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On the ballistic performance of the AA7075 based functionally graded material with boron carbide reinforcement

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Abstract

In this study, the functionally graded materials (FGMs) bearing three layers were produced via hot pressing to investigate their ballistic performances against 7.62 mm armor piercing (AP) projectile. In the FGM samples, the bottom layer was considered as unreinforced AA7075 alloy, whereas the middle and top layers were made of the AA7075 composite layers having various proportions of B_4C particles. Prior to the ballistic testing, the hardness change in the layers with respect to aging time at different temperatures was determined. And then, the ballistic testing of the samples was performed at a ballistic laboratory using 7.62 mm AP projectile. In the ballistic testing, five separate specimens for each FGM group having fixed composition and thickness were used. The experimental results showed that the ballistic impact resistance of the investigated FGMs increased with increasing boron carbide content and the thickness in the layers. Moreover, there were no separations observed between the layers in the failed samples.

Key words: functionally graded material, powder processing, aging, ballistic testing

1. Introduction

Functionally graded materials (FGMs) consisting of two or more different layers appear to be a candidate for use in armor applications [1, 2]. In this type of material, each layer has special properties to create a completely different function under specific applications which are not possible with monolithic materials [1–4]. With the development in science and technology, multi-functional materials are strongly needed to get high performance and efficiency. FGMs may become a solution in some applications to provide more than one action. In order to get various mechanical, chemical, electrical, nuclear, and/or thermal properties at different locations or layers, the FGMs have been produced using various methods, namely, thermal spraying, coating, powder metallurgy and other thermomechanical processes [3, 4]. Up to now, the studies on the FGMs were performed on the structural [5–15], thermal [16], and nuclear [17, 18] applications. And also, some studies were conducted on the ballistics of FGMs [19–22]. Pettersson et al. [19] examined the FGM of Ti-TiB_2 as an armor material which was produced by spark sintering. They tested the material using 7.62 mm and tungsten cored projectiles. It was concluded that the ballistic performance of the FGM was better than that of the monolithic TiB_2 [19]. Moreover, Dutta and DiPaolo [21] mentioned that FGMs were more successful in absorbing shock energy due to the reflections and transmissions at interfaces.

As it can be seen from the literature survey, the studies made on the impact performance of FGMs under real projectiles are very limited. Therefore, many more studies are needed to be done to clarify ballistic properties of the FGMs. Making lightweight armors is very crucial to defend against various ballistic threats. Therefore, different types of material should be developed and tested to attain lighter defence systems which maintain energy saving and enhanced mobility. The main motivation in this study was to determine the performance of the FGMs against the 7.62 mm armor piercing (AP) projectile with a steel

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core and their suitability as a lightweight armor material in some defence applications. To do this, three layered FGMs consisting of B_4C and AA7075 in various proportions with separate layers were considered. This paper presents the ballistic performance of these FGMs tested by steel-cored 7.62 mm AP projectile.

2. Experimental route

In this work, two different types of FGMs were produced with respect to the composition of middle and top layers. In the FGM samples, a heat treatable aluminum alloy, AA7075 and boron carbide ceramic particles were considered as the components. At the bottom layers of the both FGM samples, unreinforced AA7075 alloy was used. On the other hand, in the first FGM sample, 10 % B_4C and 20 % B_4C reinforced AA7075 composite layers were utilized at the middle and top layers, whereas in the second one, the 20 % B_4C and 40 % B_4C particle reinforcements were taken into account at the same layers, respectively. One of the main objectives was to detect the effect of amount of boron carbide in middle and top layers on the ballistic performance of the FGMs. The manufacturing of the samples was made via powder metallurgy technique in which hot pressing technique was applied to the samples at 580 ℃ during the period between 25 and 60 min. The details of the production can be found in our previous works [23, 24]. The first FGM sample was subjected to the artificial aging treatment at various temperatures (100 ℃, 120 ℃ and 150 ℃) after the solutionizing treatment for the sake of the comparison with the aging data on second FGM sample [24]. The micro characterizations for the first FGM were also conducted after the production. After that, the three-point bending tests were carried out for both the solutionized and peak-aged samples. Next, the 7 cm square sized FGM samples with the highest hardness (aged at 120 ℃ for a certain period) were prepared in three different thicknesses, 15 cm, 20 cm and 25 cm to analyze the effect of thickness on their ballistic impact behavior. The samples were subjected to ballistic impact using steel-cored 7.62 mm AP projectile. The setup for the ballistic impact testing is represented in Fig. 1. The mean velocity of the projectile was recorded as 785.6 $\mathrm{m\,s^{-1}}$ for all shots. For each sample having unique composition and thickness, five specimens were used and each target specimen was subjected to only one normal shot. After completing the ballistic testing, the macro failure mechanisms for the tested FGMs were examined.

3. Experimental results and discussion

Figures 2–4 illustrate the aging behavior of the first FGMs at 100 ℃, 120 ℃ and 150 ℃, respectively. The highest hardness values are reached during the aging

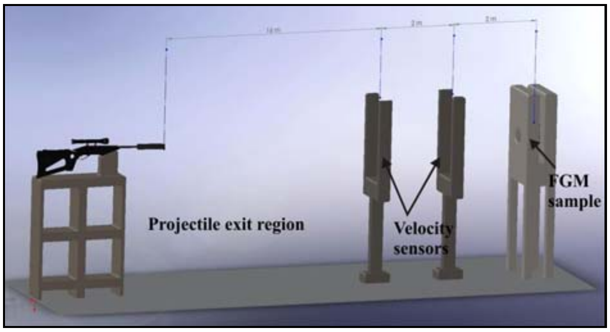

Fig. 1. The ballistic testing setup for the FGMs.

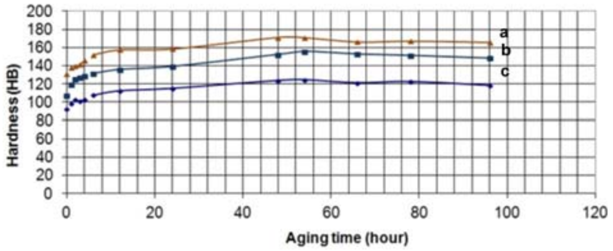

Fig. 2. Hardness in the first FGMs with aging time at 100 ℃ for a) top layer, b) middle layer, c) bottom layer.

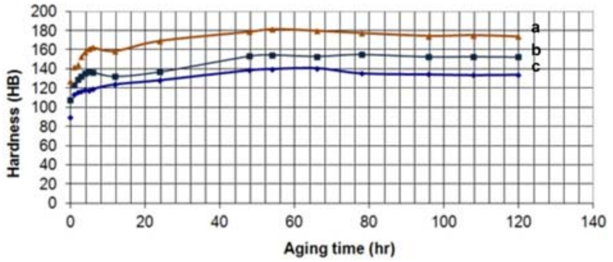

Fig. 3. Hardness variation of the first FGMs with aging time at 120 ℃ for a) top layer, b) middle layer, c) bottom layer.

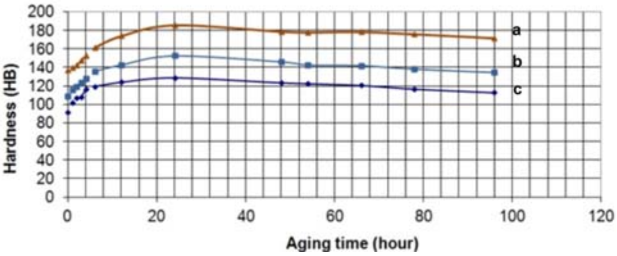

Fig. 4. Hardness profile of the first FGMs at 150 ℃ for a) top layer, b) middle layer, c) bottom layer.

at 120 ℃. At this temperature, there is a continuous increment observed in the hardness of all layers until the aging period of 54 h. The peak hardness values are HB 140, 154 and 181 at the bottom, middle and top layers, respectively, at the end of the aging period of 54 h. And then, there is a very slow reduction in the hardness observed between 54 and 120 h. At the end of the aging period of 120 h, the hardness values are recorded as HB 134, 152 and 174 for the same layers, respectively. The shapes of the curves are very similar to each other for the three layers. This means that the addition of the ceramic particles has no significant effect on the aging kinetics of the precipitates as in the case of the second FGM sample studied in the previous study [24]. At the aging at 100 and 150 ℃, the hardness values are found to be somewhat lower. As expected, the decrease in the ceramic particles in the layers caused the decrease in the macro hardness [24]. The aging affects the hardness values of the layers at a great extent due to the heat treatability of AA7075 matrix [25–27]. The main contribution to the rise in the hardness is the formation of nano-scale precipitates of the metastable phase of η' [25, 26] during the aging treatment. The highest hardness values reached in the second sample were HB 145, 181 and 247 from bottom to top layers after the aging at 120 ℃ for the range of 48–66 h of aging time [24].

The microstructure pictures for the three layers of the first FGM sample are given in Fig. 5. One can observe that there is a good distribution of the ceramic particles in the matrix. Moreover, a good metallurgical interface is formed between the layers (Fig. 6). The uniform formation of the interface is very important to transmit shock waves effectively throughout the thickness of the FGMs in the ballistic performance. Furthermore, the uniform distribution of the ceramic particles in the matrix materials leads to more homogeneous mechanical properties at the layers.

The bending strength of the first FGM sample (containing 10 % B_4C at the middle and 20 % B_4C at the top layers) is measured to be 538 MPa and 568 MPa for the solutionized and peak-aged cases, successively. There is a remarkable rise in the strength after the aging treatment due to the hardening of the matrix material. For the second FGM sample (consisting of 20 % B_4C at the middle and 40 % B_4C at the top layers), the strength values of 456 and 527 MPa were obtained at the same conditions, respectively [24]. The results of the bending testing indicate that an increase in the ceramic content of the medium and top layers causes a negative effect on the bending strength. This may be due to the fact that the reduction in the cross section of the matrix material leads to a lower resistance to the applied load. And also, the higher ceramic contents make the composite layers more brittle.

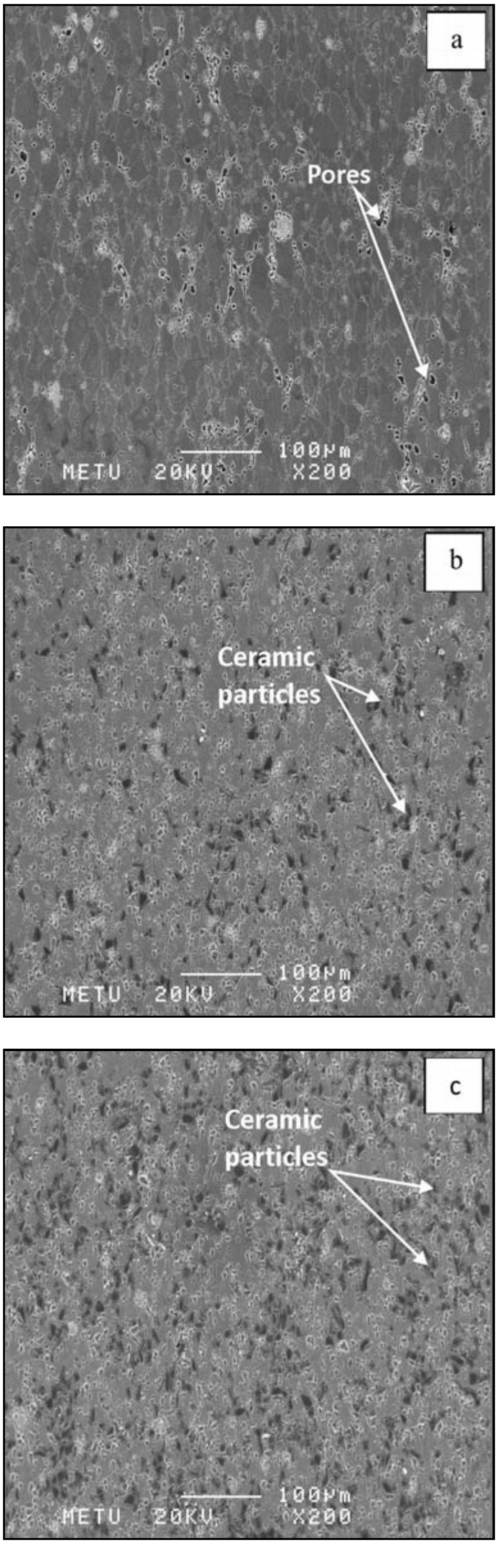

Fig. 5. The micro-photos of the first FGM at: a) bottom layer – AA7075, b) medium layer – AA7075 with 10 % B_4C, c) top layer – AA7075 with 20 % B_4C.

The investigated samples of two FGM groups failed against the impact of 7.62 mm AP projectile. According to the macro-examinations, the main failure mechanism is the plug formation for the first FGM samples. A typical picture of this failure is shown in Fig. 7 for

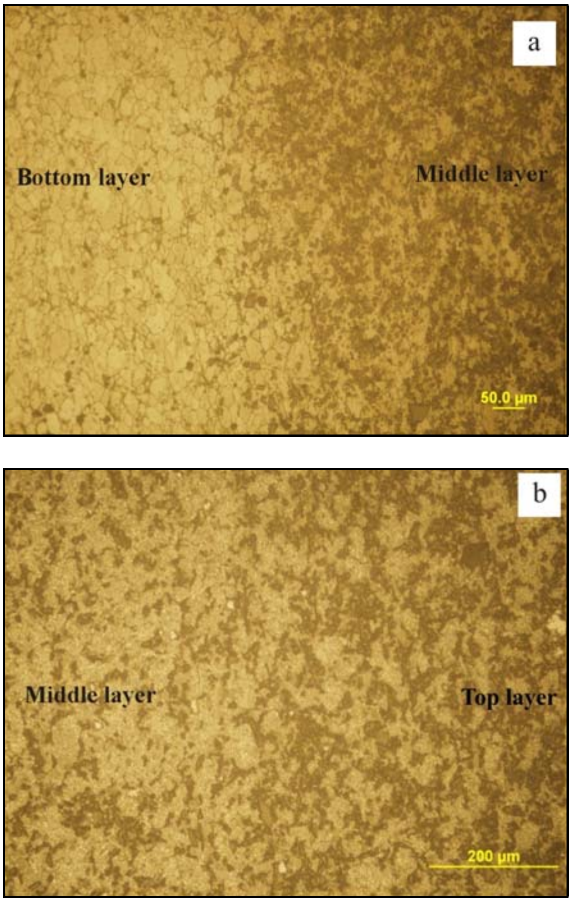

Fig. 6. Interfaces in the first FGM between a) bottom and intermediate layers, b) intermediate and top layers.

the 15 mm thick specimen. The diameter of the hole created by the projectile at the front side of the sample is lower than that formed at the rear side (projectile exit zone). This means that the kinetic energy of the projectile is spread into the larger area at the rear layers. This is generated due to the more brittleness nature of the composite layers.

For the second FGM group, the propagation of the projectile was found to be much harder. Figure 8 depicts the macro-view of the tested 20 mm thick sample. The formation of plug and radial cracks is observed in this sample group. Although an increase in the ceramic content of the layers makes the projectile propagation harder, it also increases the brittleness of the FGMs. The macro cross-sectional view of a sample along with the projectile direction is represented in Fig. 9. The shear deformation of the layers along with the projectile direction is observed apparently. And also the shear deformation of the layers can be observed around the hole created by the projectile. Moreover, due to the high temperatures caused by the friction between the material and projectile, a local melting is detected in the hole, especially Pb melting.

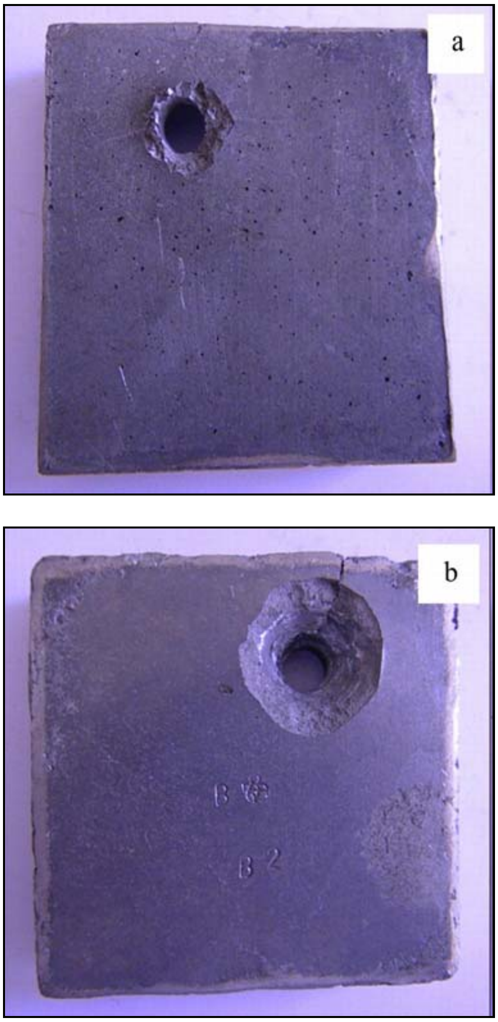

Fig. 7. The view of the tested 15 mm thick FGM with low B_4C reinforcement: a) front view, b) rear view.

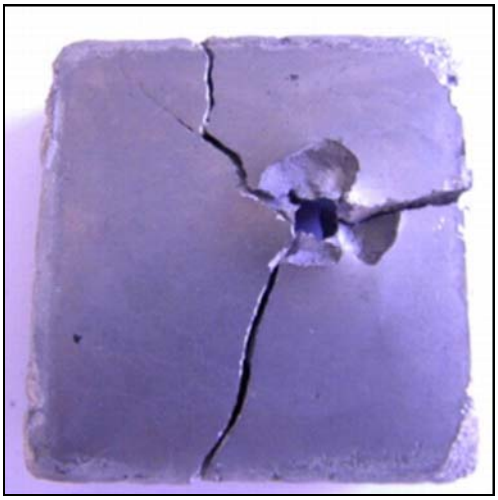

Fig. 8. The rear view of the 25 mm thick FGM sample with high ceramic reinforcements.

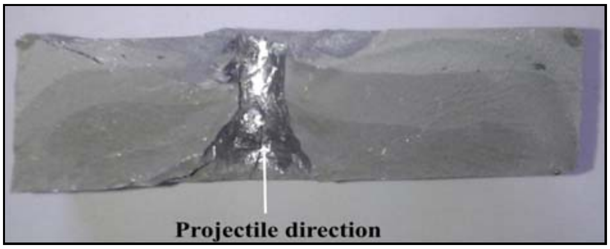

Fig. 9. Macro cross-sectional view of the FGM with low ceramic content after the ballistic testing.

The investigated FGMs did not show the ballistic success against 7.62 mm AP projectile. For this reason, their performances were found significantly lower than those of the alumina/4340 steel [28] and alumina/aluminum laminated composites [29]. In the ballistic testing of these laminated composites, the projectile was stopped at the areal density of 55 and 66 kg m^{-2}, successively. In order to get the ballistic resistance with the investigated FGM samples, the areal density must be greater than $\sim$ 65 kg m^{-2}. This means that thicker FGM samples would be required to attain the same ballistic resistance with the laminated composites. One of the main reasons for the failure of the FGMs at the ballistic testing was due to their lower efficiency in blunting and eroding the projectile compared to the monolithic ceramics since they have much lower hardness values. As a second reason, the ballistic impact resistance of the ceramic/metal laminated composites is enhanced substantially via the formation of a conoid structure on the front ceramic layer when projectile hits because this structure widens the kinetic energy of projectile to a larger area [30–35]. There was no conodial structure formation observed at the layers of the FGM samples after the ballistic impact. The composite layers could not have served as a strong and hard layer against the projectile propagation due to the distribution of micron-sized ceramic particles in the matrix.

4. Conclusions

The experimental results brought out that the investigated FGM samples containing AA7075 and boron carbide failed under the impact of 7.62 mm AP projectile. The performances of the FGMs were obtained lower than those of laminated composites [28, 29]. For this reason, the investigated FGMs appeared to be not suitable for producing lightweight armor. The main mechanism in the failure of the FGM samples was detected as formation of plug with radial cracks. The FGM samples having a thickness greater than 25 mm would be needed to withstand the projectile without any failure. In order to get a higher ballistic efficiency, much higher hardness values by increasing the ceramic content (especially at the top layer) would be required in the FGMs. However, this would be impractical or very difficult via powder metallurgy.

Acknowledgements

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