mm	10 mm, 5 mm	static	10 %, 20 %, 30 %	No
2 mm	5 mm	static	10 %, 20 %, 30 %	No
1.2 mm	5 mm	8.4 mm/s	30 %	No
1.2 mm	5 mm	8.4 mm/s	40 %	Yes

Table 1: Different test cases for the heating experiments

4.1 Static case

The experimental setup for static heating is presented in Figure 2.

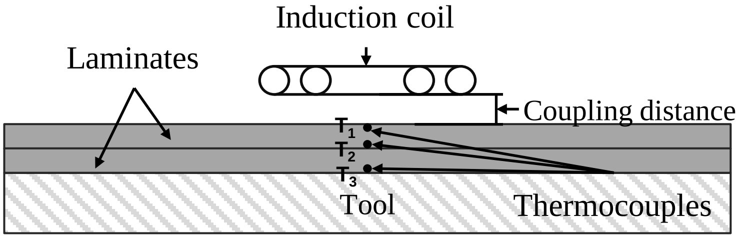

Figure 2: Static heating experiment (no surface cooling by air)

A coil was placed above a stack of two CF-PPS laminates. In order to measure the temperature, three thermocouples were used, one on top of the upper laminate (temperature T_1), one in the welding zone between the two laminates (temperature T_2) and one on the bottom of the lower laminate (temperature T_3). The results for two laminates with a thickness of 1.2 mm and a coupling distance of 10 mm are given in Figure 3.

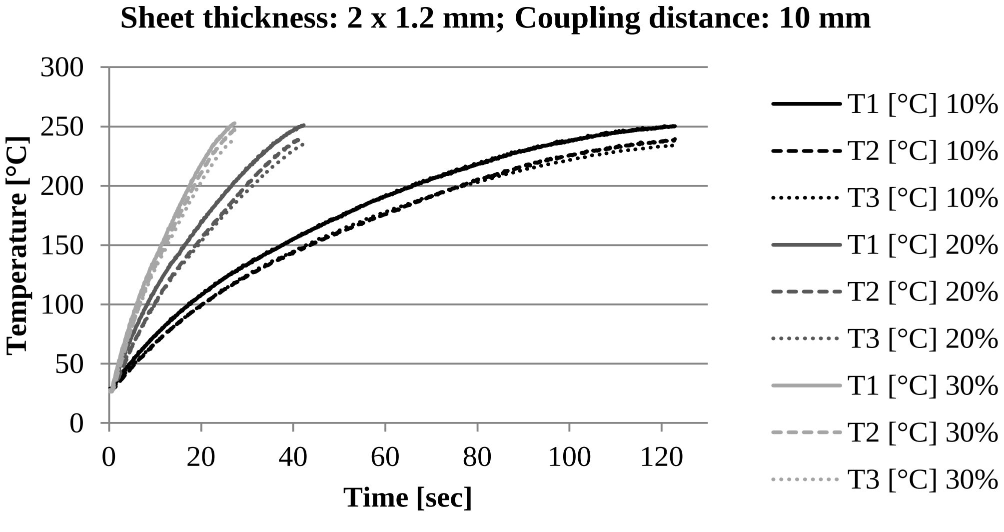

Figure 3: Static heating results for two stacked CF-PPS laminates with a thickness of 1.2 mm and a coupling distance of 10 mm (no surface cooling by air)

The specimens were always heated until the top laminate reached 250 °C. This temperature was chosen to prevent melting of the polymer which would destroy the specimen, and would require a new specimen for each test. In that case neither the exact positioning of the thermocouples nor constant laminate properties could be guaranteed. The heating curves shown in Figure 3 confirmed the previously assumed temperature distribution. The top laminate was heated the most and the temperature dropped with increasing distance to the coil. A similar behavior was observed when the coupling distance was reduced to 5 mm, as shown in Figure 4.

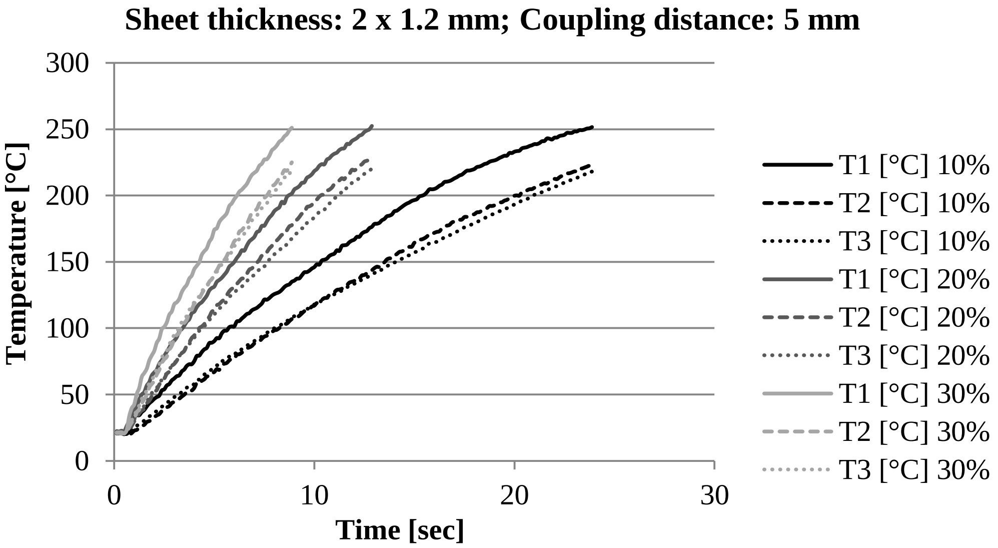

Figure 4: Static heating results for two CF-PPS laminates with a thickness of 1.2 mm and a coupling distance of 5 mm (no surface cooling by air)

A comparison of the heating times shows that a reduction of the coupling distance by 50 % led to a reduction in heating time of up to 79 %. At a power of 10 % for example, the heating time was reduced from 120 s to 25 s. This is due to the fact that the field intensity drops with increasing distance to the coil which is qualitatively described by the aforementioned Biot-Savart law. Moreover, it can be observed that a reduction of the coupling distance leads to a higher difference in temperature between the measuring points. This is on the one hand due to the fact that there is no time for temperature equilibration and on the other hand caused by the distribution of the EM filed intensity. According to the Biot-Savart law, the EM field intensity is inversely proportional to the cube of the coupling distance.

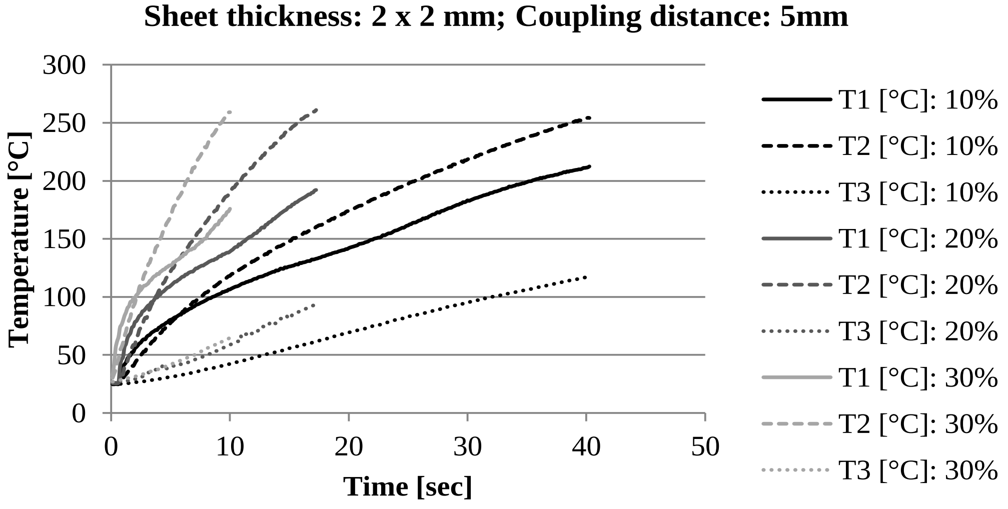

Figure 5: Static heating results for two laminates with a thickness of 2 mm and a coupling distance of 5 mm (no surface cooling by air)

That means that for small coupling distances the field intensity is much higher on the top of the laminate than in the welding zone. At higher coupling distances, however, this difference is considerably less pronounced. That leads to a more equal temperature distribution in thickness direction.

In addition, two laminates with a thickness of 2 mm were heated with a coupling distance of 5 mm. The heating curves are plotted in Figure 5. In this case, the temperature on the top laminate is overtaken by the temperature in the welding zone. One possible reason could be that the convective cooling of the surface by the surrounding air has less influence on the temperature between the laminates when the thickness of the laminates rises.

4.2 Continuous case

As a next step, continuous induction welding experiments were carried out. Compared to the static case the setup was slightly modified, as is detailed in Figure 6.

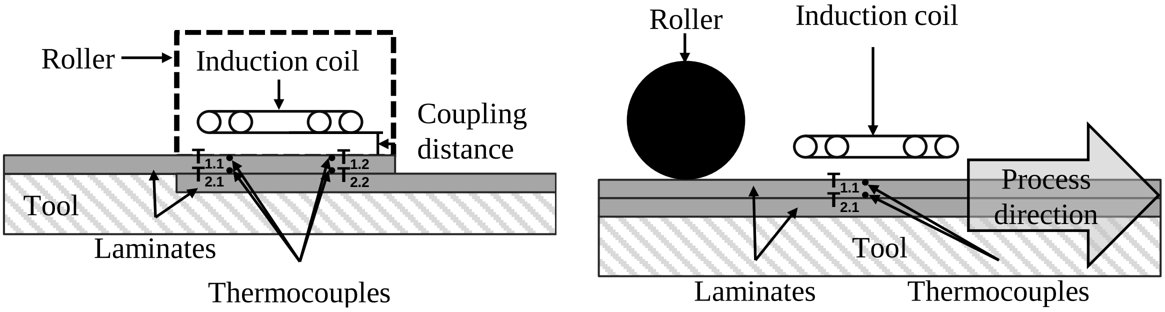

Figure 6: Continuous heating experiment: cross section (left) and side view (right)

The two laminates were arranged in an overlap position and four thermocouples were attached to each surface. The coil then moved along the overlap followed by the roller while temperatures were recorded. For the aforementioned reason, the maximum temperature was again restricted to approx. 250 °C. The welding speed was 8.4 mm/s and the coupling distance was set to 5 mm. In Figure 7, the heating curves for a generator power of 30 % are presented.

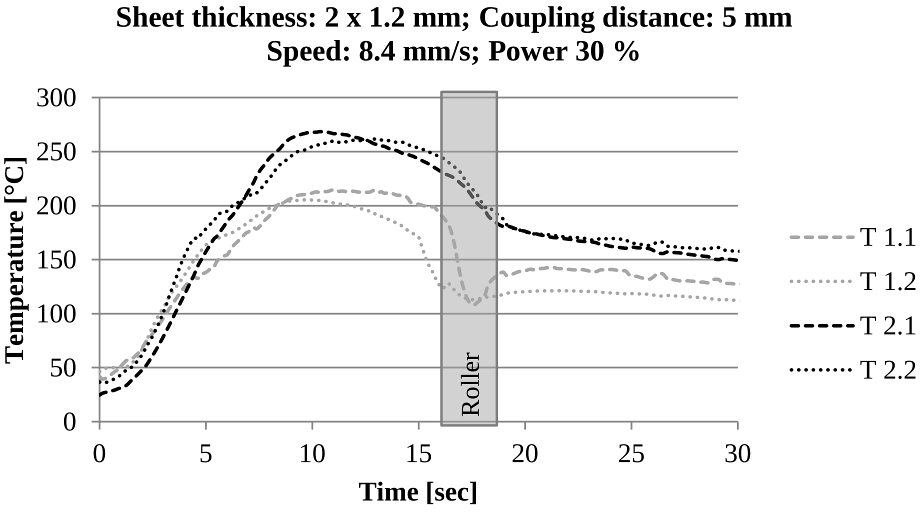

Figure 7: Continuous welding of two laminates with a thickness of 1.2 mm, a coupling distance of 5 mm, a speed of 8.4 mm/s, and a power of 30 % (no surface cooling by air)

It was found that during continuous heating, the top surface was approximately 50 K colder than the surface between the two laminates. This temperature distribution indicates that the findings from static experiments cannot be fully transferred to continuous welding. The temperature curves also show the influence of the roller on the temperature of the laminates. The temperature of the top surface dropped significantly as the roller passed by. This is important to prevent deconsolidation, since the temperature in the laminate must stay below its melting temperature after the passing of the roller. With increasing speed, this drop becomes less pronounced until the temperature remains too high to ensure a good weld quality.

The experiment was repeated while the surface cooling unit was used, results are given in Figure 8. The power was increased to 40% in order to reach 250 °C. Due to the cooling, the temperature on the top surface remained nearly constant at around 120 °C to 130 °C and the difference between the top and the welding zone could be doubled to approximately 100 K. Therefore, thermal damage on the top surface and a complete deconsolidation of the laminate can be prevented.

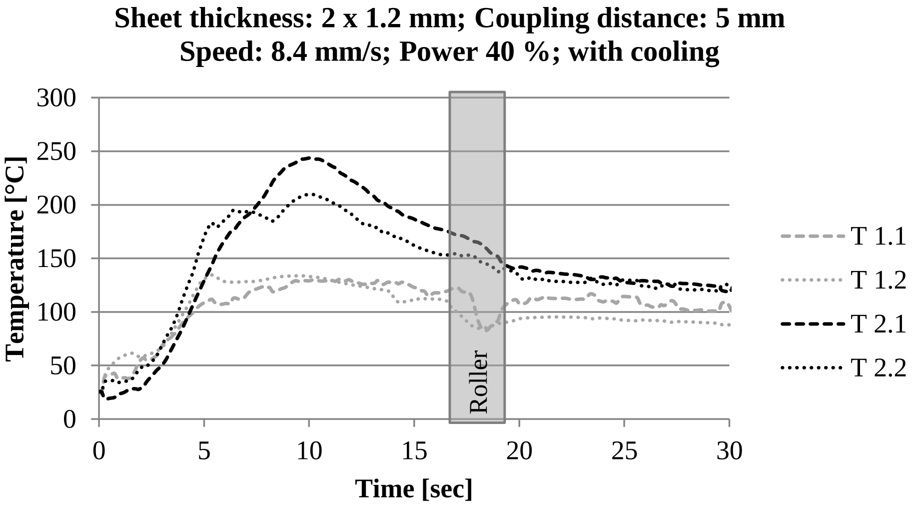

Figure 8: Continuous heating of two laminates with a thickness of 1 mm, a coupling distance of 5 mm, a speed of 8.4 mm/s, a power of 40 %, and surface cooling

5 Conclusion

In previous works on continuous induction welding, static single plate heating experiments were used to analyze and predict the temperature distribution during welding. These experiments showed that the top surface of the upper laminate heats stronger than the welding zone. The paper at hand investigates the static and continuous heating of two plate arrangements. It could be shown, that the previous assumption is true only for relatively thin laminates (1.2 mm), but not for thicker laminates (2 mm) and neither for continuous heating. In the latter cases, the welding zone is hotter than the top surface. A possible explanation for this observation is that the natural convective cooling of the surface by the surrounding air has less influence on the temperature between the laminates when the thickness of the laminates rises. Another approach is described by Wentworth [10] and focuses on the applicability of the skin effect. While equation (1) assumes the conductor to be an infinite slab of material it has a finite geometry in reality. Most of the EM field is reflected when it reaches a conductor-air interface, e.g. the back of the conductor [10]. The reflected EM field changes the current density in the conductor, thus changing the penetration depth. For conductor thicknesses exceeding 5δ the skin depth equation (1) is accurate. However, other approximations and methods should be used for thinner conductors [10]. During induction heating of carbon fiber reinforced laminates the penetration depth is usually higher than the laminate thickness.

Taken together, these findings implicate that the temperature distribution must be studied by welding trials and cannot be derived from single plate heating experiments. The present findings constitute an initial step toward an improved induction welding process.

REFERENCES

[1] P. Mitschang; R. Rudolf; M. Neitzel "Continuous Induction Welding Process, Modelling and Realisation. *Journal of Thermoplastic Composite Materials, Vol.* 15 2, pp 127–153, 2002.
[2] S. Yarlagadda; B. K. Fink; J. W. Gillespie "Resistive Susceptor Design for Uniform Heating during Induction Bonding of Composites. *Journal of Thermoplastic Composite Materials, Vol.* 11 4, pp 321–337, 1998.
[3] J. Border; R. Salas "Induction Heated Joining of Thermoplastic Composites Without Metal Susceptors". *Tomorrow's materials: Today,* Reno, pp 2569–2578. 1989.
[4] A. K. Miller; C. Chang; A. G. M. Payne; E. Menzel; A. Peled "The nature of induction heating in graphite-fiber, polymer-matrix composite materials. *Sampe Journal, Vol.* 26 4, pp 37–54, 1990.
[5] P. Berlin; O. Dickman; F. Larsson "Effects of heat radiation on carbon/PEEK, carbon/epoxy and glass/epoxy composites. *Composites, Vol.* 23 4, pp 235–243, 1992.
[6] V. Rudnev; D. Loveless; R. Cook; M. Black "*Handbook of induction heating,* ASM International, 2003.
[7] M. Marinescu: „*Elektrische und magnetische Felder“*. Springer, 2012.
[8] L. Moser "*Experimental Analysis and Modeling of Susceptorless Induction Welding of High Performance Thermoplastic Polymer Composites,* Institut für Verbundwerkstoffe,
[9] P. Mitschang; M. Hümbert; L. Moser "Susceptorless continuous induction welding of carbon fiber reinforced thermoplastics". *19th International Conference on Composite Materials,* Montreal. 2013.
[10] S. M. Wentworth; M. E. Baginski; D. L. Faircloth; S. M. Rao; L. S. Riggs "Calculating Effective Skin Depth for Thin Conductive Sheets". *Antennas and Propagation Society International Symposium 2006, IEEE,* pp 4845–4848. 2006.