Composites: Part B 59 (2014) 21–32

Contents lists available at ScienceDirect

Composites: Part B

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

Experimental and numerical investigations of low velocity impact on functionally graded circular plates

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ARTICLE INFO

Article history:
Received 31 August 2013
Accepted 18 November 2013
Available online 26 November 2013

Keywords:
A. Layered structures
B. Impact behaviour
C. Finite element analysis (FEA)
E. Powder processing

ABSTRACT

This paper addresses low-velocity impact behaviour of functionally graded clamped circular plates. An experimental work was carried out to investigate the impact behaviour of FG circular plates which is composed of ceramic (SiC) and metal (Al) phases varying through the plate thickness by using a drop-weight impact test system. The influence of the compositional gradient exponent and impactor velocity on the contact forces and absorbed energies was concentrated on the tests. The explicit finite element method, in which a volume fraction based elastic–plastic model (the TTO model) was implemented for the functionally graded materials, was used to simulate their drop-weight impact tests. Effective material properties at any point inside FGM plates were determined using Mori–Tanaka scheme. The experimental and numerical results indicated that the compositional gradient exponent and impactor velocity more effective on the elasto-plastic response of the FG circular plates to a low-velocity impact loading. The comparison at the theoretical and experimental results showed that the use of the TTO model in modelling the elasto-plastic behaviour of FG circular plates results in increasing deviations between the numerical and experimental contact forces for ceramic-rich compositions whereas it becomes more successful for metal-rich compositions.

1. Introduction

Engineering structures can experience impact loads during manufacturing, service and maintenance operations. Impact response of structures is strongly dependent on impact conditions. Metal and metal alloys exhibit elastic and plastic deformations under impact, and the damage can be visually inspected on the impact surface. However, composites exhibit limited plastic deformations since impact energy is converted to damage forms, such as delamination, matrix cracking, or fibre breakage and these damage forms do not allow a visual inspection [1]. The impact responses of particulated or layered composite structures have been investigated numerically and experimentally [2–13]. Limited studies on the impact response of functionally graded materials (FGMs) are available. A necessity is evident for a comprehensive analysis to understand the impact behaviour of functionally graded materials.

Functionally graded materials have been increasingly used in design of impact resistance structures as well as in design of advanced thermal barrier coatings. A plate with a functionally graded layer from ceramic to metal through its thickness combines the superior features of ceramic and metal. Thus, the ceramic-rich side provides good protection against projectiles while the metal-rich side offers toughness and strength to maintain the integrity of the structure as long as possible. Therefore, the ceramic plates are used for single impact applications whereas the FG plates can be used for multiple impact applications requiring high ballistic performance [14].

Gong et al. [15] carried out an analytical study on elastic response of functionally graded cylindrical shells subjected to low-velocity impact. They employed Reddy's third order shear deformation theory to accommodate the transverse shear deformation for analysis. Apetre et al. [16] addressed the low velocity impact problem of a sandwich structure with functionally graded core. They concluded that the use of FGM cores in sandwich structures can reduce the impact damage. The another study on low velocity impact response of sandwich structures with functionally graded core was performed by Etemadi et al. [17]. They compared the results of sandwich beams having FG cores the those of sandwich beams with a homogenous core and concluded that the impact performance of the sandwich beams with FG cores is much better. Kubair and Lakshmana [18] investigated the effect of a FG core in layered structures subjected to low velocity impact loading on the energetics of the progressive damage. They simulated damage

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http://dx.doi.org/10.1016/j.compositesb.2013.11.022

initiation and growth using cohesive based finite element framework and showed that the energetics of damage is altered by the presence of a FG core in layered structures. To obtain an effective modelling of FGMs in engineering practice, Larson et al. [19] performed numerical simulations and experimental tests. They achieved a good agreement between numerical and experimental results. Gunes and Aydin investigated elastic [20] and elasto-plastic [21] impact behaviours of functionally graded circular plates under low-velocity impact loads using the explicit finite element method. Mao et al. [22] presented a method to analyse nonlinear dynamic response of FG shallow spherical shell under low velocity impact in thermal environment and investigated the effects of temperature, material and geometrical parameters on contact force and dynamic response of the FG shallow spherical shell structure. Mao et al. [23] developed a mixed hardening plastic model based on conventional theory of mechanism-based strain gradient plasticity using the constituent thermodynamic formulations and performed some parametric analysis by applying in dynamic analysis of micro FGM beams. They introduced some theoretical basis for tailoring FGM beam for engineering applications. Khalili et al. [24] investigated low-velocity impact response of FG plates with temperature dependent properties. They developed a simple computational procedure based on classical plate theory, and used an analytical spring-mass model defining contact behaviour between the impactor and the plate. The effect of impactor velocity, type of FG function and temperature on dynamic behaviour of the system of target plate and the impactor were discussed in detail. Shariyat and Jafari [25] carried out nonlinear analysis a radially preloaded two directional FG circular plate subjected to low-velocity impact by a rigid projectile having spherical nose and presented some results that can be used for both radially and transversely graded circular plates. Kiani et al. [26] investigated low velocity impact response of thick functionally graded beams with general boundary conditions in thermal field. They implemented third order shear deformation beam theory to derive the governing equations and employed a modified contact force model in which the property variations are considered through the thickness. They studied in detail the effect of some parameters such as impactor velocity, impactor mass, graded property profile, boundary conditions, thermal environment and impact energy. Zhang and Zhang [27] investigated optimal design of functionally graded foam material subjected to ball impact. They solved a structural optimization problem with the objective of maximizing the crush force efficiency by using response surface method (RSM) and their optimal design showed a gradually decreasing density from top to the bottom. Unfortunately, we observed that experimental studies about the elasto-plastic impact response of FGMs are insufficient; thus, the manufacturing the FGMs are very difficult and they require high production costs and such produced materials have limited availability in practice.

In this study, the elasto-plastic behaviour of functionally graded clamped circular plates under a low-velocity impact loading was investigated using experimental and computational techniques. In order to examine the influence of the impact energy and the compositional gradient exponent on the impact response of functionally graded circular plates, impact tests were performed using a drop-weight impact testing machine. Three-dimensional explicit FE analyses were carried out using the explicit finite element code LS-DYNA [28] to examine the effects of impact energy and material composition on the plastic strain and stress distributions as well as on the local deformation behaviours in the specimen. The TTO (Tamura–Tomota–Ozowa) model [29] was implemented using user-defined routines in the LS-DYNA code to define the elasto-plastic behaviour of the FG circular plates. The applicability of TTO model was discussed based on the elasto-plastic stress and strain variations especially the properties of local damage regions.

2. Experimental procedure

2.1. Specimen geometry and design

Low-velocity impact tests of Al/SiC functionally graded circular plates were carried out. All layers of the FG specimens were prepared with homogeneous mixture of metal (Al) and ceramic (SiC) powders with a given volume fractions for the experiments.

Specimens were prepared using aluminium alloy (Al 6061) powder with a particle size of 10 μm and silicon carbide (SiC) powder has a particle size of 50 μm. The mechanical properties of Al and SiC are given in Table 1. Circular specimens were used for testing. The geometry of the specimens is schematically shown in Fig. 1. The FGM specimens are of 10 layers, in which the ceramic constituent varied linearly or nonlinearly by means of the compositional gradient exponent (n). The bottom layer of the specimens is pure metal and the top layer has a ceramic volume fraction of 70% (Fig. 1). The FGM specimens were manufactured in five different through-thickness material composition variations (n = 0.1, 0.5, 1.0, 5.0 and 10.0) in order to investigate the effects of compositional gradient exponent on the impact response of FG circular plates. Fig. 2 shows the through-thickness variations of the volume fraction of the ceramic for n = 0.1, 0.5, 1.0, 5.0 and 10.0 between the pure-metal bottom surface and the ceramic-rich top surface. The FGM Al/SiC specimens are 50 mm in diameter and approximately 10 mm in thickness and each of 10 layers is 1 mm (approx.) in thickness.

2.2. Specimen fabrication

All test specimens were prepared by powder stacking-hot pressing technique. Aluminium and silicon carbide powders at different volume fractions were blended mechanically for 5 h in a motorised mixer for proper mechanical alloying. The required quantity for a mixed and blended stock of Al and SiC powders was weighted and put into a circular die made of hot-work tool steel. Then, a unidirectional green compaction was applied to this mixture in the die under an applied pressure of 70 MPa in the thickness direction (Fig. 3). The applied pressure was increased gradually from 0 to 70 MPa, and was held for a period of 1 min at the maximum pressure and then removed. Likewise, each layer of different stock was put on the previous ones by ensuring a uniform thickness and distribution of powders and then the green compaction process was repeated for each layer. The thickness of each layer was kept constant as possible. Later, the compacted specimens in the die were sintered under a pressure of 100 MPa inside a protective Argon atmosphere at a temperature of 640–650 °C for a sintering period of 1 h, and were left to cool under a

Table 1
Material properties of constituents of functionally graded circular plate.

Materials	Young's modulus (GPa)	Poisson's ratio	Density (kg/m^3)	Yield stress (MPa)	Hardening exponent
Al	67	0.33	2702	95.1	7.35
SiC	302	0.17	3100		