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A study of composite material damage induced by laser shock waves

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ABSTRACT

A laser shock wave technique has been used to study the damage tolerance of T800/M21 CFRP (Carbon Fiber Reinforced Polymer) composite material with different lay_ups. Different levels of damage have been created according to various laser irradiation conditions. Several characterization methods such as Optical Microscopy, X-ray Radiography, or Interferometric Confocal Microscopy have been used to quantify these defects. The nature of the defects induced by the shock wave propagation has been studied. The sensitivity of the composite material damage to the shock conditions has been shown and quantified. Moreover, the experimental results gathered with each technique have been compared to each other and it leads to a better understanding of the CFRP behavior under high dynamic loading. These original results have enabled the definition of a specific damage criterion for CFRP under dynamic loading.

1. Introduction

Nowadays, composite materials are used in aeronautics for their good mechanical properties and their low weight. Increasing their part in aircraft structures is a compulsory step to achieve a better eco-efficiency. The gain could be important, especially thanks to new assembly technologies as bonding which is meant to replace the current techniques like riveting or bolting [1,2]. These methods are expensive, and are not well-adapted to composite materials since complex machining has to be set up (drilling leading to delamination or fiber breakage) [3–5]. Moreover, the use of the bonding technique would enable a significant weight lightening of the aeronautic structures, which means an aircraft consumption reduction. However, several implementation problems can penalize the bonding process, while manufacturing or during the aircraft lifetime. The bond quality can be weakened by a bad curing cycle, a surface contamination before bonding, etc. [6,7]. Moreover, there is no non-destructive technique currently available to quantify the bonding mechanical resistance. Facing this issue, a European Project has been started in November 2010: ENCOMB (Extended Nondestructive testing for COMposite Bonds). New methods are developed to enable first the characterization of the composite surface state before bonding, and then, the certification of the bonding mechanical quality. One of the developed methods is the laser shock wave technique first developed by Vossen and Gupta [8,9]. This technique can create a short but intense inside tensile loading on bonded materials. If these stresses are well-located into an interface, the bond line resistance can thus be tested. The LASAT technique was developed for many cases, especially for metal assemblies or metal coatings, for which it is now well understood [10]. Under some conditions, this technique has already been successfully used to test different bonding strengths of composite assemblies [11–13]. Nevertheless, more investigations remain necessary in order to optimize the technique and to better understand the associated complex physical phenomena. In particular, the composite material dynamic response to laser shocks has to be understood to develop a technique efficient for any kind of bonded composite assembly [14].

From another point of view, the aeronautical composite structures can be subjected to high energy impacts during their lifetime. Indeed, some external loadings can induce high levels of stress with a high strain rate, such as high velocity impacts of various kinds of projectiles (birds, ice stones, etc.). Under some conditions, the laser shocks induce stress levels comparable to the ones induced by high velocity impact. The laser shock wave technique presented in this paper can also be used as a way to test and damage composite material [14–16].

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In both case, a first step is to study the dynamic response of the composite material, which is key information for the applications presented. The laser shocks are used as a laboratory tool able to produce different levels of damage inside the composite material. This technique differs from others as drop weight systems. They are used to produce impacts on composite samples at low energy and long solicitation duration compared to what can be done using a laser shock setup. In case of classic impact loading on CFRP composite, multi delamination and transverse cracks can be observed under the loading area. The propagation of the delaminations mainly depends on the stacking sequence [17–20]. Many numerical models are developed to restitute the composite behavior in these cases of loading. The recent damage models are able to simulate the delamination propagation and the ply cracks initiation and propagation. The 3D models results are useful to understand the dynamic behavior of the composite by comparing simulation and experimental results [21–25]. In this study, laser shocks have been performed on CFRP T800/M21 composite materials. Several diagnostics providing complementary information have been tested to analyze the damage extent and nature resulting from the laser shock wave propagation. Especially, the use of Interferometric confocal microscopy has been extended to the shock composite sample in order to quantify their residual deformation. With these post-shock test methods, the main features of these defects have been obtained: location, anisotropy, main dimensions. The laser shock wave technique has been used as a characterization method to establish the damage threshold of the CFRP composite material tested and the experimental data gathered could provide useful information to optimize numerical modeling results.

2. Material investigated

A T800/M21 (Hexcel) composite material has been used in this investigation. It is well-known as a classic composite material for aeronautical applications, more specifically for structures which are prone to impacts. It is made of a non-conventional matrix, mixed from a thermoset epoxy resin and thermoplastic nodules whose mechanical behavior should enhance the global composite shock resistance. On the tested samples, this composition has been checked using DSC (Differential Scanning Calorimetry) characterization. The glass transition of the epoxy was evaluated around 194 °C and the thermoplastic phase has been identified from the endothermic melting peak close to 212 °C. Micrographs of a 6 mm thick T800/M21 sample are presented in Fig. 1a–c with three different magnifications. This sample is made of 33 pre-impregnated plies assembled with different orientations $[45°/0°/0°/-45°/0°/0°/45°/0°/0°/-45°/0°/-45°/0°/0°/45°/0°/0^{\circ}_{0.5}]_S$ and cured by autoclave.

On Fig. 1, the thermoplastic nodules can be observed mostly between the plies as round dark grey shapes, but are sometimes present inside the plies, forming channels or veins (see Fig. 1a and b). Their approximated diameter has been evaluated in the range [10–20 μm] (see Fig. 1c). The pre-impregnated plies are about 180 μm, but the presence of the thermoplastic nodules induces a strong deviation of the ply thickness. This 6 mm thick T800/M21 material has provided all the samples tested in this study.

3. The laser shock wave technique

The laser shock wave technique consists in a high power laser irradiation of a target. When focused on a material, this irradiation results in plasma sublimation on its surface. The plasma expanses rapidly, which induces a shock wave into the material by reaction. The shock wave is then propagating through the thickness toward the target back face, according to properties depending on the material characteristics. Reaching the sample back face, the reflection of this shock wave creates a release wave propagating backward. This release wave is crossing the incident unloading wave coming from the front face and initiated by the end of the loading (see in Fig. 2). It is the crossing of these two release waves which can lead to a local high tension area which could damage the material if the stress level is high enough compared to its damage threshold. In fact, the tensile stress level is directly linked to the laser shock amplitude whereas its location mainly depends on the material properties and the pulse characteristics. In order to amplify the pressure level on the sample, a water confinement has been used to enhance the plasma expansion effect [26]. Therefore, the damage initiation for a given material can be controlled by changing the laser source parameters, especially the energy level for the stress intensity, and the pulse duration for the position of this stress area.

All the samples have been coated with aluminum painting before laser irradiation in order to produce a more controlled shock loading. Indeed, if the laser interaction with the aluminum has already been deeply investigated, very few investigations have been conducted on the laser interaction on composite materials [27–30]. Consequently, the correlation between the laser intensity and the corresponding pressure loading on the sample front face is well documented for aluminum.

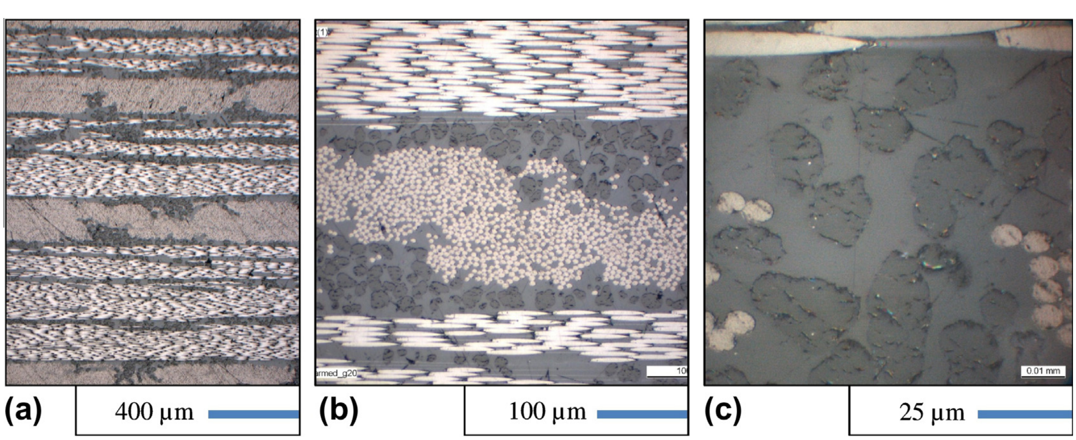

Fig. 1. Optical micrographs (a–c) of a 6 mm thick T800/M21 sample. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).