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About the influence of stamping on thermoplastic-based composites for aeronautical applications

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ABSTRACT

An experimental study has been conducted to investigate changes in the mechanical behavior of carbon woven ply PPS laminates, obtained from thermo-compression, for aeronautics purposes. The influence of stamping on mechanical properties (tensile, compressive, in-plane shear, inter-laminar shear) of PPS-based laminates under severe environmental conditions (120 °C/hygrothermally aged) has been quantified, as well as for structural testing conditions (bolted joint). From the meso-structure observations, two important phenomena, re-compaction of fiber network and migration of resin melt, can be associated with the re-consolidation process of C/PPS laminates during stamping. This second thermo-compression improves the impregnation of fiber bundles by the PPS matrix and the interlaminar adhesion, which can be correlated with higher mechanical properties of PPS-based laminates under severe conditions.

1. Introduction

In composite materials, as well as in unreinforced materials, the use of thermoplastics predominates, although their use is usually restricted to short fiber reinforced injection moldable formulations [1]. Long and continuous fiber reinforced composites are still dominated by thermosetting polymer matrices. In long and continuous fiber reinforced composites, thermosets are particularly suited for impregnation into the reinforcing fibers by manual or semi-automated means. Thus, thermosetting (TS) matrix composites have been widely used for aeronautical applications over the last four decades. However, TS-based composites show some issues in their manufacturing process (low-temperature storage, long curing cycles, irreversible process, etc.). Nowadays, high-performance thermoplastic matrix composites (e.g. PEEK and PPS) are presenting promising alternative to those drawbacks. Crystallinity in high-performance polymers is important, because it has a strong influence on chemical and mechanical properties: the crystalline phase tends to increase stiffness and tensile strength, while the amorphous phase is more effective in absorbing impact energy [2]. The degree of crystallinity (DOC) is determined by many factors, including the type of polymer and processing conditions. There are numerous engineering reasons why TP composites are attractive as aerostructures, such as increased toughness compared with TS alternatives and inherent flame retardancy. At the same time, low-cost processing is obtained by using manufacturing processes like thermofolding, stamping, welding and co-consolidation [3–6]. Because the processes of material consolidation and stamping do not involve exothermic curing reactions they can use shorter autoclave cycle times (which is ideal for large production), although the temperatures involved are generally higher than those for thermosettings. The meltability of the material also provides better potential for recycling. The purpose of this work is to establish the ability of stamped TP-based composite to be used in aircraft engine nacelles by performing basic tests (tensile – compressive – interlaminar shear), and structural tests (bolted joints). A nacelle is the structure surrounding an aircraft engine, and its service conditions might be qualified as severe (120 °C after hygrothermal aging). Many parts of nacelles can be manufactured from stamped fiber-reinforced TP composites: ribs and spars are subjected to significant mechanical loads, whereas fairing or thrust reverser bulkhead (see Fig. 1) are subjected to lower stresses. To meet certification requirements, it is necessary to evaluate the influence of stamping on the behavior of consolidated laminates under severe conditions.

2. Literature review

At first, the present literature review is aimed at introducing the mechanisms associated with the stamping of TP matrix composites. The second sub-section examines the mechanical behavior of TP-based composites under severe conditions, and a special attention is paid to PPS-based laminates.

2.1. About the stamping of TP matrix composites

Melt- and solid-state stamping are viable options for producing simple parts from semi-crystalline thermoplastic matrix sheet

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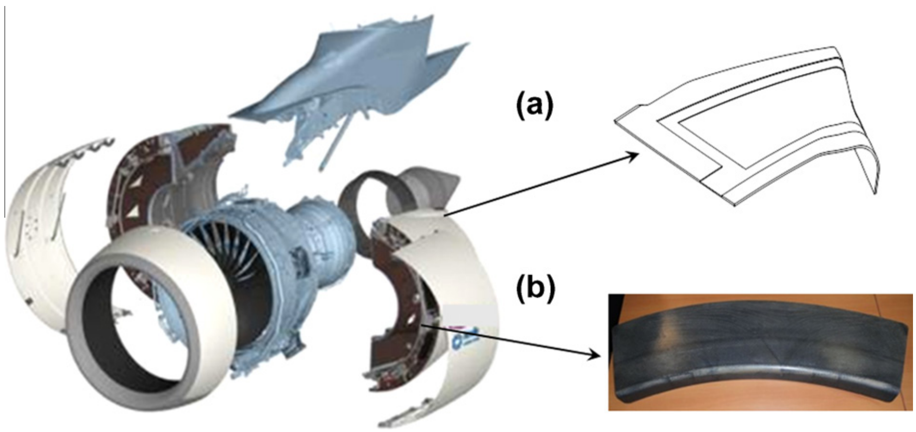

Fig. 1. Examples of parts of a nacelle that can be manufactured from stamped fiber-reinforced TP composite materials: fairing and thrust reverser bulkhead.

composites [1]. There are mainly four stamping mechanisms for fiber reinforced thermoplastics: intraply shearing, interply slip, resin percolation and transverse squeeze flow. The first two mentioned mechanisms are the most important ones: intraply shear, if double curvature shapes have to be formed, and interply slip if laminates have to be bent. Friction tests can be conducted in order to investigate the interply slip of 5-Harness satin C/PPS composite layers against each other, and against the forming tools [7,8]. During the thermoforming process, the change in angle between warp and weft fibers is very small, due to the two-dimensional character of the process. However, large variations are encountered in the thickness of stamped sheets depending on the local processing conditions (temperature, pressure and velocity of the die). Indeed, the stresses generated during cooling have an important impact on the distortion and strength of the stamped parts [9]. The deformation mechanism known as interply slip at high temperatures is representative of solid-phase and melt-phase forming [10]. Interfaces slip results from the movement of plies oriented parallel to the deformation direction and from plies of differing orientation. The primary parameters influencing interply slip are temperature and interfacial shear rate, which is narrowly associated with the forming rate. From the design standpoint, such parameters are very important to avoid occurrence of ply wrinkling or buckling during forming, resulting from compressive stress in the plies on the inner radius of curvature [11]. In addition, the interply slip significantly depends on the structure reinforcement [12]. Stretch in the fiber direction is smaller than the maximum elastic extension of fibers. Reduction of the angle between the crossing fibers is quite large when the satin woven fabric composite is pulled in the 45° direction. The flexibility of the satin woven fabric composite material is sufficient for the plate to be formed into a hemisphere, as long as the processing conditions (temperature, forming rate) are well controlled. As it was previously emphasized, the processing conditions such as mould temperature, consolidation pressure and forming time are utmost important from thermo-mechanical behavior standpoint of TP-based laminates [13,14]. The reduction in physical properties can also be correlated with the reduction in mechanical properties [15]. Due to high processing temperatures and pressures, the residual stresses in TP composites are inevitable, and result in spring-in phenomena, which means that the material is unable to completely retain the formed shape [16]. The other major problem induced by thermoforming of PPS-based composites is the de-consolidation of laminates during heat-up. Even though they are initially well consolidated, thermoplastic matrix composites may suffer unexpected de-consolidation in meso-structure and performance deterioration. De-consolidation is also proved to be dependent on the structure reinforcement [17]. Such drawbacks can be observed when the processing temperature is above the melt temperature (for crystallized resins) or glass transition temperature (for amorphous resins), if the pressure applied during post-thermal processing is not sufficiently high. Two important phenomena, de-compaction of fiber network and migration of resin melt, can be observed during the thermal de-consolidation process of C/PPS laminates [18]. In order to limit the voids formed on the metal tool surface (due to quick cooling), higher pressures, higher speed and higher pre-heating temperature are needed to stamp 5-Harness satin C/PPS than plain weave C/PPS [19]. To the authors' knowledge, most of the studies on the behavior of stamped TP-based composites have investigated their mechanical behavior at room temperature/moisture. There are very few references in the literature about the influence of stamping on the behavior of PPS-based laminates under severe conditions, i.e. [20]. The question is therefore to know whether such a process is detrimental to the microstructure, which are closely associated with the macroscopic properties of PPS-based laminates, or not.

2.2. Influence of environmental conditions on TP-based laminates

Advanced aeronautics structures, and particularly nacelles, require high-performance fiber-reinforced polymer matrix composites, which can be used at temperatures up to about 120 °C. This temperature level corresponds to high temperatures for polymer-based composites. A few references are available in the literature about the high temperature behavior of UD PPS-based laminates [21–24], and carbon fabric reinforced PPS laminates [25,26]. So far, there is a lack of available experimental data on the behavior of fabric reinforced PPS composites at high temperature. Around their glass transition temperature, the nonlinear behavior of fiber-reinforced composites becomes significant, especially under off-axis loading conditions [27,28]. This nonlinear response, associated with the shear deformation of the polymer matrix along reinforcing fibers, is enhanced at high temperature due to the viscoplastic nature of the TP matrix [29,30]. In addition, hygrothermal aging refers to the process in which the deterioration of the mechanical performance and integrity of composite materials results from the combined action of moisture and temperature. Therefore, polymer stiffness decreases and its behavior becomes more ductile. In CFR composites, moisture absorption and diffusion occur at the fiber–matrix interface, which affect its cohesion [31–33]. Thus, an increase in moisture content results in a decrease in shear strength. In addition, according to the nature of the polymer resin (TP or TS), water diffusion behavior differs: in TP composites, the average saturation gain is lower than in TS