EFFECT OF MESH CONFIGURATION ON THE INDUCTION WELDING PROCESS OF THERMOPLASTIC COMPOSITES

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Abstract

Induction welding is a fusion-bonding technique that has gain interest for joining thermoplastics composites (TPCs). For non conductive materials, as glass fiber TPCs, alternating current is used to magnetically excite an implant placed at the joint interface of the two parts to be welded. In this work three types of metal meshes have been analysed under the effect of two induction coils with the aim of selecting the most promising for welding.

1. Introduction

Composite parts are replacing more and more parts, traditionally made from aluminium in aerospace industry [1, 2]. Compared with thermosetting composites (TSCs), thermoplastic composites (TPCs) are more environmentally friendly for both manufacturing and recycling processes [3]. However, due to the limited deformation of reinforced fibers, production of large complex parts becomes problematic. Therefore, bonding becomes an inevitable step in the production process of TPCs structures. For this kind of structures, welding technique demonstrates to be a very suitable bonding technique. Fusion bonding has several advantages over well-known bonding techniques, such as adhesive bonding and mechanical fastening, like reduced curing cycle, less surface preparation and the absence of stress concentrations [4].

Induction welding is a fusion-bonding technique that is quite promising for thermoplastics. Some works focused on carbon fiber TPCs arose that demonstrated the induction heating without any additional material in the joint [5]. But for non conductive materials, as glass fiber TPCs, alternating current is used to magnetically excite an implant placed at the joint interface of the two parts to be welded. This implant, or susceptor, is a magnetically susceptible and electrical conductive material, which undergo heating when subjected to high frequency electromagnetic fields [6]. Heat conduction causes the surrounding thermoplastic matrix and the joint surfaces to heat up and melt. Pressure then can be applied to the joint during or after the heating process, this aids wetting of the molten thermoplastics, and a weld forms as the joint cools (Figure 1). The heating element or induction susceptor is an important parameter, not yet elaborately investigated, that highly affects the strength of a bond. Basically two types can be used: powder and metal meshes.

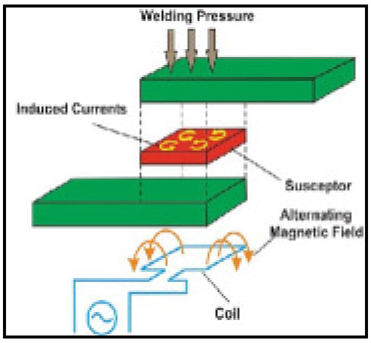


Figure 1. Induction welding process [6]

The studies focused on the use of metallic powder inter-dispersed in thermoplastic resin showed that the frequency needed to heat the weld with such inserts is up to one order of magnitude higher than metal mesh inserts and the more costly vacuum tube power source are needed [7]. Additional disadvantages of powders based inserts is the development of the particles dispersion in the polymer, which besides have to be the same that the TPCs matrix. Steel meshes avoid these drawbacks and have shown one of the best results regarding the induction heat generation. The prerequisites are that they are susceptible to the effects of an electromagnetic field, have enough electrical resistance to produce heat and form a conductive closed-loop network. The current in the induction power source, and in consequence the heating effect, is influenced not only by the workpiece itself (susceptor) but also by the geometry of the inductor (coil). Heat energy, E, is mainly produced according to Joule's law, $E = I^2Rt$ where I is the current, R is the resistance and t is the time of exposure to the magnetic field. In this work three metal meshes and two coil geometries have been analyzed.

2. Materials and experimental procedure

Three metal meshes have been studied in this work based in different material; galvanized steel and stainless steel, with different mesh dimensions; wire diameter, width and thickness (Figure 2). The mesh material and main definition parameters are summarized in Table 1.

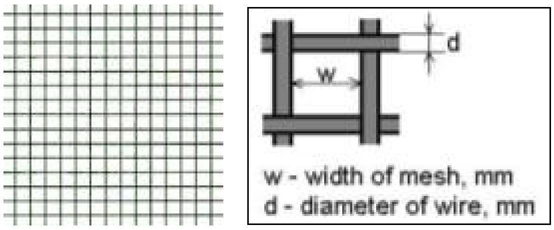


Figure 2. Example of metal mesh and definition of two parameters of the meshes (width and diameter of wire)

Reference	Mesh material	Wire diameter (mm)	Width of mesh (mm)	Thickness (mm)
Mesh 1	Galvanized steel	0.300	1.440	0.400mm
Mesh 2	Stainless steel AISI 304L (M24)	0.200	0.858	0.400mm
Mesh 3	Stainless steel AISI 304L (M200)	0.040	0.090	0.080mm

Table 1. Description of the meshes.

Two induction coil geometries have been used, as shows Figure 3. Coil 1 is a solenoid type with 3 spires, 43mm diameter, and coil 2 is a hair pin type with a 53x25mm concentrator. Both are hollow water-cooler copper tube and the concentrator is also made with copper. The induction machine was an Ambrell – EasyHeat model, working with alternating current maximum value of frequency 500 kHz. The variable parameter applied on the induction trials has been the induction power, controlled by the intensity of the current, between 30-240A. The heating distribution on the meshes has been measured by IR camera (Cedip IR Systems, Titanium) and the achieved temperature versus time has been registered using thermocouples positioned in different points of the meshes. The thermocouples have been covered with kapton adhesive tape to insulate them, avoiding metal-metal contact.

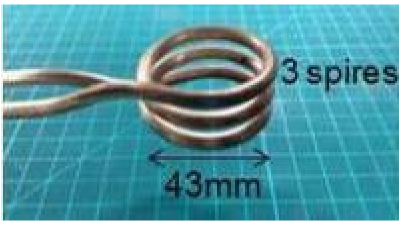
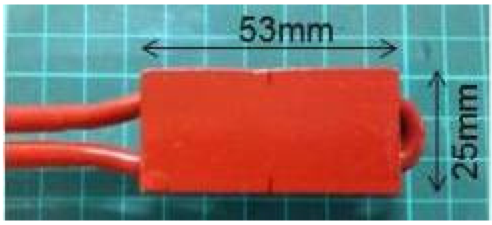
<table>
<tr><th>COIL 1</th><th>COIL 2</th></tr>
<tr><td>
</td><td>
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Figure 3. Coils used in the study.

Two mesh dimensions were employed to study the induction behavior with different amount of metal as well as to study the edge effect. The sizes were: 90x90mm ("large mesh") and 25x13mm ("small mesh"), which is the dimension of the overlap in a single lap specimen for shear tests in the future welding experiments. To avoid gaps of air effects and with the aim of having a uniform heating, a vacuum bag was employed during the induction experiments (Figure 4). The distance between the coil and the meshes was fixed to 5mm.

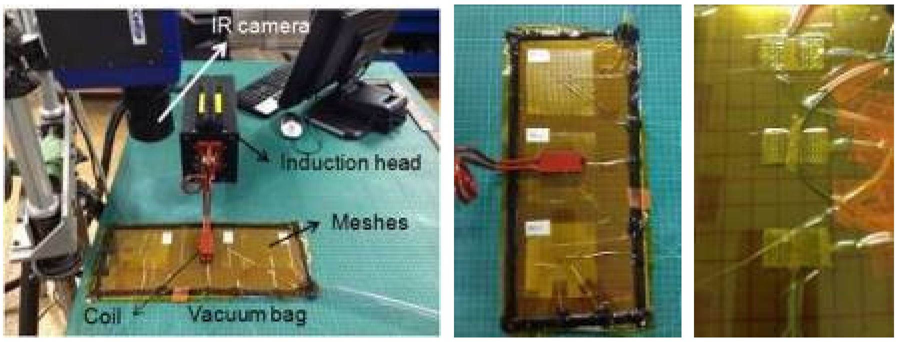

Figure 4. Left: Set-up of the induction trials. **Center:** Large meshes. **Right:** Small meshes.

3. Results and discussion

Temperature *vs* time curves were obtained from thermocouple measurements at different locations in the meshes. Moreover, IR-camera images were used to study the heat distribution in the meshes. The trials were carried out applying induction heating, at different intensities, during a period of time. Once induction heating is applied, the temperature increases, and after stopping the current, the temperature decreases.

3.2. Thermocouple results

The positions of the thermocouples where the temperature has been registered in the large meshes are shown in Figure 5. Gray area represents the mesh that is below the 2 coils, and the numbers represent the positions where the thermocouples were located.

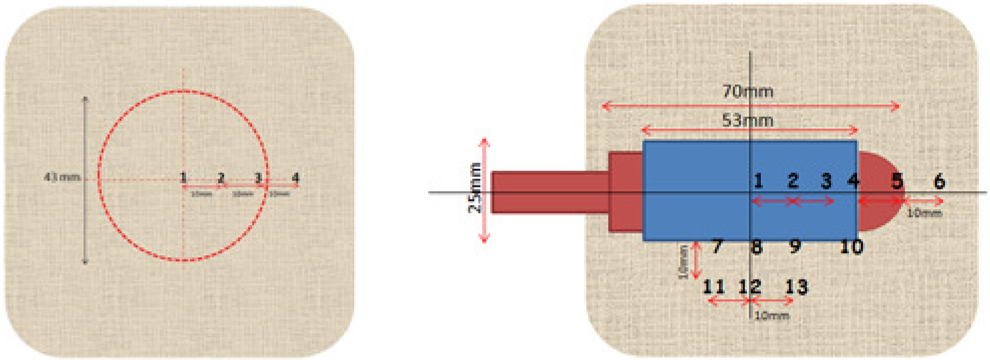

Figure 5. Positions of thermocouples in large meshes. Left: coil 1. Right: coil 2.

The thermocouples curves show how the temperature increases while the induction intensity is working and afterwards it immediately drops when the induction is stopped.

As Figure 6 shows (curves for coil 2, mesh 1, 30A) the achieved temperature is non-uniform and very dependent on the position. The higher temperature values are in the positions below the coil concentrator (P1-P4 and P7-P9) while in positions that are away from the coil (P5-P6 and P10-P13) registered very low heating rates

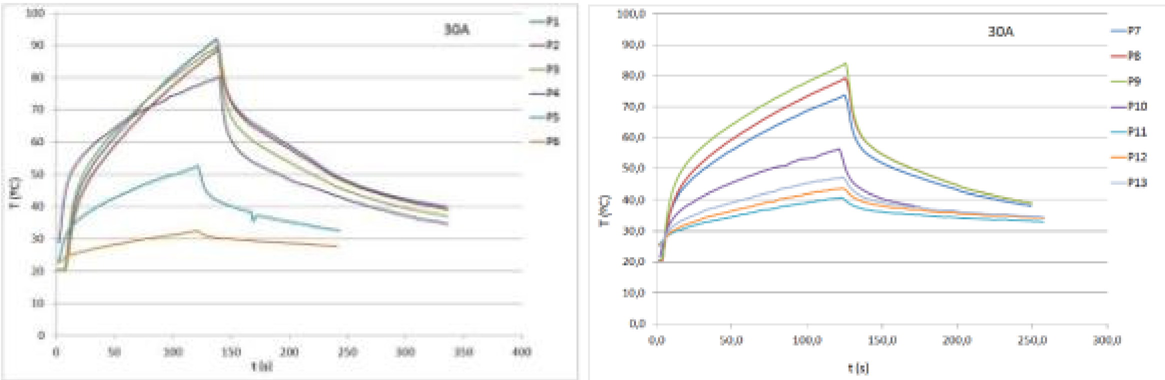

Figure 6. Temperature *vs* time curves for coil 2, mesh 1, 30A.

Similar heat distributions were obtained for the thermocouples positioned on mesh 2 and 3, and with different induction power, even though the maximum temperatures were different. As Figure 7 – left shows, where the maximum temperature values are represented for 30-60-80A in the three large meshes, the higher the power, the higher the temperature reached. Clear differences have been found in the maximum temperature in the following sequence: T_{Mesh1} > T_{Mesh2} > T_{Mesh3}.

Comparing large and small meshes, it has been found that large meshes achieved much higher temperature than the small ones, as shown in Figure 7. For example, at 60A, mesh 1 achieved 275 ºC in the large mesh and 200 ºC the small one.

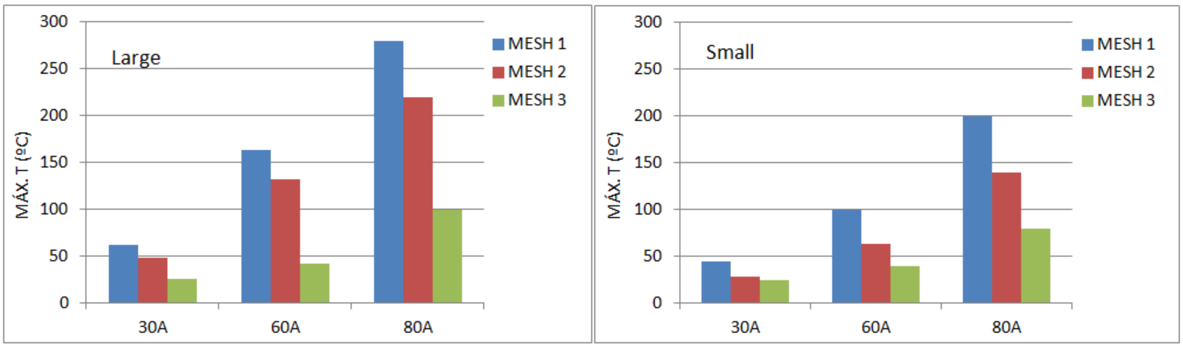

Figure 7. Thermocouples measurements (Coil 2) Left: large meshes. Right: small meshes.

The heating patterns when coil 1 is applied over large mesh are shown in Figure 8. Position P3 achieved the highest temperature while in the center of the coil (P1), the lowest temperature was found. Similar results were obtained in mesh 2 and 3.

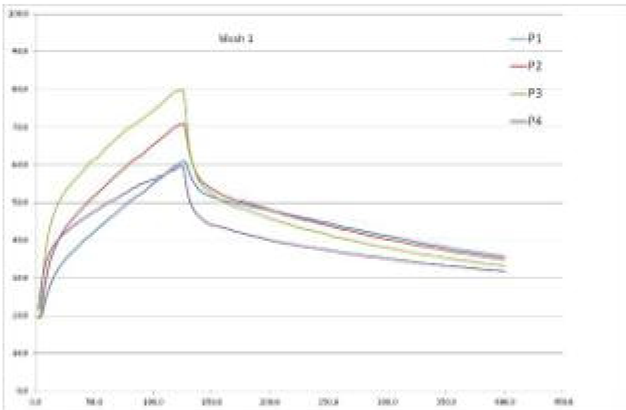

Figure 8. Temperature vs time curves for coil 1, mesh 1, 30A.

3.1. IR-camera results

The IR images were obtained after 30s of heating and removing the coils to observe the heating distribution below them. Temperature distributions are depicted in Figure 9 (large meshes) and Figure 10 (small meshes). The eddy currents induced in the large meshes are mirror images of the coils. Coil 1 form a circle but with low power, 30A, is not completed, and with higher power, 60-80A the circle can be seen in mesh 2 and 3. Mesh 1 has the less uniform heat distribution. All of them present a cool region in the center. This hole is the consequence of the magnetic field around the spires of the coil reacting with the metal mesh, in the center of the coil magnetic field does not occur. In the coil 2 the heating pattern is a quasi-rectangular image. The induction concentrator of the coil acts to focus the magnetic field in the meshes. A better distribution occurs with high power (60A) than with low power being the best result with mesh 2. In the case of small meshes, heating with coil 1 is very poor in mesh 2 and 3, and very high power (200-240A) is needed to see just an incipient heating. In mesh 1 heating is faster. With coil 2 the heating is much better than with coil 1, and again with mesh 1 is more uniform. In both coils with small meshes 2 and 3, there is a hole in the center, due to the edge effect of the magnetic field.

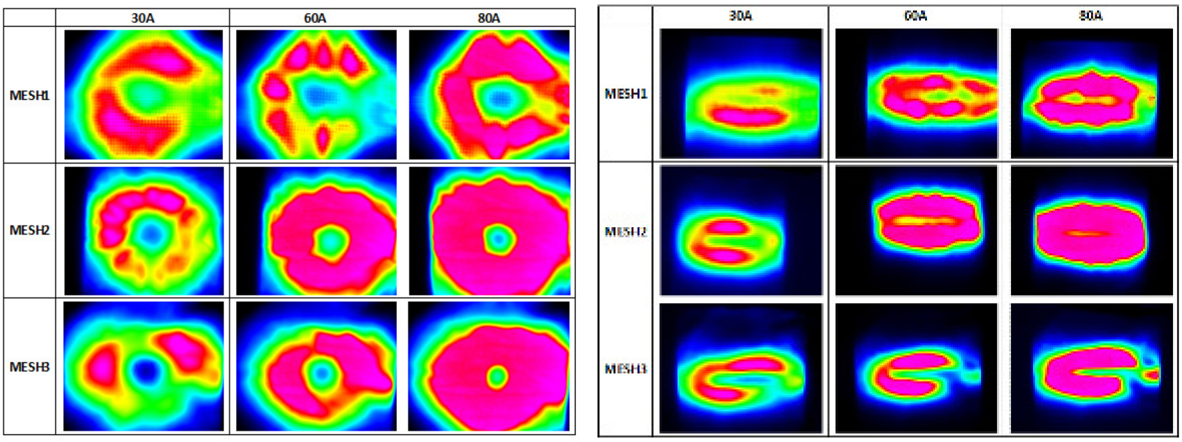

Figure 9. IR-camera images obtained during induction heating in large meshes. Left: Coil 1. Right: coil 2.

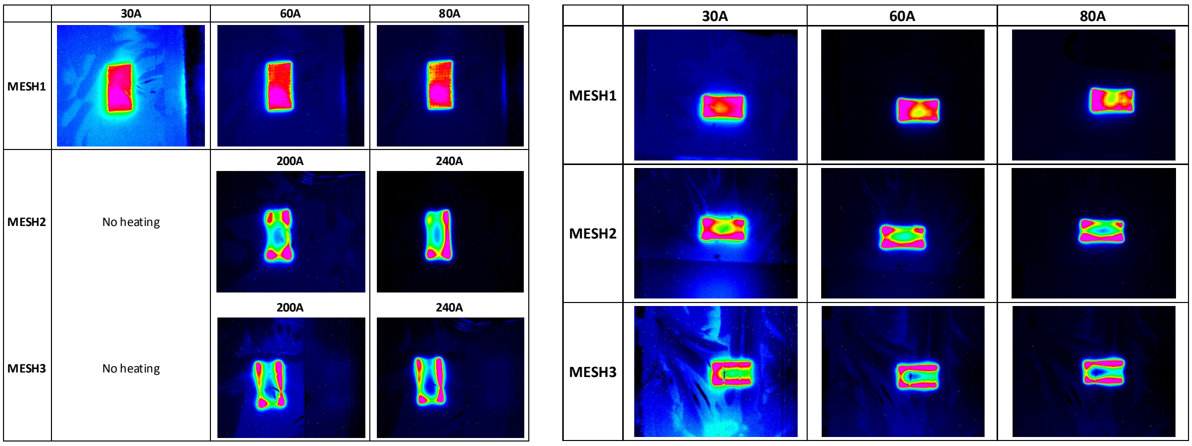

Figure 10. IR-camera images obtained during induction heating in small meshes. Left: Coil 1. Right: coil 2.

Regarding the maximum temperatures obtained from the IR-images (Figure 11) the following conclusions can be extracted: Coil 1: in the large meshes, with intensity higher than 30A, the maximum temperature is the same in mesh 1, 2 and 3. But it doesn't heat the small mesh 2 and 3, and even with 240A the heating is negligible. Coil 2: in the large meshes, result is similar to coil 1, but in small meshes the achieved temperature is higher than in coil 1. So, the coil geometry has a great influence on the heat generated within the workpiece. It means that for the welding trials, with an overlap of 25x12.5mm, the coil 2 would be more effective for heating. The sequence of the temperatures achieved in the small meshes: $T_{Mesh1} > T_{Mesh2} > T_{Mesh3}$ is in agreement with the thermocouple measurements.

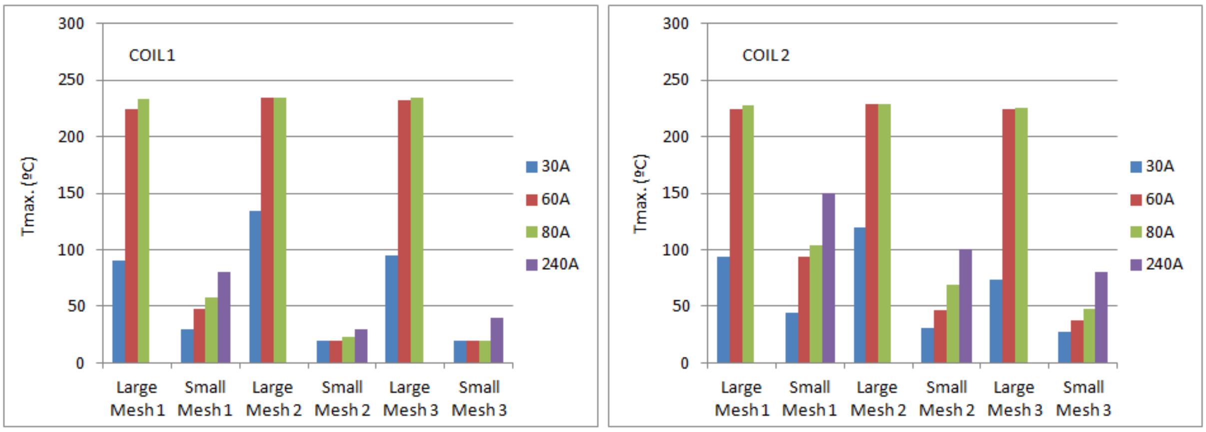

Figure 11. IR-camera max. temperatures

The rate of induction heating is dependent on the frequency and intensity, which for each trial have been kept constant, and the thermal conductivity and electrical resistance of the material [8]. Table 2 shows these values for the two metals used in this work.

Material	Thermal conductivity (W/mK)	Electric resintance (µOhm/cm)
Galvanized steel	47-58	20
Stainless steel AISI 304L	16	70-74

Table 2. Properties of meshes materials.

The higher electric resistance of the stainless steel explains the better heat distribution in the large meshes for mesh 2 and mesh 3, so the magnetic field is higher in these cases due to the higher eddy currents. But with small meshes, the edge effect in both mesh 2 and 3 is very pronounced and the thermal conductivity is the dominant effect. Since the galvanized steel has higher thermal conductivity, in small meshes, mesh 1 presents better heating distribution. The lower temperature achieved by mesh 3 compared with mesh 2, being made out of the same material, can be explained on the basis of the skin depth is lower than the diameter of the wire and therefore the very thin wire are not able to generate as much current as the thicker ones.

4. Conclusions

Three different metal meshes have been analyzed under two different induction coils with the aim of understanding the heating behavior in the welding process using metal meshes as susceptors. The IR images showed that the better heating distribution occurs in mesh 2 and 3 (stainless steel) when there is a large mesh, but with small meshes, number 1 (galvanized steel) has a better behavior. Thermocouples show that higher temperatures are achieved in mesh 1. The use of metal meshes as a magnetic susceptor has a few advantages over using the fibres themselves. Firstly, heat can be provided exactly where needed and thermal stress build-up is prevented in other areas of the workpiece and assembly. Moreover, non-conductive fibres, such as glass or aramid, are not excluded and can also be welded.

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