HIGH IMPACT VELOCITY ON MULTI-LAYERED COMPOSITE OF POLYETHER ETHER KETONE AND ALUMINIUM

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Abstract

This work presents an experimental and numerical investigation on the perforation behaviour of layered polymer/metal composite. Penetration tests have been conducted on sandwich panels of aluminum 2024-T3 skin and PEEK cores using spherical projectiles. The perforation experiment covered impact velocities in the range 250 m/s to 500 m/s. The initial and residual velocities of the projectile were measured and the ballistic limit velocity obtained for the considered configuration. The impact mechanical behaviour of PEEK core is compared with Ti6Al4V titanium core, for the same areal density of protection. It has been shown high perforation efficiency of PEEK material and a promised application for aeronautical protections. A numerical modeling is presented and validated with experimental data.

1. Introduction

Impact and blast threats exist in a wide range of engineering, security and defence sectors. The protection of civil infrastructures and critical industrial facilities are topics of increasing relevance to defence agencies and governments. In the transport industry, energy absorption and crashworthiness are key points in the design process of vehicles, vessels and aircrafts. Development of protective composite structures capable of sustaining an impact keeping the structural integrity is thus one of the main challenges of modern industry. In the design and development of lightweight structural solutions suitable for energy absorption under impact loading, the material selection represents a crucial decision [1]. Moreover, impact on composite metallic plates is a complex and complete problem including dynamic behaviour, fracture, damage, contact and friction. We observe an internal energy which is an irreversible thermodynamic process due to transfer of kinetic energy, dynamic plastic flow, elastic and plastic wave propagation and large plastic deformation at high strain rates inducing thermal softening responsible of instabilities. It has been observed during this kind of projectile-plate impacts that the nose shape of the projectile used changes the energy absorbed, the failure mode and the ballistic limit, which is a decisive variable for optimum design [2]. This process is strongly coupled to hardening, strain rate and temperature of involved material.

In recent years, metal-polymer-metal sandwich sheets show a high potential in forming and design to be used in protective structures versus monolithic metal plates [3]. Of all possibilities for designing hybrid systems, three-layered metal-polymer-metal or multi-layer sheets, offer a great potential for automotive, construction, naval industries and aeronautics. Examples are given by the well known, GLARE (aluminium layers and Glass Fiber Reinforced Epoxy), wich has been applied in aviation industry (e.g. Airbus 380) or ARALL (Aramid Fiber Reinforced Aluminium),[4]. The comparison between different configurations of hybrid laminated polymer/metal with values of similar areal density is an open research topic, in terms of energy absorption, critical perforation velocity and failure mode [5]. In this context, structural polymers are often used in applications where impact resistance is required. Though specific thermoplastic such as PEEK (polyether ether ketone) shows a strong positive function of strain rate [6,7], it has not been widely investigated for high impact applications. In the present work, the impact behaviour of sandwich panels of 2024-T3 aluminum skin and PEEK core (containing 30% short-cutting glass fibers) is investigated and compared with sandwich panels of 2024-T3 aluminum skin and Ti6Al4V core. Experimental data shows similar ballistic limit for the same areal density. Additionally, a numerical modeling is presented and validated with experimental data.

2. Materials and experimental setup

The sandwich plates were composed of different combination of the following plates: 2024-T3 aluminium with 1 mm of thickness, titanium alloy Ti6Al4V with 1 mm of thickness and PEEK (Polyether Ether Ketone) with 3 mm of thickness. According to Figure 1 and Table 1, three different sandwich configurations were selected to compare the similar areal density: configuration (a) composed by 4 metal sheet (Al2024-Al2024-Al2024-Al2024), configuration (b) composed by three metal sheet (Al2024-Ti6Al4V-Al2024) and configuration (c) composed by metal and polymer sheet (Al2024-PEEK-Al2024). The characteristics of these materials are shown next.

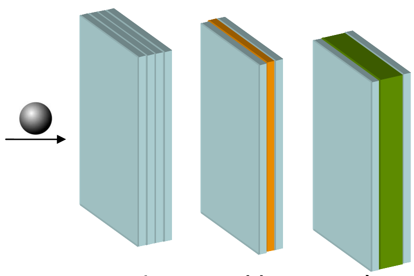

Figure 1. Scheme of multilayered system protection according to Table 1

Type	Protection	thickness configuration (mm)	Areal density [kg/m^2]
a	4 sheet of 2024-T3 Al	1-1-1-1	10,7
b	2 sheet of 2024-T3 Al + Ti6Al4V core	1-1-1	9,9
c	2 sheet of 2024-T3 Al + Peek core	1-3-1	9,9

Table 1. Areal density and thickness of multilayered system protection

2.1 2024-T3 Aluminum

The 2024-T3 is an aluminium alloy, with Cu and Mg as the main alloying elements. Applications of this material can be found in aircraft structural components, wing tension members, hardware, truck wheels, scientific instruments, veterinary and orthopaedic braces and equipment; and in rivets because of its high strength, excellent fatigue resistance and good strength-to-weight ratio.

2.*2 Ti6Al4V Titanium*

Ti 6Al-4V is a titanium alloy considered in many applications due to its high strength at low to moderate temperatures and light weight. The main applications are the aircraft turbine engine components, aircraft structural components, aerospace fasteners, high-performance automotive parts, marine applications, medical devices, and sports equipment.

2.3 G30 PEEK material

As a typical high performance semicrystalline thermoplastic polymer, polyetheretherketon, PEEK has received significant attentions in recent years. This is due to its high mechanical strength and elastic modulus, good combination of thermal and mechanical properties, chemical inertness, high toughness, easy processing, high wear resistance and friction coefficient [8]. This thermoplastic has a melting point of 608 K, and glass transition of 417 K. It can be used continuously up to 520 K without any permanent loss of mechanical properties. PEEK and its composites are good candidate materials for a variety of structural applications in aerospace, biomechanics, automotive and chemical industries. In space application, PEEK is applied for replacing aluminum because of its superior performance at high temperatures. In addition, PEEK is also one of a new generation of engineering polymers which has good cryogenic properties. Due to glass fibers (GFs) have high strength, high flexural modulus and low expansion rate, they are the most common fiber reinforcements in thermoplastics to reduce the expansion rate and increase the flexural modulus of PEEK [8]. In this work, LARPEEK 50 G/30 [9] containing 30% short-cutting glass fibers in volume fraction, was considered.

2.4 Experimental setup

Spherical projectile was used in perforation test with a diameter of 7,25 mm and a mass of 1,3 g. In addition, the projectile underwent a heat treatment to increase their hardenss. To perfom perpendicular impact tests on the multilayered plates, a pneumatic gas gun was used. It should be noticed that the diameter of the barrel was roughly equal to the diameter of projectile. No sabot was required for guidance of projectile inside the barrel, wich helps to ensure the perpendicularity of the impact. The impact velocity and residual velocity were measured using lasers coupled to photodiodes and with a high speed record camera. Perforation experiments were performed with impact velocities in the range from 250 m/s to 500 m/s. It should be noted that, for all the tests performed, the projectiles showed an absence of plastic straining, damage or erosion after the impact. Next, the experimental and numerical results are discussed.

3. Numerical model

3.1 Mesh definition and boundary conditions used during numerical simulations

The numerical model was developed using the explicit finite element code Abaqus/Explicit [10]. There were implemented three numerical models which represents the different combination of sandwich structures tested. Therefore, the numerical model consisted of various solids: the sandwich plate composed by three or four ones (depending of the sandwich selected) and the impactor or projectile. For each plate two kinds of elements were used in order to get a good damage-dependent evolution of the zone. As Figure 2 shows, each plate is divided into three zones: Zone A is the area in contact with the projectile. The four-node linear tetrahedrom element (C3D4), which allows greater freedom of damage propagation, was implemented in the impact region of each plate defined as an area of 14.5 mm diameter (twice the diameter of the projectile), zone B corresponds to the transition zone between the impact zone and the rest of the plate. It was meshed with eight-node brick hexahedral elements with one integration point (C3D8R) and zone C corresponds to peripheral region of the plate. In this zone, the sensitivity of the mesh was reduced by a gradually reduction of the element size. The sandwich plate was constrained by all its lateral faces and the rigid body was constrained not to move in the X and Y directions.

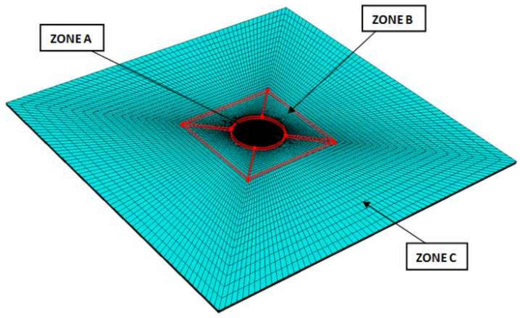

Figure 2. Mesh corresponding to sandwich configuration divided into three zones.

3.2 Modelling of thermoviscoplastic behaviour

As in this impact analysis the main aim is comparing the response of each sandwich configuration, the material constitutive law which the metal alloys are defined with, should include strain rate dependency for both material deformation and failure. Therefore, this study tries to get the J-C plasticity model by experimental tests and investigates this model to simulate the response of the different materials implemented under the impact conditions. For PEEK material, the associated thermal softening was taken into account in the Johnson Cook material model, used for other thermoplastic material as ASB [11]. The parameters of model were calibrated with the experimental data of dynamic compression test reporter in Rae et al. [11]. This model was selected because it can easily include strain, strain rates and temperature effects (below and beyond transition temperature).The Johnson-Cook (JC) plasticity model [12] was employed to model the flow stress behavior of the different materials studied in the numerical simulations. The J-C model defines the Von Mises flow stress as a function of equivalent plastic strain ($\bar{\varepsilon}_p$), equivalent plastic strain rate ($\dot{\bar{\varepsilon}}_p$) and temperature (T):

$$\bar{\sigma}(\bar{\varepsilon}_p, \dot{\bar{\varepsilon}}_p, T) = [A + B \cdot \bar{\varepsilon}_p{}^n][1 + C \cdot \ln(\frac{\dot{\bar{\varepsilon}}_p}{\dot{\bar{\varepsilon}}_0})] \cdot [1 - T_H{}^m] \tag{1}$$

where T_H is the homologous temperature defined as

$$T_H = \frac{T - T_0}{T_{melt} - T_{room}} \tag{2}$$

where T is the material temperature, T_{melt} is the melting temperature and T_{room} is the room temperature. The different constants are defined in Table 2. It is important to consider a thermal softening caused by a great location of plastic deformation. It was included a dependence of the temperature for the two titanium alloys as:

$$\Delta T(\bar{\varepsilon}_p,\dot{\bar{\varepsilon}}_p,T)=\frac{\beta}{\rho \cdot C_p}\int \bar{\sigma}(\bar{\varepsilon}_p,\dot{\bar{\varepsilon}}_p,T)d\varepsilon_p \tag{3}$$

where β is the percentage of plastic work transformed to heat (Quinney Taylor coefficient), C_p is the heat capacity and ρ is the density.

Material	A **[MPa]**	B **[MPa]**	**n**	**C**	**m**	T_{melt} **[K]**	$\dot{\varepsilon}_0$
Ti6Al4V	1098	1092	0.93	0.014	1.1	1878	1.0
2024-T3 Aluminum	352	440	0.42	0.0083	1.7	775	$3.33 \cdot 10^{-4}$
G30-PEEK	120	20	0.36	0.04	0.88	300	0.015

Table 2. Jhonson-Cook model parameters of Ti6Al4V [12, 133], aluminium 2024-T3 [14.] and polyether-ether-ketone [6].

In addition to a J-C plasticity model, it was developed a J-C progressive damage model which specifies a shear damage criterion [2]. The general expression for the equivalent plastic strain defined by this model is given by:

$$\bar{\varepsilon}_p = D_1 + D_2 \cdot \exp(-D_3 \cdot \eta) \cdot [1 + D_4 \cdot \ln(\frac{\dot{\bar{\varepsilon}}_p}{\dot{\bar{\varepsilon}}_0})][1 + D_5 \cdot T_H] \tag{4}$$

where η is the stress triaxiality and D_i are constants (Table 3) calibrated according experimental data reported in Lee et al [13]. The damage criterion of for Polyether-ether-ketone (PEEK) has been defined as constant failure strain equal to 0.85 according to experimental data of tensile test reported in [6].

Material	**D1**	**D2**	**D3**	**D4**	**D5**
Ti6Al4V	-0.09	0.27	0.48	0.014	3.87
2024-T3 Aluminum	0.112	0.123	1.5	0.007	0.0

Table 3. Constants used to define the J-C damage criterion of Ti6Al4V and aluminium 2024-T3 according experimental data [13,14]

4. Results and discussion

4.1. Experimental observations and ballistic limit

Three different sandwich configurations haven been tested at impact velocities from 250 m/s to 500 m/s. Plastic instabilities formation and progression are identified as the cause of behind the target collapse for all the impact tests conducted and progressive damage from shear to petalling can be observed in laminates from top at bottom perforation direction, respectively (Figures 3, 4, 5). The ballistic limit of *2024Al-Peek-2024* sandwich was found, $V_{bl} \approx 360 m/s$ to be just slightly greater than corresponding to *2024Al-Ti6Al4V-2024Al* sandwich, $V_{bl} \approx 332 m/s$, both of them with the same areal density (9,9 kg/m^2). Therefore, it has been shown high efficiency perforation of sandwich with PEEK core.

Figure 6 shows the residual velocity versus impact velocity $(V_r - V_0)$ curves obtained for sandwich tested. The results shown in Fig. 6, have been fitted via the expression proposed by Recht and Ipson [15]:

$$V_r = (V_0^k - V_{bl}^k)^{1/k} \tag{5}$$

where k is a fitting parameter. The value of k determined were= $k = 2$

Figure 3. Progressive damage from shear to petalling for each laminate of multilayered metal sandwich of 2024 aluminum (impact velocity=435 m/s).

Figure 4. Progressive damage from shear to petalling for each laminate of 2024Al-Ti6Al4V-2024 Al multilayered metal sandwich (impact velocity=305,8 m/s corresponding to arrest of projectile).

Figure 5. Progressive damage for each laminate of 2024Al-Peek-2024Al multilayered metal/polymer (impact velocity=298,7 m/s corresponding to arrest of projectile).

4.2 Validation of numerical modeling

A qualitative approach for experimental and numerical data was obtained by the model for force-displacement curves $(V_r - V_0)$ curves and strain distribution at failure. A agreement for residual velocity and under-estimation of about 15% was obtained by numerical model. These differences can be explained for some causes: the identification of material based only on compressive testst and the Mises yield surface used in the Johnson Cook model for PEEK material. In particular and for modelling PEEK, it could be interesting to use (or implemented) other types of models, such as damage models or Drucker-Prager model well adapted to pressure sensitivy of PEEK materials [11, 6].

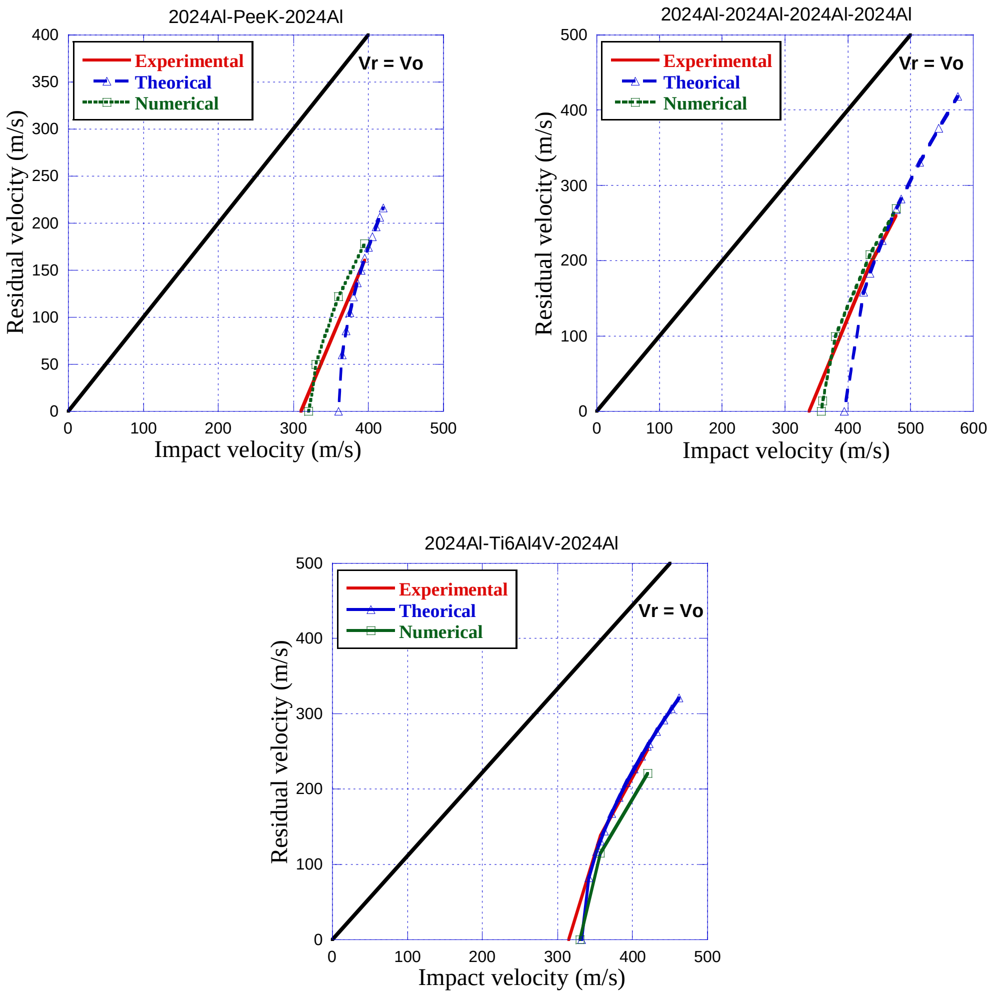

Figure 6. Residual velocity versus impact velocity for three sandwich configuration in this work (experimental, numerical and analytical data).

5. Conclusions

High impact test in gas gun have been conducted on sandwich panels of 2024-T3 aluminum skin and PEEK cores using spherical projectiles from 250 m/s to 500 m/s initial velocity. The experimental and numerical results support the following major conclusions. A qualitative agreement for residual velocity and under-estimation of about 15% was obtained by numerical model. The ballistic limit of metal sandwich with PEEK core (containing 30% short-cutting glass fibers) was found slightly greater than corresponding to metal sandwich with titanium core for the same areal density. Therefore, it has been shown high perforation efficiency of peek materials.

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