Modelling ultrasonic debulking of tape lamination

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ABSTRACT

A numerical model is presented, which has been developed to study the quality of the ultrasonic debulking of a composite laminate. The quality of the debulking level will depend, primarily, of the temperature raised in the laminate. For that reason, the evolution in time of the temperature inside the composite laminate has been studied. To this end, a thermal model has been developed which leads to the determination of the temperature inside the laminate from the values of the temperature at the tip of the ultrasonic horn. To validate the model, the numerical results have been compared with experimental measurements in a particular case.

1. INTRODUCTION

The aim of the out-of-autoclave manufacturing technique in which the present study is focused is to obtain composite laminates of high performance. To this end, an automatic tape lamination head is employed that places the layers over a working table. The head is equipped with two compaction rollers with adjustable pressure and temperature and a ultrasonic compaction device (sonotrode) located between them, which has the function of continuously debulking the tape after it is placed. The main advantage of this system is that it eliminates the need for vacuum-bag debulking the laminate every certain number of plies. Instead, the layers are being compacted as they are placed. This means an enormous saving in time in the manufacturing process. It also permits the coupling with an out-of-autoclave curing system which may activate the polymerization of the resin in the tape, layer by layer, after it is placed and compacted.

The quality of the laminate is highly dependent on the debulking of the plies. The air entrapped between plies has to be properly removed and this will occur under sufficient applied pressure if the resin is fluid enough, that is, if the temperature in the laminate is raised to a certain level during a certain period of time.

The objective of the model presented in this paper is to analyze the heat flux and the temperatures reached in the composite laminate using as an input the temperature measured in the ultrasonic horn during the debulking process.

The use of this model will reduce the need of controlling the temperature in the laminate placing thermocouples in it. To validate the results obtained with the numerical model, a comparison is made with the experimental measurements of the temperature in the bottom of the laminate (obtained with a thermocouple) when the ultrasonic horn is maintained in the same position for 12 seconds. Note that it can not be a priori assured that the comparison yields good results, since the experiment is made on fresh material while the properties employed in the model have been measured on cured material.

The compaction equipment is shown in Fig. 1. This equipment consists of the ultrasound compactor with a titanium tip (sonotrode) that has the function of vibrating over the material to be compacted. The composite layers are placed with an automatic lay-up system (ATL). Below the laminate can be found, in the following order: a layer of peel-ply to fix the first ply to the tool surface, a polyamide film to demould the panels and an aluminium plate to give the panels their flat shape.

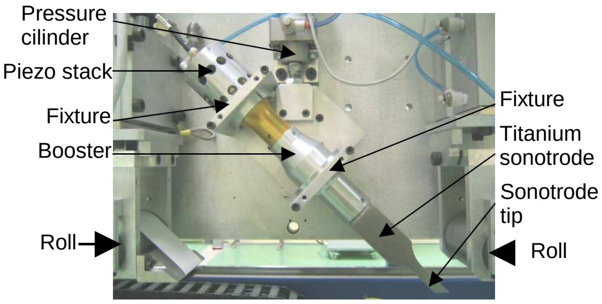

Fig. 1. Ultrasonic compactor.

2. FINITE ELEMENT MODEL

The components that have been considered in the model are the titanium tip of the sonotrode and the composite laminate to be compacted, see Fig. 2(a). The temperature measurements have been made at the node showed on Fig. 2(b), located at the bottom surface of the laminate under the sonotrode, since it is in this position where the thermocouple has been placed during the experiments. A conforming mesh has been employed in order to obtain smooth transitions in the heat transfer between the solids.

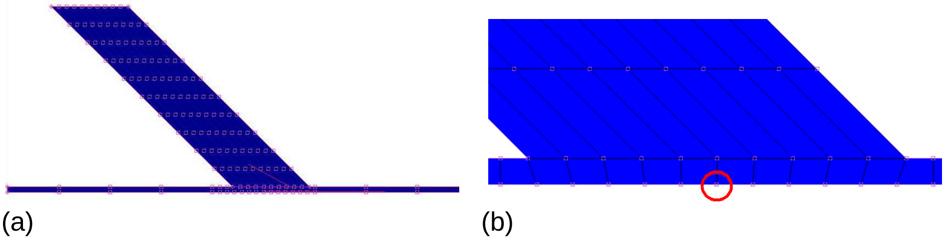

Fig. 2. (a) FEM model of the sonotrode and the laminate. (b) Measuring node.

It is assumed that the only heat exchanges that will affect the problem are: conduction between the sonotrode and the laminate, convection between the sonotrode and the environment and convection between the laminate and the environment. The properties of the materials are shown in the Table 1.

Material	$\rho\ [kg\, m^{-3}]$	$c_P\ [J\, kg^{-1}\, K^{-1}]$	$k\ [W\, m^{-1}\, K^{-1}]$
Titanium	4430	580	7,1
Composite laminate	1570	1180	0,6 (transverse) 1 (longitudinal)

Table 1. Material properties.

The problem is formulated in two steps. In the first step ($0 < t \le 12\, s$) both bodies are in contact, initially at 25 ºC, and the temperature of the sonotrode increases, transferring heat to both bodies. The temperature rise in this stage is shown in Fig. 3(a); it has a high slope at the beginning and a lower slope afterwards, since it is supposed that the heating rate will decrease as the maximum temperature is being reached. It must be noted that in actual fact it is the sonotrode tip that heats up as a consequence of friction and heat generated within the composite when subjected to the ultrasonic vibration. In the second step ($t > 12\, s$) the sonotrode is removed instantaneously, allowing the laminate to cool freely, driving the stored heat away through the laminate itself (to the sides) and to the air by convection.

3. RESULTS

Temperature measured in the model at the node shown in Fig. 2(b), that coincides with the point where the temperature have been measured in the experiments, is shown in Fig. 3(b) as a function of time.

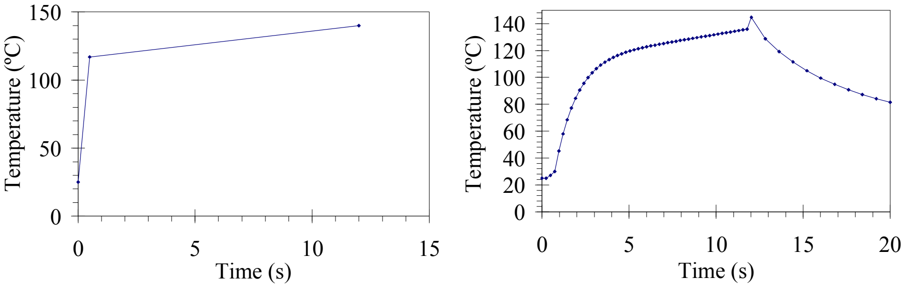

Fig. 3. (a) Imposed temperature on the sonotrode tip. (b) Numerical solution of the temperature at the monitored node.

As expected, a rapid initial increase of the temperature is obtained (in about 2 seconds). After that, once a 120 ºC temperature is reached, the temperature gradient becomes slower. Finally, the free cooling of the laminate is obtained. The 140 ºC peak appears immediately after the moment when the sonotrode is lifted.

The temperature distributions inside the laminate at the beginning of the heating and just after the cooling are respectively shown in Fig. 4(a) and (b). As can be observed, before lifting the sonotrode, the temperature raised in the laminate is uniform through the thickness (in a range of 133±5 ºC).

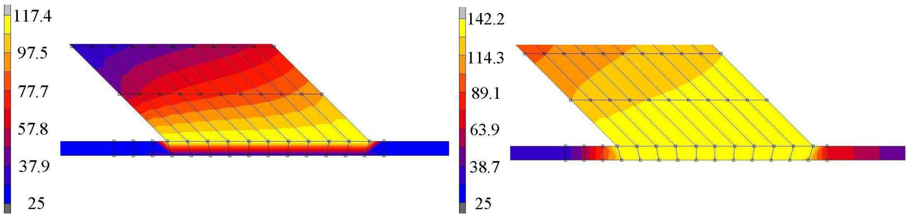

Fig. 4. Evolution of the temperature into the sonotrode and the lay-up (a) At the beginning of the process (b) Before cooling.

Taking the experimental results shown in Seebacher 2008 and superimposing this curve to the numerical results obtained in the thermal model described above, Fig.5 is obtained, where a reasonable agreement between the numerical and experimental data can be observed. As can be seen, the heating peak after the lifting of the sonotrode is not a distortion of the sensor, as was thought at the beginning. This peak appears as a consequence of the heat that was being evacuated through the titanium tip, which, in the absence of it, is concentrated in the laminate.

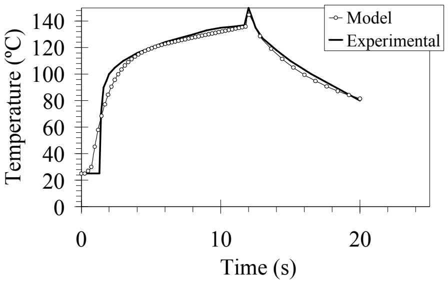

Fig. 5. Comparison with experiments.

4. CONCLUSIONS

A numerical model has been developed to determine*,* from the measured temperature of the ultrasonic sonotrode, the evolution of the temperature field inside the laminate. This model can be employed to determine the temperature reached in the laminate during the actual compaction process. It is expected that these measurements will be directly related to the quality of the compaction. Hence, the use of the present model avoids the need to install thermocouples in the panels (a more complex and expensive technique than monitoring the temperature of the sonotrode) to determine the temperature in-situ each time the manufacturing parameters are changed.

REFERENCES

SEEBACHER, S. (2008) Contributions to the investigation of in-situ ultrasonic tape lamination of composite thermoset prepregs. *Master Thesis.* Private Fachhochschule Göttingen, Germany.