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Effect of varied alumina/zirconia content on ballistic performance of a functionally graded material

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ABSTRACT

Functionally graded materials (FGMs) are characterized by continuous variation in their composition and structure with thickness or volume. Hence, the corresponding changes in the properties and functions of the FGMs can be investigated to create new materials. In this study, four-layered FGM specimens with three different compositions, i.e., Al_2O_3/(0, 5, 10, 15%) ZrO_2, Al_2O_3/(0, 10, 20, 30%) ZrO_2 and Al_2O_3/(0, 15, 30, 45%) ZrO_2, were designed. The ceramic specimens were hexagons whose sides were 11 mm long. Accordingly, 6061-T6 Al was used as a back plate. A ballistic test was conducted using 0.3″ armor-piercing bullets with an initial speed of 868 ± 15 m/s. Numerical simulation software, i.e., LS-DYNA, was employed to analyze stress transfer and the fracture of the FGM specimens under impact. The ballistic test showed that the Al_2O_3/(0, 5, 10, 15%) ZrO_2 FGM exhibited the best impact resistance performance. The investigation of microstructures through observation using a SEM did not show delamination in the FGM interlayer after impact. Furthermore, the abrasion between the ceramic and projectile increased. XRD analysis verified the phase transformation of ZrO_2 from the tetragonal phase to the monoclinic phase. This transition delayed crack growth and increased material toughness, thereby promoting the impact resistance performance of the FGMs.

1. Introduction

In recent years, various fields, including material and structural design, numerical simulation, and mathematical theory, have advanced with the development of science and technology. Research in impact and penetration mechanics has provided beneficial results. This complex engineering field is still being extensively studied and discussed because of its wide range of applications. It has been more than fifty years since ceramics were first used in protective materials. Initially, ceramics were widely used in bulletproof vests and helicopter seats during the Vietnam War [1]. Ceramics have high strength, hardness, abrasion resistance, high-temperature resistance, and mechanical performance. Currently, they are globally used in the electronics, automotive, nuclear power, aerospace, biomedical science, and protection industries. The impact resistance design of military structures, armored vehicles, bulletproof vests, spacecraft, carriers, and satellites primarily targets low weight, low costs, and easy manufacturing. Therefore, gradient distribution has become a critical consideration in the new techniques for material design and structure control. Functionally graded materials (FGMs) are new materials that are characterized by continuous and monotonic variation in elements (composition and structure) along their thickness, which results in corresponding changes in material properties and functions. Tests have verified that the impact resistance performance of an FGM structure is superior to that of ceramic/metal composite armor [2]. Therefore, improvements in the impact resistance performance of materials introduced by a functionally graded design would make FGMs one of the leading future trends. Lightweight design primarily reduces consumption of fuel, which results in energy conservation and carbon reduction. Therefore, the design of protective battlefield armors is moving toward lightweight materials (Fig. 1) [3].

Z. He et al. [4] employed a simple method involving die pressing and pressureless sintering in their study on ceramic/metal FGMs to manufacture a five-layered Al_2O_3/Fe FGM. Analysis indicated that the FGM exhibited significant improvement in fracture toughness and crack deflection at weak interfaces, as compared to a monolithic Al_2O_3 ceramic. Z. Zhang et al. [5] adopted spark plasma sintering (SPS) to produce a four-layered TiB/Ti FGM. The results showed that a stable graded temperature field could be obtained without cracks on a microstructure's observation surface during SPS. Furthermore,

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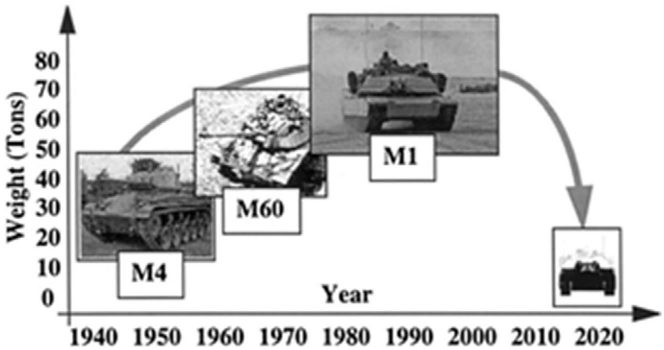

Fig. 1. Radical weight reduction for future ground vehicles.

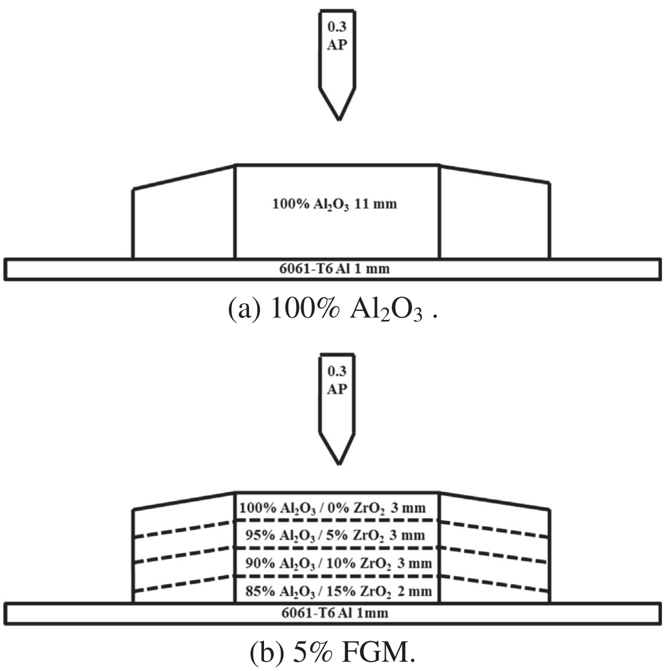

Fig. 2. Specimens for AP ballistic test.

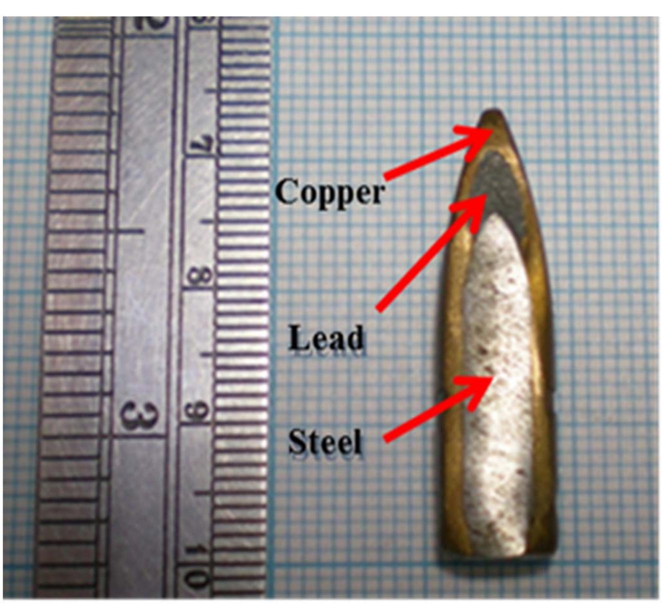

Fig. 3. Section of 0.30″ armor-piercing bullet.

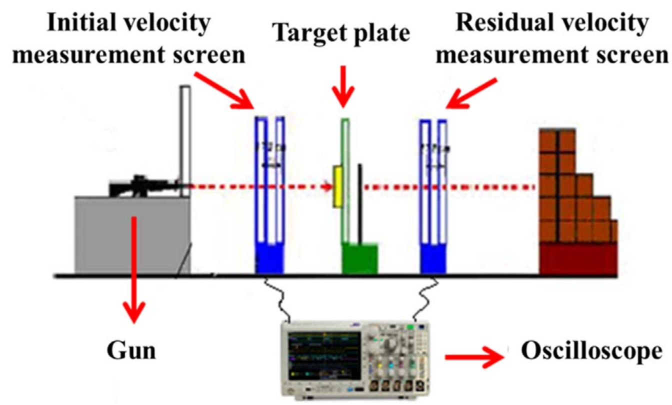

Fig. 4. Schematic diagram of the ballistic test.

microhardness was relatively high at interfaces, which indicated a good combination between every two layers of the material. M.S. El-Wazery et al. [6] successfully produced a six-layered (ZrO_2/Ni) FGM and conducted in-depth research and analysis on its linear shrinkage, electrical conductivity, fracture toughness, and Vickers hardness by utilizing the powder metallurgy technique. R. Zhang et al. [7] prepared 3Y-ZrO_2/(3Y-ZrO_2 + Ni) sandwich ceramics using cold isostatic pressing and pressureless sintering. In addition, they conducted detailed research on porous ZrO_2 and ZrO_2/(ZrO_2 + Ni) sandwich ceramics. Under the same low thermal conductivity (approximately 0.85 W/m K), the mechanical performance of 3Y-ZrO_2/(3Y-ZrO_2 + Ni) sandwich ceramics was better than that of monolithic porous ZrO_2 ceramics. This result was attributed to the effects of metal toughening and sintering-induced residual thermal stress on the mechanical performance of the sandwich ceramics. H. Tsukamoto [8] employed SPS to manufacture the ZrO_2/Ti FGM, and based on tests, they concluded that higher ZrO_2 content leads to a higher microhardness value.

Several studies have been conducted on ceramic/ceramic FGMs. V. Trombini et al. [9] and F. Meng et al. [10] used SPS to sinter nanocomposite materials. V. Trombini et al. added 5 vol% (60–100 nm) ZrO_2 into Al_2O_3-based (0.2 μm) materials. Meng et al. added 5–10 vol% (40 nm) ZrO_2 into the same materials (0.6 μm). Consequently, ceramic hardness or fracture toughness improved significantly. A. Reyes-Rojasa et al. [11] sintered a ceramic material, Al_2O_3/ZrO_2 (1.5 mol% Y_2O_3), using hot isostatic pressing (HIP). Tests verified that compressive strain could be improved by increasing t-ZrO_2 content. F. A. T. Guimarães et al. [12] applied pressureless sintering to produce a nanocomposite material, Al_2O_3, with 1 vol%, 3 vol%, and 5 vol% m-ZrO_2 contents. Microstructural analysis showed that the microhardness, flexural strength, and wear resistance of Al_2O_3 with 5 vol% m-ZrO_2 increased by 8%, 11%, and 23%, respectively, as compared to those of inclusion-free Al_2O_3. L. Sun et al. [13] discovered that residual stress was generated during ceramic sintering because sintering temperatures and thermal expansion coefficients were not close. Additionally, they determined the optimal shrinking percentage and sintering curve and successfully manufactured a three-layered Al_2O_3/ZrO_2 FGM. In 2012, E. M.M. Ewais et al. [14] designed an eleven-layered Al_2O_3/ZrO_2 FGM by employing reaction sintering. Furthermore, they analyzed its microstructure, hardness, and fracture toughness. The optimal sintering temperature and sintering time were 1650 °C and 6 h, respectively.

FGM conceptual design has been applied in the field of protective materials with gradually advancing research achievements. A. Pettersson et al. [15] sintered and produced a TiB_2/Ti FGM using SPS, in which 7.62 mm armor-piercing bullets were utilized to obtain an FGM with a more superior ballistic resistance than that obtained using HIP. In addition, the SPS realized low-temperature sintering in a short period and the growth of small crystal particles to achieve higher densification. X.F. Zhang et al. [16] analyzed the ballistic resistance performance of a 95% Al_2O_3 ceramic and 10% ZrO_2 toughened alumina