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Residual stress measurement of fiber metal laminates using incremental hole-drilling technique in consideration of the integral method

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A R T I C L E I N F O

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A B S T R A C T

In this manuscript, integral method was used for the approximation of residual stresses field in fiber-metal laminates (FMLs). Initially, calibration coefficients matrix for the integral method were determined numerically by the finite element program using ANSYS software. The calibration coefficients were used to relate the measured strains relaxation field with the existing residual stresses prior to the IHD process. Subsequently, FML specimens with symmetric stacking sequence of $[AL/0^\circ_2/90^\circ_2]_S$ were manufactured. Next, the IHD experiment by high speed drilling machine were performed and released strains caused by the change in hole-geometry have been obtained. Finally, experimental results from IHD experiment were compared with the theoretical predictions from classical lamination theory. Very good agreements with the experimental and theoretical results show that, the IHD technique can be successfully applied for measuring residual stresses in FML composites.

1. Introduction

Fiber metal laminates (FMLs) are a new type of hybrid composite structures which consists of thin sheet layers of metal alloys and plies of fiber reinforced polymer composites (Fig. 1) [1]. FMLs combine the superior durability of metals with the attractive properties of fiber-reinforced composite materials such as high fatigue resistance, good moisture resistance, excellent impact, corrosion resistance, fire resistance, weight-savings and specialized strength properties [2]. The most commercially available FMLs are ARALL (aramid reinforced aluminium laminate), CARALL (carbon reinforced aluminium laminate), and GLARE (glass reinforced aluminium laminate) [3].

There are many articles about experimental and theoretical investigations, regarding to adhesion between metal sheet and fiber, stacking arrangements, mechanical properties, composite volume fractions and etc. [4–6], while there are a limited number of studies concerning the residual stresses in FML materials. Therefore, this important issue still need more understanding and attention.

The residual stresses in FML materials are produced during the fabrication process. Shrinkage during curing and the mismatch of coefficients of thermal expansion (CTE) between metal sheet, fiber and matrix are the most important reasons for residual stresses [7]. The magnitudes of these stresses depend on material properties, lay-ups and curing cycle (non-uniform heating or cooling during manufacturing) [8]. Residual stresses reduce the performance of composite structures and can cause matrix cracking, fiber breakage, delamination, warpage, interface debonding and dimensional instability [9,10].

There are a number of destructive and non-destructive methods, which are used for determination of residual stresses. One of them is hole drilling method [11]. This method is one of the most currently and widely used methods for residual stress measurement. It is standard, relatively simple, inexpensive, quick, versatile, and well adapted method to a wide range of materials [11,12]. This method is well established for measuring the residual stresses in homogeneous isotropic materials.

The basic hole drilling calculations described in ASTM E837 [11] is applicable to the residual stress profile determination where in-plane stress gradients are small. The stresses may remain approximately constant with depth (uniform stresses) or they may vary significantly with depth (non-uniform stresses). Only uniform stress measurements are specified for thin workpieces, while both uniform and non-uniform stress measurements are specified for thick workpieces. More recently, focus has fallen on measuring the variation of the residual stress with depth by the incremental hole drilling (IHD) method and developing solutions for non-uniform residual stresses fields. The most common way of estimating non-uniform residual stress distributions in the IHD method is integral

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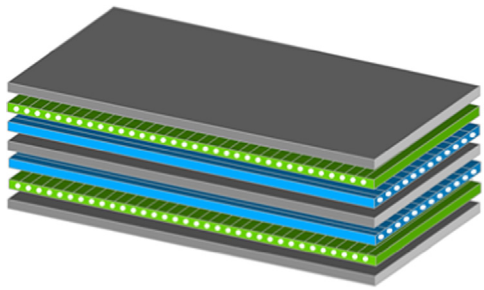

Fig. 1. FML structure with a stacking sequence of $\{Al/0/90\}_S$.

method.

The hole drilling method for determination of non-uniform residual stresses in isotropic and orthotropic materials have been developed well. Schajer [13,14], Flaman et al. [15,17], Sicot et al. [18,19], Pagliaro and Zuccarello [20], Ghasemi et al. [21,22], and Shokrieh and Ghasemi [23,24] have studied the determination of non-uniform residual stresses in metal and composite materials based on the IHD method. Extending the hole drilling method to determine the residual stresses in orthotropic materials was presented by Schajer and Yang [25]. The released strains, which are measured by the hole drilling method, are converted to the residual stresses using calibration coefficients. These coefficients can be determined by closed form, numerical, and experimental methods. Shokrieh and Ghasemi [23] simulated the hole drilling method for measurement the residual stresses in isotropic, orthotropic, and laminated composites. They also presented an exact solution for prediction of calibration coefficients in points of strain gauge rosette for the orthotropic materials. Using these factors, the residual stresses can be obtained from the measured strains based on the CHD experiment [24].

Drilling speed and feed rate are important parameters in hole drilling method. Flaman and Herring [16] used the high-speed turbine and carbide milling blades for measuring the residual stresses. Andersen [26] used the normal milling method on thick isotropic samples, regardless of its effect on the measurement precision of the strains released. He indicated that the normal hole drilling method could be used to calculate the residual stresses in depth of the specimens with no effect on the accuracy of the measurements. The hole drilling of multi-layer composites at milling speed of 5000 r/min and feed rate of 10 mm/s has been done by Sicot et al. [18,19]. Ghasemi and Shokrieh [27,28] used the hole drilling of multi-layer composites using a high-speed CNC milling machine during determination of non-uniform residual stresses. The results showed that incremental hole drilling can be properly used for determination of non-uniform residual stresses in composite and metal materials.

The main purpose of this study is developing a theoretical, numerical and experimental study regarding the evolution of non-uniform residual stresses in FML materials from incremental strain data by the integral method. For this purpose initially, numerical models using finite element (FE) method are used to determine the calibration coefficients of the IHD method. For model verification, the FML specimens with $[AL/0^{\circ}_2/90^{\circ}_2]_S$ lay-ups are fabricated. Subsequently, by installing a strain gauge rosette on the surface of each specimen, and measuring the incremental strains, the residual stresses in each step of the IHD experiment are determined. Finally, to validate the accuracy of the experimental results, the residual stresses are also compared with the values predicted by theoretical methods. The theoretical study relies on the classical laminate theory (CLT).

2. Principles of incremental hole drilling method

In this section, the IHD method is presented to measure experimentally with accuracy residual stresses in each ply of a laminate. In this method, a strain gauge rosette is placed on 0°, 90° and 225° in surface of specimen containing the residual stresses (Fig. 2). This method involves three major aspects to determine the non-uniform residual stresses distribution in depth:

- Drilling a small hole in the specimen in the area of interest,
- Measuring the released strains around the hole, using strain gauges rosette,
- Computing the corresponding residual stresses, using recorded strains.

The major error which may have appeared the IHD method and almost all other destructive methods for measuring residual stresses is due to the physical limitations [13,14]. The sensitivity of the IHD method reduces with the hole-depth. In this method, the rosette is attached on the samples surface and the strains on the parts surface are read, while the non-uniform stresses are through the thickness. This difference in the locations of the target stresses and the measured strains creates a substantial computational challenge [29]. Therefore, for the IHD method, the relationship between the residual stresses and the measured strains does not have a simple one to one form and has the form of an integral equation [30]:

$$\epsilon\left(h_i\right)= \int_0^{h_i} C(x,\, h_i)\sigma(x)dx \;\; 1 \le i \le n \tag{1}$$

where $\varepsilon\left(h_i\right)$ is the measured strain in the hole-depth "h_i". $\sigma(x)$ is corresponded to the residual stresses and Kernel function $C(x,h_i)$ describes the measured strain caused by a unit stress at depth "x" within a hole-depth "h_i". In the hole drilling method, this function is usually obtained using a FE analysis.

In order to solve Eq. (1), an initial distribution for the residual stresses must be considered. The most important methods to estimate residual stresses in the IHD method are the integral, incremental strain, power series and average stress methods [31]. Integral method considers a constant and uniform residual stress analysis at each hole-depth increment (Fig. 3). The assumptions are that each step of drilling is influenced by the previous one. Therefore this method is suitable for calculating of non-uniform residual stresses. The unknown residual stresses in the integral method are estimated by the Eq. (2) [30]:

$$\sigma(x_j)= \sum_{j=1}^{n} \sigma_j U_j(x) h_{j-1} \le x \le h_j \tag{2}$$

where σ_j is the value of residual stress at the jth hole-depth

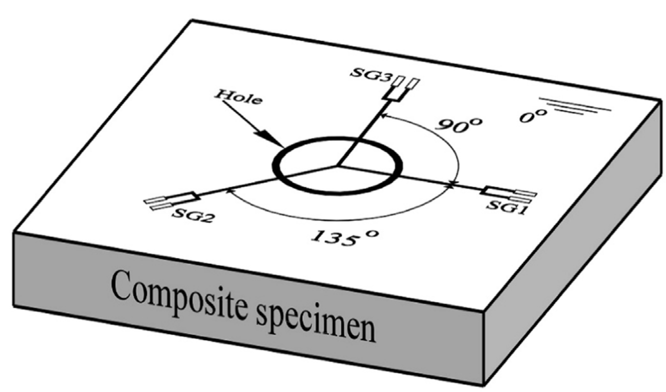

Fig. 2. Specimen, hole geometry and position of the strain gauge rosette.