NUMERICAL MODELING OF DYNAMIC PUNCH OF HYBRID METAL COMPOSITE FOR PROSTHETIC INTERVERTEBRAL DISCS (IVD)

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Abstract

This work deals with the mechanical behavior under impact loading (5 m/s $\leq V_0 \leq$ 15 m/s) of the hybrid sandwich sheets composed by titanium skins (Ti6Al4V and Ti6Al7Nb) and polymer core (polyether-ether-ketone, PEEK). These configurations are widely used in intervertebral prosthesis. Firstly, the experimental method has been carried out using a drop weight tower; secondly, the numerical model of punching process has been developed with finite element method. Fracture observations reveal that the sandwich specimens fail predominantly as the result of intensive localisation shearing. The numerical analysis considers the influence of impact velocity, specific energy absorbed by the specimens and failure mode. A qualitative agreement for the strain distribution and an under-estimation of about 20% of the maximum impact load was finally obtained by the model.

1. Introduction

The degeneration of the intervertebral disc (IVD) affects a large portion of population [1]. In the recent years, development of intervertebral disc prosthesis has been a great concern to the world of medicine and science. Substitution of the spinal disc or its part being displaced or damaged due to trauma or a disease process for the artificial structure well imitating high tensile properties and elasticity of the real disc would highly improve the existing treatment techniques. Therefore, a substantial need exists for an easily implantable, prosthetic spinal disc of load-bearing ability and cushioning action simulating the natural disc physiology [2]. Around 70-80% of prostheses are made of metallic biomaterials [3]. The principle advantage for using an all-metal total disc replacement is the inherent high fatigue strength of these materials [4]. It is why the first prosthesis was constituted by a single metal piece, which was in charge of maintaining the space between vertebras. Typically Ti6Al4V titanium alloy was used for this application. Titanium alloys have many advantages compared with conventional stainless steels and cobalt-based alloys, including a lower elastic modulus, superior biocompatibility and an enhanced corrosion resistance [5]. Also this material has good osseointegration properties, allowing adjacent bone cells to grow around the surface of titanium implant. This caused the prosthesis was perfectly attached to the bone, impeding normal movement of the vertebrae. Furthermore, the Young's modulus of titanium is higher than that the one cortical bone, so bone atrophy occurs due to stress shielding between the implant and bone. Moreover, the non-metallic materials, such as polymers and elastomers, have a more similar to the mechanical properties to the natural disc. With a lower Young's modulus, it is easier, in the short term, to replicate disc dynamics. Polyether ether ketone (PEEK) is one of the most used non-metallic materials in biomedicine because of its proven biocompatibility [6]. Difficulties, however, arise when trying to develop a long-lived component having a stable interface between the structure and vertebrae, because the non-metallic materials are not capable for this. In order to solve this problem, different metal-polymer-metal sandwich prostheses have been developed [2], which allow the original movement of a healthy spinal disc, as the one shown in Figure 1. The material used for the metallic part usually is the extensively studied Ti6Al4V titanium alloy. However, it has been recently verified biochemical instability because Vanadium ions might be released [7].

Figure 1. ProDisc-C Total Disc Replacement [1], and simplified sandwich sheet structure

The objective of this study was to compare the mechanical properties of this metal with a new more biocompatible titanium alloy, as Ti6Al7Nb alloy. The procedure followed was to analyze the behavior of two sandwich structures (Ti6Al4V - PEEK - Ti6Al4V and Ti6Al7Nb - PEEK - Ti6Al7Nb) subjected to low velocity perforation. Since animal studies have shown that compressive forces can induce degeneration, it seems there may be a correlation and a limit to the loads the IVD can support before experiencing degeneration. The IVD is a viscoelastic tissue having time dependent responses to loading and experiences nonlinear anisotropic behaviour. Therefore, static and dynamic compressive tests can be used as preliminary indicators of devices and biomaterial structures for potential spinal disc applications [8]. The quasi-static mechanical responses of these titanium alloys are relatively well understood [9]. However, the corresponding response under high strain rates is less clear. In order to determine the optimum formability conditions of such components, and to ensure the mechanical integrity of the finished components, it is necessary to develop a detailed understanding of the mechanical deformation behavior of these alloys over a wide range of strain rates [5]. In this work, experiments in a drop weight tower at different impact velocities (5 m/s and 15 m/s) were carried out. Primary interest is determining the parameters affecting the energy absorption of sandwich configuration. Failure mode and post-mortem deflection of the plates have been examined. In addition experimental test are necessary to validate the proposal of numerical model. This numerical analysis provides relevant information about the mechanical behaviour of IVD prosthesis during the forming process and operation conditions.

2. Material

Three different materials have been used in order to make the composite laminate (Figure 1):

2.1. Ti6Al4V Titanium

Approximately 20–30% of commercially available medical devices are made of Ti6Al4V alloy. Good biocompatibility of that alloy has been attributed to the formation of passive oxide film on its surface. This thin, stable, continuous and adherent oxide layer on the titanium surface protects the metallic substrate from the aggressive environment [10]. Nevertheless, oxidation of the titanium alloy surface may not be sufficient to eliminate the release of titanium, aluminium and vanadium into tissues, organs and body fluids when wearing implants.

2.2. *Ti6Al7Nb Titanium*

Ti6Al7Nb is a high strength titanium alloy with excellent biocompatibility for surgical implants. It is replaced the other alloy in biomedical applications because this alloy is more biocompatible than the alloy that contains vanadium [5]. However this alloy is more expensive and there is not enough research to show that both alloys are mechanically equivalent.

2.3. *Polyether-ether-ketone, PEEK*

PEEK is a linear aromatic polymer which is semi-crystalline and is widely regarded as the highest performance thermoplastic material. PEEK is an ideal replacement for stainless steel, other types of metal tubing, and even glass, for weight reduction, comparable strength/mass, chemical resistance, hardness, and low extractable. Applications of this material may be found in aerospace, medical and chemical industrials. Because of its great biocompatibility, this material is being used for intervertebral prosthesis [11]. The peek used in this study test has been ceded by the company LATI. In particular we have used the Larpeek 50 [12].

3. Experimental setup for low velocity perforation of hybrid sandwich material

The tests were carried out with the machine Ceast 9300 - drop tower impact systems. This experimental configuration allows a perpendicular impact on the sheets within the range of impact velocities 0.5 m/s $\leq V_0 \leq$ 20 m/s. The tested square like specimens possess a size of A_t = 130x130mm^2 and a thickness of h=1 mm for titanium alloys sheets or h=3 mm for PEEK sheets. Tests have been performed both on individual plates of different materials, such as sandwich structures combining PEEK with one of the two titanium alloy. They were clamped by toggle clamps and screws all around the active surface of A_t = 100x100mm^2. Toggle clamps and screws were symmetrically fixed in order to avoid any disturbance during the test. The steel striker used has a hemispherical shape. Its larger diameter is φ_p = 20 mm and its mass is M_p = 0.177 kg. The striker was attached to the instrumented bar of the drop weight tower, whose mass is M_{bar} = 1.182 kg. The bar at the same time is attached to a metal frame, whose mass is M_f = 4.3 kg. Additional mass was added to the setup in order to increase the effective mass to M_{total}= 10.159kg. The time dependent displacement $\delta_s(t)$ of the striker during perforation may be calculated by integration of the impact force versus time curve F(t):

$$\delta_s(t) = \int_0^t \left[V_0 \int_0^t \frac{F(t) \cdot M_{total} \cdot g}{M_{total}} dt \right] dt \tag{1}$$

4. Finite element modeling

4.1. Numerical Model

It has been implemented a three-dimensional numerical model which represents the different low-velocity impact tests carried out in the drop-weight tower. This numerical model was developed using the explicit finite element code Abaqus/Explicit [13]. This numerical model consisted of various solids: the sandwich plate composed by three ones and the striker. 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.In the simulation, the striker was modeled as an analytical rigid because it does not show significant deformation.For the sandwich plate two kinds of elements were used in order to get a good damage-dependent evolution of the zone. As the Figure 2 shows, each plate is divided into three zones. The zone A is the area in contact with the striker. The four-node linear tetrahedron element (C3D4), which allows greater freedom of damage propagation, was implemented in the impact region of each plate defined as an area of 40 mm diameter (twice the diameter of the striker). The zone B is the area corresponds to the transition zone of radial symmetry. It was meshed with eight-node brick hexahedral elements with one integration point (C3D8R). Finally, the zone C is the peripheral region of the plate. In this zone, the sensitivity of the mesh was reduced by a gradually reduction of the element size.

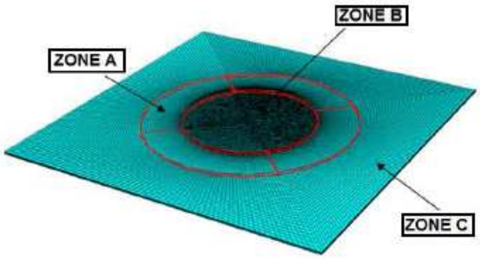

Figure 2. Mesh corresponding to plate divided into three zones.

4.2. Material models

For numerical analysis of the response of each titanium alloy in conjunction with PEEK, the material constitutive law should include strain rate dependency for both material deformation and failure. For PEEK material, the associated thermal softening was taken into account in the Johnson Cook material model, used for other thermoplastic material as ASB [14]. 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 [15] 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):

$$\bar{\sigma}(\bar{\varepsilon}_p,\dot{\bar{\varepsilon}}_p,T)=[A+B\cdot\bar{\varepsilon}_p{}^n][1+C\cdot\ln(\frac{\dot{\bar{\varepsilon}}_p}{\dot{\bar{\varepsilon}}_0})]\cdot[1-T_H{}^m] \tag{2}$$

where T_H is the homologous temperature defined as

$$T_H=\frac{T-T_0}{T_{melt}-T_{room}} \tag{3}$$

where T is the material temperature, T_{melt} is the melting temperature and T_{room} is the room temperature. The different constant and their meaning are defined in Table 1. It is important to consider a thermal softening caused by a great location of plastic deformation. Iit was included a dependence of the temperature for the two titanium alloys as:

$$\Delta T(\bar{\varepsilon}_p,\dot{\bar{\varepsilon}}_p,T)=\frac{\beta}{\rho\cdot C_p}\int\bar{\sigma}(\bar{\varepsilon}_p,\dot{\bar{\varepsilon}}_p,T)d\varepsilon_p \tag{5}$$

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
Ti6Al7Nb	928	1092	0.93	0.014	1.1	1878	1.0
PEEK	120	20	0.36	0.04	0.88	300	0.015

Table 1. Jhonson-Cook model parameters of Ti6Al4V and Ti6Al7Nb [16, 5] and polyether-ether-ketone [11].

In addition to a J-C plasticity model, it was developed a J-C progressive damage model which specifies a damage initiation criterion as well as damage evolution [15]. The general expression for the equivalent plastic strain defined by this model is given by:

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

where η is the stress triaxiality and D_i are constants (Table 2) calibrated according experimental data reported in Lee et al [5]. The damage criterion of for Polyether-ether-ketone (PEEK) has been defined as constant failure strain equal to 0.25 according experimental data of tensile test reported in [11]

Material	**D1**	**D2**	**D3**	**D4**	**D5**
Ti6Al4V	-0.09	0.27	0.48	0.014	3.87
Ti6Al7Nb	-0.03	0.27	0.48	0.014	3.87

Table 2. Constants used to define the J-C damage criterion of Ti6Al4V and Ti6Al7Nb according experimental data [5].

5. Results and discussion

5.1. Experimental observations

Tests have been performed both on individual plates of different materials, such as sandwich structures combining PEEK with one of the two titanium alloy. Plastic instabilities formation and progression are identified as the cause of behind the target collapse for all the impact tests conducted. Fracture observations reveal that the Ti6Al7Nb and Ti6Al4V skin fail predominantly as the result of intensive localisation shearing. The presence of an adiabatic shear band containing voids is clearly observed within the fractured specimen (Figure 3).The growth and coalescence of these voids during the impact process leads to the formation of a macroscopic crack, which ultimately results in the complete separation of the specimen into two parts [5]. The Ti6Al7Nb shows a higher value of maximum force due to higher strain rate sensibility (Figure 5) according to experimental data reported in [5].

Figure 3. Macroscopic cracks by adiabatic shear in Ti6Al7Nb (left), Ti6Al7Nb (center) and Ti6Al4V (right) thin plates tested in drop tower at impact velocity, respectively: 5 m/s, 15 m/s and 15 m/s.

For PEEK core, it is observed changes in the failure mode from ductile for individual thin plates to brittle for polymer core of hybrid sandwich composite (Figure 4). It is observed an increment in the number of craks for higher values of impact velocity (Figure 3 and Figure 4).

Figure 4. Failure of PEEK material: ductile (for individual thin plates) and brittle (for internal core of sandwich material and Ti6Al7Nb skin). Different impact velocity from left to right: 1 m/s, 5m/s, 5 m/s, 15 m/s.

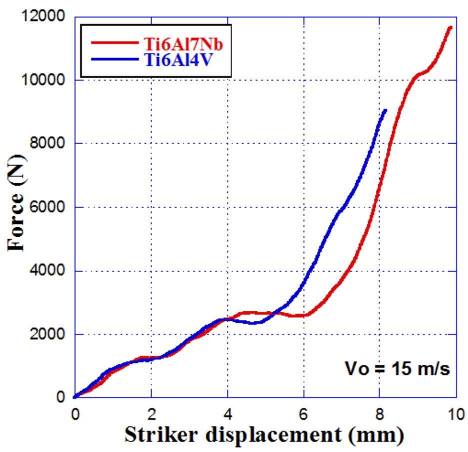

Figure 5. Force displacement curves for individual thin plates of Ti6Al7Nb and Ti6Al4V at impact velocity of 15 m/s

5.2 Validation of numerical modeling

A qualitative agreement for experimental and numerical data was obtained by the model for force-displacement curves (Figure 6) and strain distribution (Figure 7). As the impact velocity increases the value of force peak increase too, due to the effect of the material hardening caused by the strain rate. The plastic work represents 100 % of the energy absorbed by the plate for velocities near to the perforation limit, while for higher impact velocities the inertial effect of the process begin to be relevant[17].

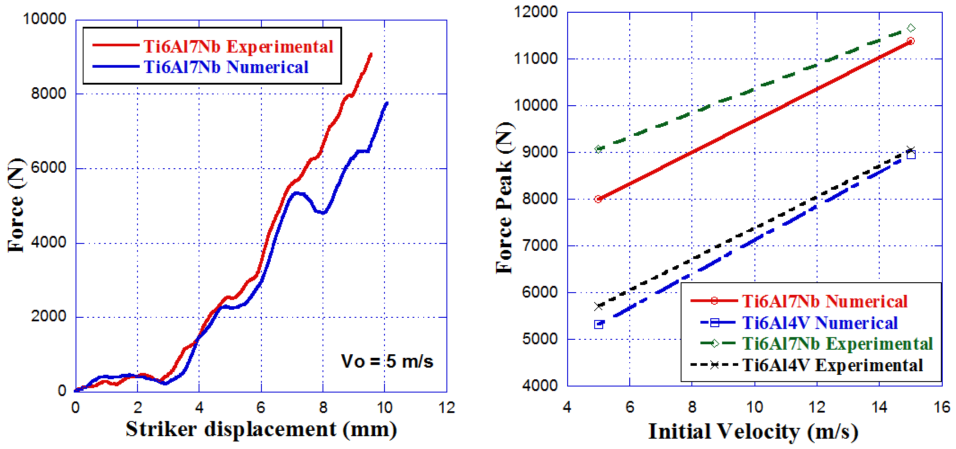

Figure 6. Comparsion beetwen experimental and numerical data Left: force displacement curves, right: force peak versus impact velocity.

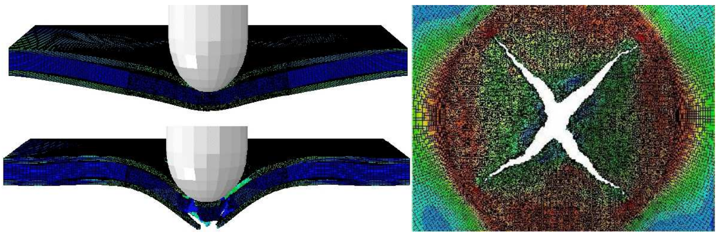

Figure 7. Strain distribution for failure in sandwich Ti6Al7Nb+Peek+ Ti6Al7Nb subjected to impact at 15 m/s in drop tower.

6. Conclusions

The low-velocity impact deformation behavior of Ti6Al4v, Ti6Al7Nb and sandwich configurations with both of these alloys in conjunction with a core of PEEK has been investigated at initial impact velocity from 5 m/s to 15 m/s using a drop weight tower. The experimental and numerical results support the following major conclusions:

-Ti6Al7Nb alloy shows a better puncture resistance than the Ti6Al4V alloy. This effect is considerably neglected when the metal plates are tested in conjunction with a core of PEEK. Therefore, it can be highlighted that structural effects like the geometry or configuration of the composites have more influence than possible local effects. Titanium sheets in hybrid sandwich configuration subjected to punching drop tower test show a principal direction of the failure propagation. It can be observed a main fissure along the direction perpendicularly to the rolling direction, and a secondary fissure along the rolling direction.

-The Johnson-Cook (JC) plasticity model was employed to model the flow stress behavior of the different materials studied in the numerical simulations of hybrid sandwich metal composite. The model includes strain, strain rates and temperature effects (below and beyond transition temperature of polymer). A qualitative agreement for the strain distribution and an under-estimation of about 20% of the maximum impact load was obtained by the model.

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References

[1] B. Whatley, X. Wen. Intervertebral disc (IVD): Structure, degeneration, repair and regeneration. *Materials Science and Engineering C* 32:61-77, 2012.
[2] D. Darwis, P. Stasica, M. Razzak, J. Rosiak. Characterization of polyhydrogel for prosthetic intervertebral disc nucleus. *R Physics* 63:539-542, 2002.
[3] M. Niinomi, M. Nakai, J. Hieda. Development of new metallic alloys for biomedical applications. *Acta Biomaterialia* 8:3888-3903,2012.
[4] Q. Bao, G.McCullen, P. Higham, J.Dumbleton, H. Yuan. The artificial disc: theory, design and materials. *Biomaterials* 17(12):1157-1167,1996.
[5] W. Lee, C. Chen. High temperature impact properties and dislocation substructure of Ti–6Al–7Nb biomedical alloy. *Materials Science and Engineering: A*. 576:91-100, 2013.
[6] D. Williams, A. McNamara, R.Turner. Potential of polyetheretherketone (PEEK) and carbon-fibre-reinforced PEEK in medical applications. *Journal Materials Science Letters* 6(2):188-190, 1987.
[7] M. Metikos-Hukovic, A. Kwokal, J. Piljac. The influence of niobium and vanadium on passivity of titanium-based implants.*Biomaterials*,24(21):65-75, 2003.
[8] J. Iatridis, S. Nicoll, A. Michalek, A. Walter, M Gupta. *Role of biomechanics in intervertebral disc degeneration*. The Spine Journal 13: 243-262, 2013.
[9] M. Niinomi. Mechanical properties of biomedical titanium alloys. *Materials Science and Engineering A*. 243 (1):231-236, 1998.
[10] S. Bruni, M. Martinesi, M. Stio, C. Treves. Effects of surface treatment of Ti–6Al–4V titanium alloy on biocompatibility. *Acta Biomaterialia*, 1:223-234, 2005.
[11] P. Rae, E. Brown, E. Orler. The mechanical properties of poly(ether-ether-ketone) with emphasis on the large compressive strain response. *Polymer*, 48: 598-615, 2007.
[12] LATI. Lati Polyether-ether-ketone materials properties data table. *Technical Report* <http://www.lati.com>; 2014.
[13] H. Hibbitt, B. Karlsson, P. Sorensen. Abaqus user's manual. *Abaqus Explicit 6.12*,2012.
[14] H. Louche, F. Piette-Coudol, R. Arrieux, J. Issartel. An experimental and modeling study of the thermomechanical behaviour of an ABS polymer structural component during an impact test. *International Journal of Impact Engineering*, 36: 847-861, 2009.
[15] A. Arias, J.A. Rodríguez-Martínez, A. Rusinek. Numerical simulations of impact behaviour of thin steel plates subjected to cylindrical, conical and hemispherical non-deformable projectiles. *Eng. Fracture Mechanics*, 75 (6): 1635-1656, 2008.
[16] X. Wang, J. Shi. Validation of Johnson-Cook plasticity and damage model using impact experiment. *International Journal of Impact Engineering*, 60: 67-75, 2013.
[17] J. Rodríguez-Martínez, A. Rusinek, A. Arias. Thermo-viscoplastic behaviour of 2024-T3 aluminium sheets subjected to low velocity perforation at different temperatures. *Thin-Walled Structures*, 49: 819-832, 2011.