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Autoclave cycle optimization for high performance composite parts manufacturing

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Abstract

In aeronautical production, autoclave curing of composite parts must be performed according to a specified diagram of temperature and pressure vs time. Part-tool assembly thermal inertia and shape have a large influence on the heating and cooling rate, and therefore on the dwell time within the target temperature range. When simultaneously curing diverse composite parts, the total autoclave cycle time is driven by the part-tool assembly with the lower heating and cooling rates. With the aim to minimize the autoclave cycle time and energy consumption improving the manufacturing system resource efficiency, a new parameter was defined to characterize the part-tool assembly thermal and geometric properties. This parameter was applied to determine the optimal positioning of the parts on the autoclave charge floor.

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Keywords: Autoclave curing; Composite parts; Optimization; Resource efficiency

1. Introduction

In the aeronautical industry, small numbers of different composite material parts need to be manufactured with high quality and performance requirements. Autoclave vacuum bag manufacturing technology, which entails applying carefully controlled levels of heat and pressure to parts and assemblies, is particularly suitable and largely employed for this purpose [1].

In autoclave vacuum bag manufacturing, the quality of advanced composite material parts strongly depends on the thermal and pressure cycles imposed to the composite material during the curing process [2,3].

Modeling and control of an autoclave cure cycle during the processing of thermoset matrix composites have always been challenging problems for manufacturers of high performance composite materials, particularly in the case of high thickness of the parts to be manufactured, as referred in Soo et al [4] and Martinez [5]. The curing of each part must be performed following a specified diagram of temperature and pressure vs time, which depends on the specific composite material.

Once the thermal and pressure cycles have been selected according to the composite material to be cured, the manufacturing setup must ensure that, during the process, cycle parameters such as part heating rate, cooling rate and dwell time at constant temperature are respected [6].

As a consequence, when simultaneously curing diverse composite parts having different thermal and/or geometric properties, the total autoclave cycle time is driven by the part with the lower heating and cooling rates. The resulting long curing times negatively affect the manufacturing system productivity and determine a very low energy efficiency.

In current aeronautical industry practice, planning of autoclave manufacturing processes is still carried out by grouping the composite parts to be cured together according to their polymerization specifications (i.e. parts having the same curing temperature), with very limited consideration for the shape, size and material of which the parts are made, and no consideration for the tools on which they are mounted.

In order to achieve higher resource efficiency and shorter

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cycle times, a new criterion for the effective aggregation of different parts to be cured simultaneously and for the selection of the optimal strategy for positioning the part-tool assemblies on the autoclave charge floor is proposed in this work.

For this purpose, a new parameter, S, which allows to characterize the geometry and thermal inertia of the part-tool assemblies, is defined. Based on the value of the S parameter for each part-tool assembly, it is possible to group all the assemblies according to their thermal behavior in order to simultaneously process in the autoclave harmonized groups with similar parameter values. Moreover, the value of the S parameter can be used to select the optimal positioning of the parts on the autoclave charge floor.

2. Thermal behavior during autoclave curing of diverse composite material parts

Autoclave curing of composite material parts must be performed according to a specified diagram of temperature and pressure vs time, which depends on the specific composite material. In general, most aeronautical epoxy-based prepreg systems require curing temperatures around 121 °C or 180 °C, and the application of adequate pressure assisting the consolidation, eliminating the excess resin and helping suppress voids in the laminates. Fig. 1 shows the autoclave curing cycle for an epoxy resin based prepreg.

For a successful curing process, the manufacturing setup must ensure that the following cycle parameters are controlled during the process [6]: heating rate and cooling rate, to be kept lower than critical values, and dwell time within the curing temperature range (e.g. 179.4 ± 5.6 °C in Fig. 1), that should be at least equal to the recommended duration.

When simultaneously curing diverse composite parts having different thermal and/or geometric properties, in order to satisfy the process requirements for all parts, the total autoclave cycle time must be fixed on the basis of the behavior of the part-tool assembly with the lower heating and cooling rates.

In fact, the curing process is properly performed only if each composite part-tool assembly remains at the curing temperature for the defined time required by the part prepreg resin. Therefore, the cooling phase, carried out by the autoclave forced cooling system, may only start when the last part in order of time has spent the required dwell time at curing temperature. This generates long curing times which negatively affect the system productivity and determine a very low efficiency in terms of energy consumption and resource utilization.

In order to observe the thermal behavior of diverse composite material parts during simultaneous autoclave curing, monitoring of the thermal profiles of the diverse part-tool assemblies during an industrial autoclave curing process is performed by measuring the in-process temperature with thermocouples inserted within the material to be cured.

Fig. 2 shows the thermal profiles of part-tool assemblies and autoclave during an industrial curing cycle: each assembly reaches the minimum value of the curing temperature range at a time different from those of the other assemblies and of the autoclave ambient.

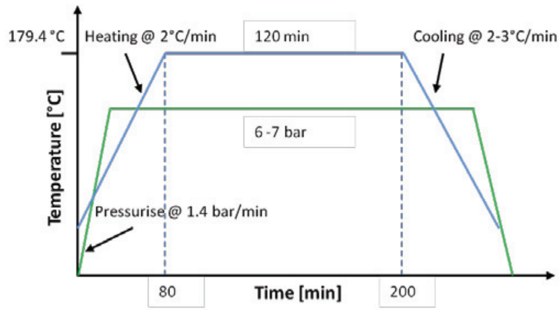

Fig. 1. Temperature/pressure vs time for an epoxy resin based prepreg.

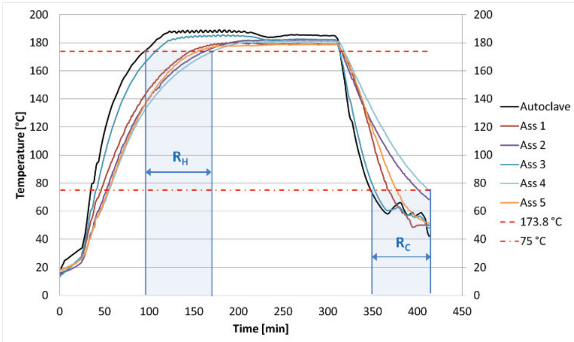

Fig. 2. Thermal profile of part-tool assemblies (coloured lines) and autoclave (black line) during a curing cycle.

The interval of time elapsed from the instant at which the autoclave environment reaches the cure temperature and the instant at which the last part-tool assembly in order of time reaches the curing temperature can be defined as the heating delay of the entire autoclave charge, R_H (Fig. 2).

Likewise, the interval of time elapsed from the instant at which the autoclave environment reaches the end cycle temperature and the instant at which the latest component reaches the end cycle temperature can be defined as the cooling delay of the entire charge, R_C (Fig. 2).

As mentioned before, the overall duration of the autoclave cure cycle depends on the delay with which the slowest part reaches the cure temperature and the end of cycle temperature.

A number of studies on autoclave curing showed that heating and cooling delay for each part depend on the material of the parts to be cured as well as of the tools on which they are mounted in the autoclave charging floor [7,8].

However, in this paper additional factors are taken into account. As a matter of fact, beyond the thermal properties related to the material of the part-tool assembly, also their geometry should be taken into account, as it has a large influence on the heating and cooling rate, and therefore on the dwell time within the target temperature range.

Moreover, the position of each part-tool assembly on the autoclave charging floor (the scheme of the industrial autoclave employed in this work is shown in Fig. 3), e.g. close to/far from the autoclave front door, significantly affects the heating and cooling rates.