Tribology International 102 (2016) 38–43

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

A study of friction between composite-steel surfaces at high impact velocities

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ARTICLE INFO

Article history:
Received 5 March 2016
Received in revised form
6 May 2016
Accepted 8 May 2016
Available online 10 May 2016

Keywords:
High impact velocity
Friction
Woven composite
Compression

ABSTRACT

The Hopkinson Split Pressure Bar system allows to carry out compression tests at high impact velocities corresponding to high strain rates up to 5000 s^{-1}. For composite materials, however, negative phenomena related to wave propagation and specimen geometry may disturb experimental analysis and, therefore, should be taken into account. Potential errors are mainly due to friction, inertia and wave dispersion. In order to provide a complete analysis of experimental results for composite materials under dynamic compression, a procedure was developed to estimate friction and dispersion effects at the specimen-bar contact zone. For this purpose, dynamic tests were carried out on woven glass-fiber-reinforced Polyamide (PA6) composites using Hopkinson's bar and pin-on-disk tribometer tests techniques. Results showed that the state of friction characterizing the PA6/glass material differs as per the orientation of fibers. The frictional regime is relatively more severe in case where the fibers are normal to the direction of friction.

1. Introduction

In the domain of structures subjected to impact loading, the main incertitude of mechanical properties estimation is to not take into account the material damage. Indeed, it is linked to the macroscopic response of the structure and depending on the complexity of the loading. The problem is particularly critical for composite materials in which the loss of mechanical resistance under shock is worrying and still not well characterized. Various types of tests are available as a function of the material type, but the results extracted from these tests cannot be easily compared. Facing this fact, it seems necessary to normalize the dynamic test procedures on composite materials in order to meet the increasing need of industrial clients. However, the problems encountered are of a complex nature. In fact, the degree of anisotropy for each composite material depends on the fibers orientation, the stacking sequence and the type of ply. The initial anisotropy complicates the phenomena close to the specimen-bar interface.

The Hopkinson bar system has become the most adopted and most used test to determine the dynamic properties of composite materials [1–7]. In this dynamic system, the influence of the impedance adaptation as well as the nature of the supports used for the specimen fixing are sources of problems related to the specimen dimensioning. An improper choice of the material and geometry of the bar and supports provides unpredictable results in the form of wave signals which cannot be analyzed [1,2]. This problem is often superimposed on another one, related to the dispersive nature of the composite matrix. In fact, the wave speed depends on the frequency, thus the incident wave is transformed into a set of waves packets which penetrate the composite material.

The main objective of this paper was to examine the effect of dynamic friction between composite materials and steel bar within the system of Hopkinson bar dynamic test. For this purpose, a number of dynamic tests were carried out using composite specimens made of woven glass-fiber-reinforced Polyamide (PA6). In order to minimize the radial inertia and the effect of the wave propagation in a composite specimen, a small size specimen is usually used for compression tests. However, a larger composite specimen would be more

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http://dx.doi.org/10.1016/j.triboint.2016.05.011
0301-679X/

representative to properly define the global behavior of composite materials under impact. In other words, the size of composite specimen should be large enough in comparison to ply dimensions. To reduce this problem, two tests arrangements were developed in this study. The first one is a test system based on the Hopkinson bar for compression tests and the second one is a pin-on-disk tribometer to allow friction coefficient measurements. The latter was designed for different fibers orientations and for high slip velocities.

2. Method of material characterization using dynamic compression

In order to develop an experimental procedure to study dynamic friction that occurs between PA6 composite and steel at high impact velocities, the Hopkinson bar system (Fig. 1) was used in this study. The test setup is composed of three parts; each has its own distinct function as schematically described in Fig. 1. The first part is made of a pneumatic launcher which propels a projectile with the required impact velocity V_i. The second part is formed by the incident and transmitted bars of the same diameter, being perfectly aligned. The specimen, which is the third part, is placed between these two bars. The loading is realized by the impact of the projectile at the free end of the incident bar, which produces an incident longitudinal compression wave that propagates along the bar. Once the wave reaches the specimen, a part of it is reflected and another part continues through the transmitted bar (the phenomenon due to the mechanical mismatching of impedance).

The signals of the incident and reflected waves are measured by the gauges glued to both bars (Fig. 1), where $\Delta x_1 = 750$ mm and $\Delta x_2 = 150$ mm are the distances between the measuring points and the specimen-bars interfaces. The length of the incident bar is 1500 mm, the diametre of bar is 20 mm and the length of specimens is 9 mm. The strain rate is 100 s^{-1} for L_1 and L_2 directions and 150 s^{-1} for direction T.

If the incident wave ε_I, reflected wave ε_R and transmitted wave ε_T are known, it is possible to describe a stress–strain history in the specimen. The theory of the elastic wave propagation allows to demonstrate that the displacement $u(t)$ is linked to the deformation $\varepsilon(t)$ by the following relation:

$$u(t) = c_0 \int_0^t \epsilon(\xi) d\xi \tag{1}$$

where c_0 is the elastic wave speed in the bar.

As shown in Fig. 1, the displacement $u_1(t)$ at the face of the incident bar is a consequence of two deformations $\varepsilon_I(t)$ and $\varepsilon_R(t)$ which propagate in the x-positive and x-negative directions, respectively. Thus, $u_1(t)$ can be expressed as:

$$u_1(t) = c_0 \int_0^t \epsilon_I(\xi) d\xi + (-c_0) \int_0^t \epsilon_R(\xi) d\xi \tag{2}$$

or:

$$u_1(t) = c_0 \int_0^t \left[\epsilon_I(\xi) - \epsilon_R(\xi)\right] d\xi \tag{3}$$

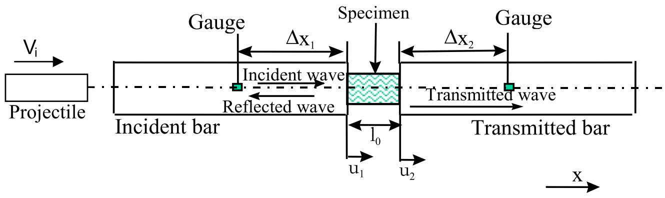

Fig. 1. Hopkinson pressure bars test setup for dynamic compression.

As far as the transmitted bar is concerned, the displacement $u_2(t)$ is deducted uniquely from the deformation $\varepsilon_T(t)$, the latter propagates in the x-positive direction. It can be defined as follows:

$$u_2(t) = c_0 \int_0^t \epsilon_T(\xi)\, d\xi \tag{4}$$

Once the displacements at each specimen interface are defined, the mean strain rate can be calculated as follows:

$$\epsilon^s(t) = \frac{\partial}{\partial \mathrm{t}}\left[\frac{u_1(t) - u_2(t)}{l_0}\right] = \frac{c_0}{l_0}[\epsilon_I(t) - \epsilon_R(t) - \epsilon_T(t)] \tag{5}$$

where l_0 is the initial specimen length.

This expression can be simplified if we assume equilibrium of the specimen. In terms of deformations, this hypothesis can be presented by the following expression:

$$\epsilon_I(t) + \epsilon_R(t) = \epsilon_T(t) \tag{6}$$

In this case, the mean strain rate $\dot{\varepsilon}_s(t)$ in the specimen is equal to:

$$\epsilon^s(t) = -2\frac{c_0}{l_0}\epsilon_R(t) \tag{7}$$

Finally, the nominal deformation in the specimen $\varepsilon_s(t)$ can be obtained by simple integration of the strain rate over the total time.

In order to calculate the average stresses generated in the specimen, it is sufficient to consider the forces applied at each specimen side. $F(t)$ is the force at the contact between specimen and incident bar surfaces and it is given by:

$$F_1(t) = E_b\, A_b\, [\epsilon_I(t) + \epsilon_R(t)] \tag{8}$$

Similarly, the force acting on the face between the specimen and the transmitted bar is obtained as follows:

$$F_2(t) = E_b\, A_b\, \epsilon_T(t) \tag{9}$$

where E_b is the Young's modulus of the steel bar and A_b is its cross-section. By making use of the equilibrium condition given in Eq. (6) and considering the average of these two contact forces the mean stress developed in the specimen can be calculated as follows:

$$\sigma_s(t) = \frac{F_1(t) + F_2(t)}{2\, A_s} = E_b\left(\frac{A_b}{A_s}\right)\epsilon_T(t) \tag{10}$$

where A_s is the initial cross-section of the specimen.

3. Adaptation of the Hopkinson bar system for composite materials

The principal problem of using the Hopkinson bar system for compression tests [11] of composite materials is linked to the elastic wave propagation. During experiments, deformations are measured at the surface of the bar. Theoretically, they should correspond to the axial displacement of the full cross-section of the bar. This may happen only if the propagating wave is unidimensional; this means all points of the cross-section are uniform. However, during the impact of the projectile on the incident bar, the generated waves are very complex at the initial stage.

This is particularly due to geometrical imperfections of the specimen-bar interface and due to the propagation of the other types of elastic waves. Fortunately, the parasite effect is dispersed while the wave covers a distance equal to ten times the Hopkinson bar diameter. A simple technical solution is then to place all gauges far enough from the impact point. Therefore, they are glued at a distance of over ten times the bar diameter to avoid any perturbation signals.