# OUT OF AUTOCLAVE CURING OF THERMOSET MATERIALS

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## ABSTRACT

In the current paper, a study of the viability of the application of curing techniques based on microwaves and radiofrequency in an integrated out-of-autoclave tool is presented.
This integrated out-of-autoclave tool is provided with automated means for placing the prepreg tapes, compacting means for the composite material and a generator of the specific cure technology. With this out-of-autoclave tool, two different manufacturing processes are considered: 1) in which the cure process is performed ply-per-ply (immediately after the lay-up of each ply) or 2) in which the composite material is cured once all the material is placed on the lay-up table.
Both technologies, microwaves and radiofrequency, are considered for application in these two different manufacturing processes. A study of the feasibility of the integration of both techniques in the out-of-autoclave manufacturing process is presented.

## INTRODUCTION

Composite materials are increasingly more appealing for a wide variety of uses in the aeronautical industry due to its high stiffness and strength-weight ratio. The composite materials more widely used in the aeronautical industry are made up from carbon fibres and epoxy resins and presented in preimpregnated form.

The process for manufacturing structures from these materials generally requires compaction to obtain the desired fiber volume fraction and eliminate porosity and entrapped air from the composite and a curing process at elevated temperature to get the cross-linking of the resin. These structures have traditionally been manufactured by means of the application of pressure, vacuum and heat inside an autoclave where a controlled atmosphere is created. The main disadvantages of this process are:

- the high energy required by the autoclave to achieve and maintain the curing temperature
- the elevated time needed to manufacture the structure, including the lay-up of the composite material, debulking, cure cycle of the structure inside an autoclave (taking into account its thermal inertia) and the movement of the part from the lay-up area to the autoclave

Besides the cost of the process another disadvantage to be considered is that the size of the autoclave limits the size of structure to be manufactured.

Nowadays, new manufacturing processes are being developed in order to manufacture large structures and to decrease the cost and the time invested in the process.

This study is focused on assessing the viability of alternative curing technologies for out-of-autoclave processes applicable to the materials with high properties and qualified by the aeronautical industry.

## OUT-OF-AUTOCLAVE PROCESS

One of these new manufacturing processes to manufacture large structures and decrease the cost and the time invested in the process, under development at Airbus is an out-of-autoclave process in which the cure process will be performed during the lay-up of the composite material (partially curing each ply) or once all the material is laid-up but performing the cure cycle in the lay-up table without using an autoclave in order to decrease the time and the energy invested in the current manufacturing process (autoclave).

For this purpose a special tool is designed to combine lay-up, compaction, and cure technologies. This tool comprises a lay-up table (8) and a movable head (9) with relative motion between them. The movable head is provided with automated means for placing the tapes, compacting means for complete debulking of the composite material and a generator of the specific cure technology.

The manufacturing process can be performed in two different ways:

1) Cure ply per ply: where the manufacturing process consists of the following steps:
   a) Automated lay-up of the composite material in the form of tapes on the lay-up table, compacting it and partially curing it after its placement
   b) Repeating step a) until completing the lay-up of the part
   c) Curing the last ply of the material to the required extent of cure

2) Single step cure: where the manufacturing process comprises the following steps:
   a) Automated lay-up of the composite material in the form of tapes on the lay-up table and compacting until completing the lay-up of the part
   b) Curing the material to the required extent of cure

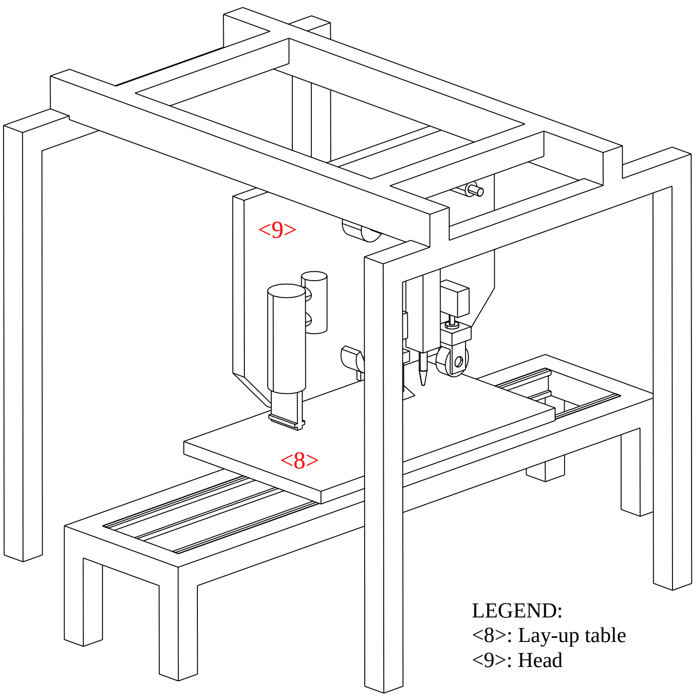
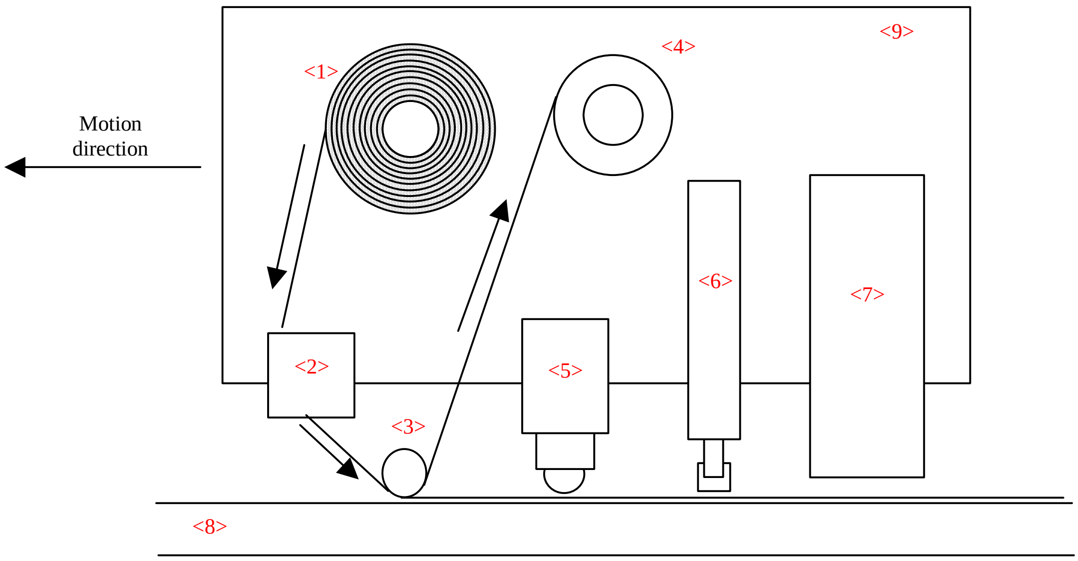



Figure 1.- Integrated out-of-autoclave tool




LEGEND:
<1> to <4>: Automatic tape lay-up
<5> to <6>: Compaction means
<7>: MW / RF emitter
<8>: Lay-up table
<9>: Head

Figure 2.- Movable head

In order to study the viability of the use of these techniques (microwave and radiofrequency) in the ply-per-ply cure process or in the single step cure process without using an autoclave it is necessary:

- to check if materials already used and qualified by the aeronautical industry can be cured by means of these technologies (microwave and radiofrequency), and
- to determine if the integration of the curing technique is feasible in the out-of-autoclave tool

## MICROWAVE AND RADIOFREQUENCY TECHNIQUES

Microwave and radiofrequency heating are processes within the scope of electroheating techniques, such as induction, direct resistance or infra-red heating, all of which utilise specific part of the electromagnetic spectrum.

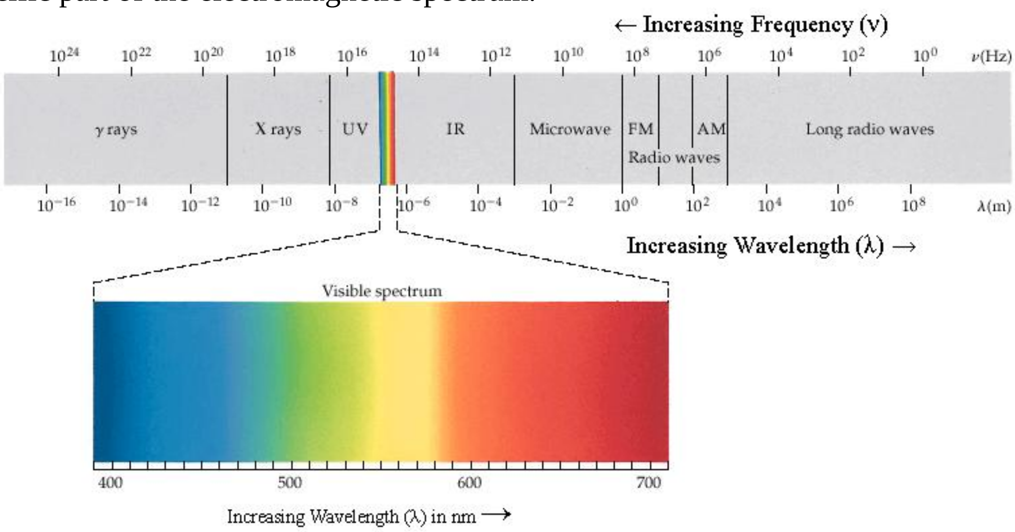



Figure 3.- Electromagnetic spectrum

The major advantages of using this type of technologies for industrial processing are rapid heat transfer, volumetric and selective heating, compactness of equipment and speed of switching on and off.

Preliminary investigations carried out for the monitoring of the extent of cure on prepreg samples subjected to specific power and time of microwaves (500W, 20 minutes to 50 minutes) and radiofrequency (100W to 200W, 10 minutes to 40 minutes) have conduced to similar degree of cross-linking for both processing techniques (30% to 50%).

These tests were performed using the laboratory-scale microwave installation and the radiofrequency emitter shown in figures 4 and 5.

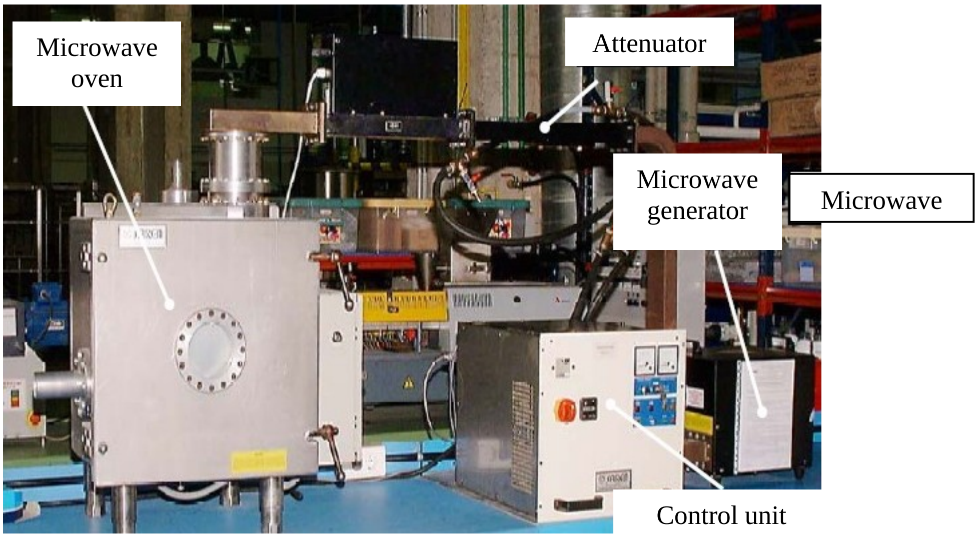



Figure 4.- Microwave oven used in the preliminary tests

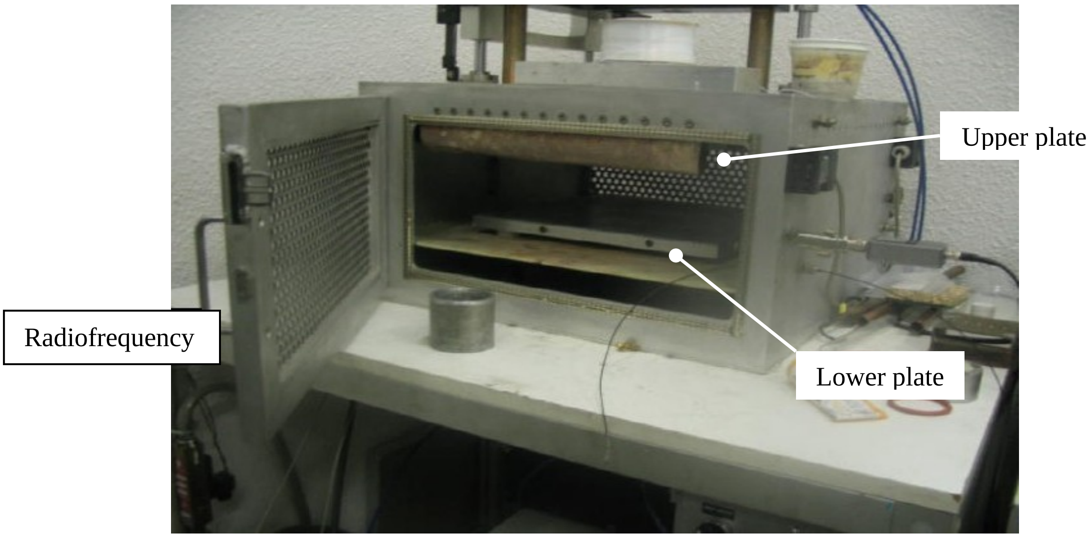



Figure 5.- Radiofrequency emitter used in the preliminary tests

Further investigations are still running in order to optimize the processing conditions for these techniques to reach extent of cure values above 90% - 95% (typical extent of cure value for the aeronautical materials).

## RADIOFREQUENCY CURING

The equipment of radiofrequency in essence consists of an electrical capacitor where the material to be cured is placed between its two parallel plates.

The electric field created between both plates of the capacitor depends on the distance between both plates, the gap between the upper plate and the material surface and the dielectric properties of the material to be polymerized.
The distance between the material and the upper plate must be minimized to avoid the existence of a thick air layer between them, which would influence the dielectric properties, but without contact between them as this contact could damage the surface of the composite material (partially cured or uncured).

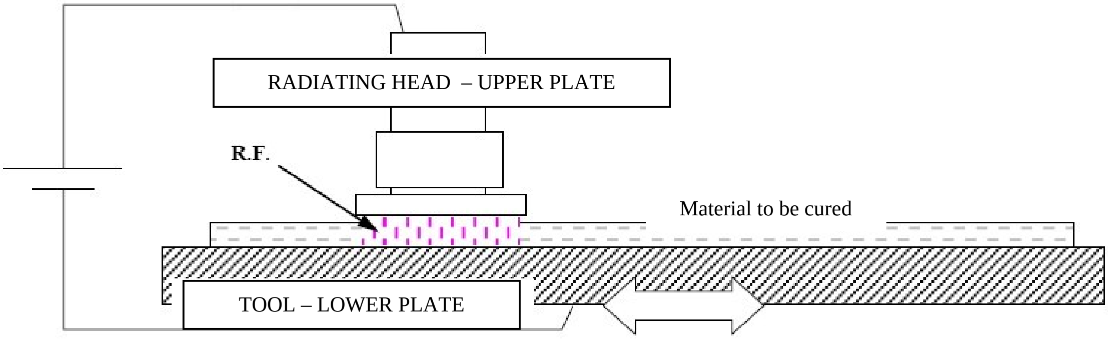



Figure 6.- Radiofrequency equipment scheme

As the material to be cured is part of the electric circuit, the process could be controlled by means of a closed loop. The dielectric material properties change while the material is being polymerized; as a change in the dielectric properties will produce a change in the electrical response, the process can be therefore monitored and controlled in real-time, by modifying the electrical field applied as needed.

Extreme changes on the dielectric properties of the material would allow a potential detection of defects; for instance, changes to high conductivity values could mean fibres not properly placed and changes in the dielectric properties to low conductivity values could be due to porosity. Monitoring the dielectric response within the material, possible defects could be detected if any unexpected deviation arises.

Both plates (upper and lower) must be metallic, so the lay-up table where the composite material is laid-up, can be used as one of the plates (lower plate). Therefore, as the material will be in contact with a metallic surface, a thermal insulation is advisable in order to minimize the thermal losses through the metallic tool.

As in the radiofrequency equipment the energy is confined between the two metallic plates, risk of leakages is minimized even if there is no material between the plates. This cure technique could be integrated in the out-of-autoclave without any protection, as no interferences with other equipments would be produced, unlike with microwaves.

One of the most important facts which influences the quality of the cure process is the homogeneity of the electrical field applied to the material. A uniform electric field can be created if the parallelism between both capacitor plates and between the upper plate and the material surface are kept during the cure process. Only flat panels or panels where the ply drop-offs are not very steep would be easily processed.

## MICROWAVE CURING

Microwave will be applied to the material by means of a microwave antenna. The emitted waves will be reflected, dispersed and absorbed depending on the material properties, the material geometry and the characteristics of the tool where the material is placed.

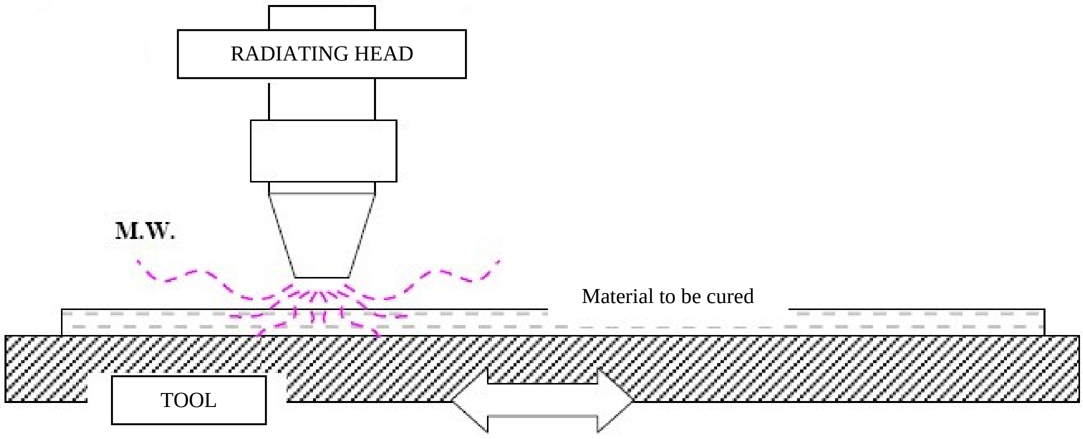



Figure 7.- Microwave equipment scheme

As microwaves are reflected by metals, the lay-up table (typically made of metal) shall be protected by a material transparent to microwaves, otherwise, the material placed near the metallic lay-up table would not be subjected to the radiation energy. The typical material used for this application is PTFE, which can be placed in film with enough thickness to achieve the total insulation (even thermal insulation) of the material with regards to the metallic lay-up tool.

The cure process of the composite material will be performed by means of the application of a certain power at a certain lay-up speed or during a certain period of time.

Contrary to radiofrequency, the process could not be inherently controlled by means of a close loop, therefore, the monitoring and the control of the process in real-time is not possible. The process should be calibrated to know the specific power and time needed for curing a certain composite material.

As the intended application of the curing technology is to be integrated in an out-of-autoclave tool, the risk of energy leakages and the homogeneity of the field are important aspects to be considered. As microwaves would be emitted by an antenna, the energy would not be confined, risks of leakage will be always present; therefore, other equipment placed near the microwave antenna should be insulated in order to avoid interferences. Furthermore as microwaves are emitted in a non-confined space the homogeneity of the field applied all over the material might not ensured.

## CONCLUSIONS

In light of the preliminary investigations carried out for the monitoring of the extent of cure it can be shown that both curing technologies (microwaves and radiofrequency) can be used for curing composite materials although further tests have to be performed in order to optimize the processing conditions (power, time, ply-per-ply or single step cure) to reach extent of cure values above 90% - 95% (typical extent of cure value required for the aeronautical materials).

Taking into account the characteristics of each curing techniques, the most promising curing technique, applicable to the out-of-autoclave process presented, is radiofrequency when compared with microwaves.

The application of microwaves to the out-of-autoclave tool should overcome some aspects of the technology as the risk of leakages, homogeneity of microwave field and the impossibility of controlling and monitoring the process in real time.

The main characteristics of radiofrequency as no risk of leakages, electric field confined and homogeneous, possibility of process monitoring and controlling in real time and potential detection of defects in the material, make radiofrequency a promising technique to be applied in the integrated out-of-autoclave tool presented.

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