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Original Article

A comparative study on mechanical and ballistic performance of functionally graded Al6061 composites reinforced with B₄C, SiC, and Al₂O₃



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ABSTRACT

In the present study, functionally graded Al6061 composites reinforced with boron carbide (B₄C), silicon carbide (SiC), and alumina (Al₂O₃) were prepared using the stir and centrifugal casting techniques. Arc-shaped functionally graded metal (FGM) specimens were treated with a hot-rolling process to enhance their mechanical properties and obtain laminated plates. Then, the impacts of ceramic reinforcements on the density, microhardness, tensile strength, and ballistic resistance of FGMs were studied. Moreover, the microstructural properties of the specimens were analyzed to elucidate the particle gradient from the inner to the outer surface. As a result, the microstructure observations revealed that the ceramic particles are dispersed from the inner to the outer periphery of the FGMs with centrifugal acceleration. A more homogeneous particle distribution was obtained in B₄C-reinforced FGM compared to those of SiC and Al₂O₃. The hot-rolled FGM specimen reinforced with B₄C offered the lowest density. The microhardness was improved by 32% and 30.4% in the inner to outer regions of the SiC- and Al₂O₃-reinforced FGMs, respectively, while it was improved by 22.6% in B₄C-reinforced FGM. On the other hand, the tensile strength and elongation of the B₄C-reinforced FGM specimen were better than those of the SiC- and Al₂O₃-reinforced FGMs. In addition, the highest ballistic protection was achieved with B₄C-reinforced laminated FGM at an impact speed of 664.25 m/s with a penetration depth of 14 mm, while the impact speeds of SiC- and Al₂O₃-reinforced FGMs were 500.88 and 435.23 m/s, respectively.

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1. Introduction

Functionally graded materials (FGMs) are combinations of two or more compositions and different microstructure gradients in a particular direction that are mixed to achieve the desired properties from an engineering material [1]. FGMs present a solution to the tradeoff between hardness and toughness by dispersing reinforcement elements in different gradients throughout the same structure [2]. Therefore, FGM structures with uniformly distributed reinforcement particles can address this issue.

Several FGM production methods are available i.e., powder metallurgy, centrifugal casting, thermal/plasma spraying, electrochemical processing, and chemical/physical vapor deposition. Although there is more than one method, centrifugal casting is the most practical and dependable way to create FGMs among all of these techniques [3]. In the production of FGM with the centrifugal casting technique, the molten metal mixture in which the ceramic particles are homogeneously dispersed is poured into a thin-walled cylindrical mold that is rotated at a certain speed by a motor [4]. The ceramic particles are dispersed in the matrix structure from the inner to the outer periphery of the specimen owing to centrifugal force. The FGM is solidified on the internal surface of the mold based on its solidification rate [5]. The amount of centrifugal force varies due to particle characteristics, and thus enables the regulation of the particle dispersion speed. There are two types of particles in the centrifugal casting method. The first is high velocity/high density/large size particles and the second is low velocity/low density/small size particles. The most widely used ceramics are B_4C , SiC, and Al_2O_3 which have superior reinforcement ability owing to their specific characteristics especially in ballistic armor [6]. Numerous investigations have been carried out on the centrifugal casting process for producing FGMs. Some of these studies are summarized as follows: Huang et al. [7] produced aluminum-based SiC-reinforced FGM pistons using the centrifugal casting technique and investigated the characteristics of macro-morphologies and microstructures of pistons. They found that the hardness of composite pistons made by centrifugal casting increased up to 23.7 HRB (Hardness Rockwell B). Mallick et al. [8] used a horizontal centrifugal casting technique to fabricate an aluminum 356-based SiC particle-reinforced FGM composite cylinder. The authors determined the maximum hardness of 14.9 RHF (Rockwell hardness value in “F” scale) in the outermost layer of the sample reinforced with 8 wt% SiC particles, and this value gradually decreased towards the inner layer. Karun et al. [9] who manufactured functional grade A356/SiC composites using centrifugal casting, studied the hardness and wear behavior of resulting composites. It was stated that the cast and heat-treated Al-20% SiC FGM samples exhibited hardness behaviors of 72 and 126 BHN (Brinell hardness) in the outer layer, respectively. Kumar et al. [10] produced an Al_2O_3 -reinforced FGM using a vertical centrifugal casting technique at revolution speeds of 800 and 1200 rpm. The results yielded higher wear resistance and hardness in the outer region of the FGM. Prasad et al. [11] investigated the effect of rotational speed on centrifugally cast specimens. The authors achieved a hardness value of

approximately 45 VHN (Vickers hardness) at maximum speed. Jojith and Radhika [12] fabricated a WC-reinforced LM25 aluminum alloy matrix FGM using the centrifugal casting method and reported increased mechanical and wear properties in the outer region of the FGM. The researchers determined the highest hardness value of 126 HV at 1 mm from the outer perimeter. Moreover, the highest and lowest tensile strengths were measured as 156.65 and 83.67 MPa, respectively. El-Galy et al. [13] examined the mechanical and wear properties of SiC-reinforced FGMs produced through centrifugal casting. They identified a correlation between the tensile strength, hardness, and wear resistance depending on ceramic particles' size and concentration. In their study, while the maximum Brinell hardness values measured in the sample containing 2.5 wt% SiCp were 34, the maximum Brinell hardness was determined as 49 in 10 wt% SiCp. Wu et al. [14]. Manufactured 6061Al/SiCp FGMs using the vacuum hot pressing method and investigated the fracture toughness and fracture behaviors of manufactured FGMs.

FGMs with gradual ceramic content has also attracted the attention of the defense and armor industries, as it provides high protection against high-speed ballistic impacts. The reinforcement using ceramic particles enhances the stiffness of the layers. Moreover, a higher concentration of ceramic particles in the outer region provides better ballistic protection with fewer layers [15–17]. Weight, energy absorption capacity, and resistance to multiple impacts and damage are of utmost importance when selecting materials for effective ballistic protection [6]. Therefore, researchers have carried out some studies to determine the degree to which FGM materials meet these criteria. For example; Chao et al. [18] fabricated B_4C -reinforced AA2024 matrix-based FGMs using the squeeze casting method and investigated the ballistic performance of the specimens. The authors found that the ballistic performance of aluminum based-FGMs could be improved by designing a gradient structure with a B_4C ratio ranging from 25% to 70% by volume. Kurzawa et al. [19] worked on the ballistic behavior of a squeezed cast AC-44200 alloy reinforced with Al_2O_3 particles. They suggested that further research on laminated composites was required to achieve higher ballistic resistance. Sharma et al. [15] manufactured a B_4C particle-reinforced Al–Zn–Mg–Cu matrix FGM and studied its ballistic performance. The test results showed that a 70 vol% B_4C -reinforced FGM effectively distributed the kinetic energy of the projectile and exhibited significant ballistic resistance aided by the abrasive friction and adhesive properties of the FGM. Moreover, the highest hardness in the ceramic-rich top layer of FGM with 70 vol% B_4C was found to be 266.7 HV. Kirmizi et al. [20] produced a SiC-reinforced (at fractions of 15, 30, 45, and 60 wt%) AA7075 matrix FGM employing the powder metallurgy technique and then, investigated the mechanical and ballistic properties of the specimens. It was found that with the use of FGM materials, the ballistic speed has been increased from 437 to 449.6 m/s. In addition, the highest hardness value was measured as 194 HB approximately.

From the literature summary presented on the topic of the study, it is seen that various studies have been carried out on the hardness, strength, microstructure, wear properties, and ballistic performance of ceramic-reinforced FGMs. In the available literature, some important points drawn from these

studies can be summarized as follows: (i) FGMs are a good alternative to compensate for the deficiencies in the trade-off between the strength and toughness of stir casting. (ii) Compared to stir casting and powder metallurgy, centrifugal casting is more advantageous both structurally and economically in the production of FGMs. (iii) The changing mechanical properties of FGMs from the outer layer to the inner layer are critical for the defense and armor industry. (iii) Although the ballistic performance of FGMs is relatively good, the method is open to improvement. Therefore, more studies are needed to improve the ballistic performance of FGMs. (iv) While aluminum alloys are mostly used as the matrix in FGMs, SiC, Al₂O₃, and B₄C are frequently used as ceramic reinforcement elements. However, there was no comprehensive study comparing their performances in various aspects. (v) Although the highly added reinforcements increased the outer surface hardness of the FGMs, they decreased the toughness. This is especially undesirable for armor materials that are subject to multiple impacts.

This study outlines a new methodology to fabricate ballistic armor materials using centrifugal casting and laminated by hot rolling and aims to develop cost-effective functional graded lightweight armor materials. For this purpose, aluminum 6061 ingots were melted in a furnace, and 8 wt% B₄C, SiC, and Al₂O₃ particles were separately added. Then, three different cylindrical FGM specimens were fabricated by the centrifugal casting method. The resulting FGMs were cut along the perpendicular to the cylindrical axis into four sections and subjected to a hot rolling process to produce laminated FGMs and achieve higher ballistic performance. Throughout this study, the effects of reinforcements particles and fabrication routes on density, microstructure, microhardness, and tensile strength have been investigated, and then the ballistic resistances of the developed FGMs have been studied comprehensively with a 7.62×51 mm M₈₀ caliber projectile.

2. Materials and methods

2.1. Materials and fabrication process

In this investigation, commercial aluminum 6061 alloy ingots were used as matrix material. Aluminum 6061 is one of the most widely preferred aluminum alloys because it has excellent casting ability, ductility, weldability, and formability, as well as good corrosion resistance [21]. The melted aluminum alloys were reinforced with 8 wt% B₄C, SiC, and Al₂O₃ ceramic particles to increase the tensile deformation and fracture behavior of the aluminum 6061 based on the previous research results [22]. The average particle size of SiC and Al₂O₃ was less than 40 µm and B₄C was less than 50 µm. Tables 1 and 2 list the chemical composition of the AA6061 alloy and the physical properties of the ceramic particles used in this study, respectively.

Al6061/8 wt% B₄C, Al6061/8 wt% SiC and Al6061/8 wt% Al₂O₃ FGMs were fabricated by following the mechanical stir casting, and centrifugal casting routes and then subjected to hot rolling processes. A digital electric melting furnace with a graphite crucible capable of reaching 1500 °C was used to melt

Table 1 – Chemical composition of the aluminum 6061 alloy (wt%).

Mn	Fe	Mg	Si	Cu	Zn	Ti	Cr	Other	Al
0.15	0.70	1.20	0.80	0.40	0.25	0.15	0.35	0.15	Balance

the specimens. To produce each specimen, 1600 g AA6061 alloy ingots were melted at 800 °C, and reinforcement ceramics i.e., 8 wt% of SiC, Al₂O₃, and B₄C preheated at 400 °C for 30 min before they were added to the matrix alloy during mixing. The mixing process was performed in an argon-shielded gas environment. The molten metal was stirred for 60 min at a rotational speed of 1800 rpm with an overhead stirring motor mechanism until it reached the desired viscosity and uniform particle distribution in the matrix structure. To prevent heat loss during the mixing process, the molten mixture was covered using an insulated furnace cover. A specially designed mixer was used to obtain a homogeneous mixture by creating a vortex effect during the mixing process. The liquid composite material was poured into the preheated cylindrical steel mold (inner diameter of 64 mm and length of 500 mm), rotating at 900 rpm in a casting time of 4 min. The cylindrical steel mold was preheated to 400 °C for 40 min to prevent thermal shock when pouring the molten metal into the mold and keep the flow of the metal.

The mold rotation speed is an important parameter that maintains the flow characteristics of the molten metal and, most significantly, ensures an even distribution of particles [11]. Therefore, the rotation speed was determined by considering the values recommended in the literature and those provided by commercial enterprises performing centrifugal casting [23,24]. The rotation process in centrifugal casting was continued at 900 rpm for 5 min to ensure an even radial distribution of the particles owing to the centrifugal force after the melted alloy was poured. During the process, the cooling rate was slowed down by gradually reducing the temperature of the rotating cylindrical mold to prevent sudden cooling in the outer region of the specimens and obtain a finer grain structure.

After centrifugal casting, tubular FGMs with an outer diameter of 100 mm, length of 500 mm, and thickness of 18 mm were obtained. Then, FGMs were left to cool down to room temperature (RT) and were cut perpendicular to the cylindrical axis with a vertical saw machine into four sections from the same location for hot rolling. The arc-shaped FGMs were subjected to a hot rolling process to improve their mechanical properties and obtain prismatic plates. The samples were rolled at 450 °C in eight stages, during which their thicknesses were reduced to 7 from 18 mm. After hot rolling,

Table 2 – Physical properties of the matrix and reinforcement elements.

Alloy elements	Density (g/cm ³)	Melting Temperature (°C)	Vickers Hardness (kg/mm ²)
AA6061	2.70	650	
B ₄ C	2.52	2350	~4000
SiC	3.20	2730	~3000
Al ₂ O ₃	3.97	2040	~1365

the FGMs were cut into $240 \times 240 \times 7$ mm dimensions and prepared for ballistic testing.

Density, microstructure, and microhardness measurements were performed after the hot rolling of the FGMs. Tensile test specimens were cut in the rolling and transverse directions from each FGM block. At the end of the hot-rolling procedure, three hot-rolled FGMs were combined using two adhesives supplied by SUN-FIX. These adhesives are very effective in joining metals at RT and can be mechanically processed. The compressive and tensile strengths of the two adhesives were approximately 80 and 30 MPa, respectively. A 4-mm-thick-AA7075-T6 alloy was used as a support plate on the backside of the armor. A Schematic view of the FGMs fabrication process is shown in Fig. 1.

2.2. Mechanical and microstructural characterization

Density measurements were taken from the centrifugally cast and hot-rolled specimens and then compared with the theoretical density values. A Sartorius scale with 0.1 mg sensitivity based on the Archimedes principle was used to take FGMs density measurements.

Normally, the theoretical densities of the composites can be calculated using the rule of mixtures in homogenous composites with Eq. (1).

$$\rho_{FGM} = \rho_{AA6061} \times v_{AA6061} + \rho_C \times v_C \quad (1)$$

Here, ρ_{FGM} denotes the FGM density, and v_{AA6061} and v_C are the weight fraction of AA6061, and B_4C , SiC, and Al_2O_3 in FGM, respectively.

However, the reinforcement particles with high density have a greater velocity than low-density particles, and the large particles move faster than smaller particles in the molten matrix under centrifugal force. In this case, the particles exhibit more dispersion behavior toward the outer periphery of the FGMs, and the density calculation changes as stated by Watanabe et al. [25]. The calculation of the theoretical densities of the FGMs fabricated under centrifugal force requires a comprehensive study. For this reason, the theoretical densities of the FGMs are not considered in this study.

The FGM plates were cut on a wire electrical discharge machine (Wire EDM) for microstructural analysis and tensile strength tests. The surfaces of the microstructure samples were sanded on a wet rotating disc with 400, 600, 800, 1000, and 1200 sandpapers, respectively. Then, polishing processes were conducted with a diamond suspension of 3 and 1 μ m squeezed onto the felt. Optical examinations were performed with a Leica DM4000 M optical microscope. A TESCAN MAIA3 XMU scanning electron microscope (SEM) was utilized to observe the fracture surface of the tensile test specimens and ballistic effects on the FGMs.

Microhardness and tensile strength tests were carried out to determine the influence of ceramic particle reinforcement on the mechanical properties of FGMs. Surface hardness measurements were taken from the inner, middle, and outer regions of the FGMs (refer to Fig. 2 (a) and (b)) due to the differences in the radial distribution of the particles. As shown in Fig. 2 (c), the FGM hardness values were measured at three different locations at 1 mm intervals on a 7 mm cross-sectional area, and their averages were calculated. Vickers hardness measurements (HV 0.3) were performed according to the ASTM E384 standard.

The tensile test samples were cut in the rolling and transverse directions using a wire EDM according to the ASTM E8 M – 04 standard [26] and dimensions provided in Fig. 2 (d). Thus, the effect of rolling and transverse directions on the tensile strength was also investigated for FGMs reinforced with B_4C , SiC, and Al_2O_3 ceramic particles; then, the results were compared. Tensile tests were performed at a constant strain rate of 1 mm/min using an Instron 3369 universal testing device with a tensile capacity of 50 kN.

2.3. Ballistic resistance tests

Ballistic shooting experiments were done in the accredited ballistic test laboratory of Otokar, Turkey. The ballistic test setup is shown schematically in Fig. 3. Projectile shootings were done based on European EN 1522 ballistic standard [27], except for the target plate size. Ballistic shots were taken at different speeds from 10 m at an angle of 90° . 7.62×51 mm

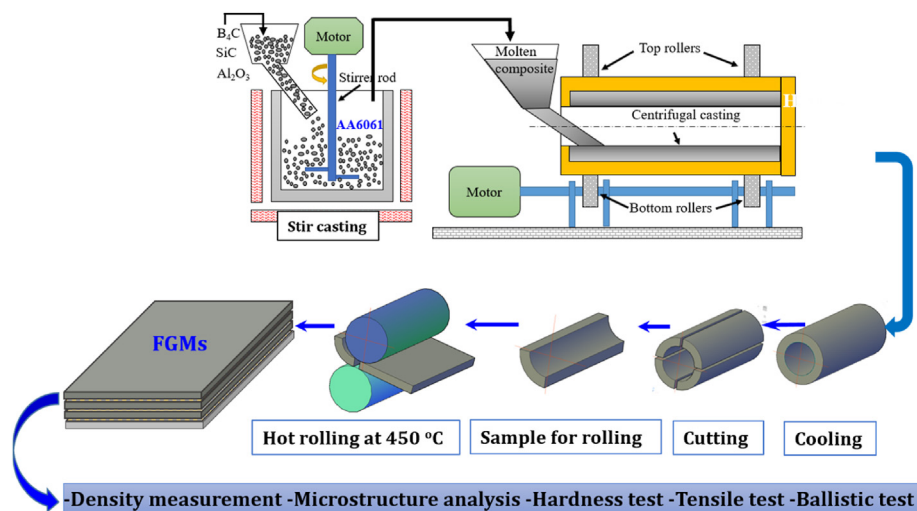


Fig. 1 – Schematic view of the FGM fabrication process.

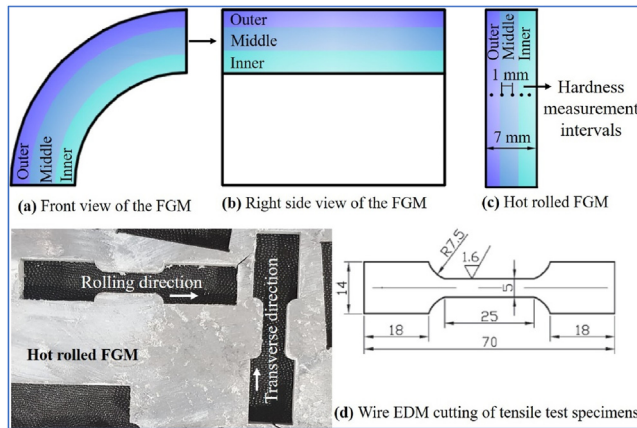


Fig. 2 – (a) Front view and (b) right side view of hardness measurement regions of FGMs, (c) hardness measurement intervals, and (d) dimensions of the tensile test specimens.

NATO Ball M₈₀ projectiles were employed in the ballistic impact experiments. The projectile impact speed was adjusted by reducing the amount of gunpowder in the cartridges. The projectile impact speed was recorded using a chronometer synchronized with two LED photovoltaic detectors located 2.5 m away from the armor. Laminated FGMs with a size of 240 × 240 mm were fixed in a holder fixture (refer to Fig. 4). Four ballistic shots were fired at each sample by reducing the projectile impact speed; subsequently, the V50 ballistic speed limit was determined. Then, the specific ballistic energy was computed using the areal density values and FGM ballistic limit velocities. The ballistic shot conditions are listed in Table 3.

3. Results and discussion

In this section, density, microstructure, microhardness, tensile strength, fracture surface analyses, ballistics performance, and specific ballistic energies of FGMs were investigated. The result and discussion for each output are presented in sub-sections.

3.1. Density

The experimentally measured density values of the FGMs and their percentage density variations are provided in Fig. 5. Density measurements of the centrifugally cast and hot-rolled specimens were separately performed. The lowest density

value was obtained for B₄C-reinforced FGM owing to the low density of B₄C ceramic particles. Depending on the density of the ceramic particles, B₄C-reinforced FGM was followed by SiC- and Al₂O₃-reinforced FGMs, respectively. It is possible to observe increased density values in hot-rolled FGMs compared to centrifugal-cast FGMs. After the centrifugal casting process, the thickness of the composite specimens was reduced from 18 to 7 mm as a result of the eight-stage hot rolling process. Thus, the hot rolling process led to a reduction in porosity and grain refinement in the matrix structure due to the pressure applied to the FGMs, which resulted in decreasing volume. Therefore, the differences in density can be attributed to grain refinement and decreasing porosity in the matrix structure owing to the hot rolling process.

3.2. Microstructure

Figs. 6 and 7 show the distribution of the B₄C, SiC, and Al₂O₃ particles in the inner, middle, and outer regions of hot-rolled FGMs after centrifugal casting. In optical micrographs, the ceramic particles were less densely dispersed in the inner regions of the samples, while their dispersion density gradually increased towards the outer parts. Since the reinforcement particles were driven from the mold axis to the outer periphery of the specimens during the centrifugal casting process with centrifugal acceleration and dispersed toward the middle and outer circumferences. Subsequently, the microstructural gradient changed, and different microstructures were achieved within the same material. In addition, it was observed from the optical micrographs and SEM images in Figs. 6 and 7 that a uniform particle dispersion is achieved in B₄C-reinforced specimens compared to those reinforced with SiC and Al₂O₃ particles. This is due to the size of the ceramic particles. That is, the particle sizes of SiC and Al₂O₃ were smaller than that of B₄C. Thus, the large particle size (or low density) of B₄C allowed it to disperse uniformly in the matrix structure, whereas the small size and high density of SiC and Al₂O₃ ceramic reinforcements led to sectoral agglomerations in the FGM's structure. Karakoç et al. [28] investigated the microstructure and mechanical behaviors of Al6061 + SiC + B₄C composite material. They noticed that reinforcement ceramics at a ratio of 6 wt%B₄C+6 wt%.SiC caused local agglomeration within the Al6061-based composite material. This was seen as an important factor in the reduction of tensile strength in composite material. In another study conducted by Harichandran and Selvakumar [29], agglomeration and micro-porosities were observed when the presence of B₄C in the molten aluminum alloy exceeded 6% by weight. The researchers attributed this to the high surface/volume ratio and low wettability of the ceramic particles [29].

Studies of microstructure in Figs. 6 and 7 indicated that the concentrations of the Al₂O₃ and SiC particles in the outer periphery of the FGMs reached their highest value and that a gradual decrease toward the inner periphery of the FGMs occurred. Because the higher density Al₂O₃ and SiC reinforcement particles are dispersed in the outer periphery of the specimen under centrifugal force, the density of the composites increases toward the outer periphery [13,30]. On the other hand, B₄C particles are dispersed in the inner, middle, and outer peripheries of the specimen since the density of B₄C

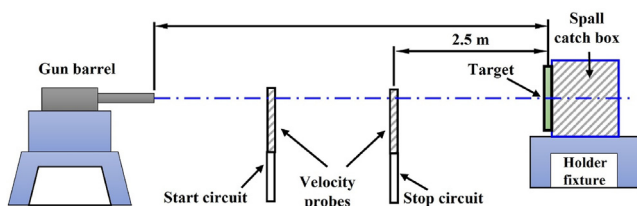


Fig. 3 – Schematic the ballistic test setup (Otokar Ballistics Test Laboratory, Turkey).

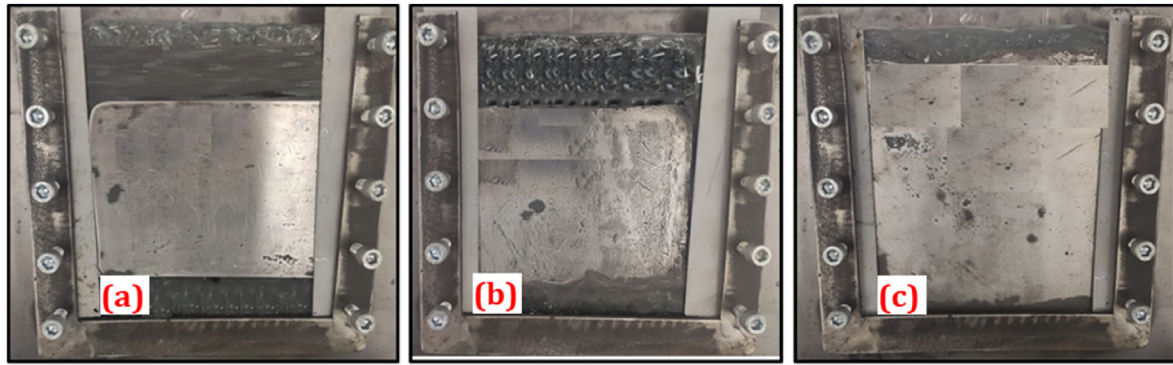


Fig. 4 – Holder fixture used to attach the target armor plates to the spall catch box for a) B_4C plate, b) Al_2O_3 plate, and c) SiC plate.

particles is lower than that of the aluminum 6061. From the optical images, it was seen that the large B_4C particles moved toward the outer periphery of the specimen, whereas the smaller B_4C particles concentrated in the middle and inner zones. This can be attributed to the fact that the motion of large particles will be faster than that of smaller particles in a viscous melted matrix under centrifugal force according to Stokes' law. Consequently, the large B_4C particles migrated preferentially toward the outer zone of the FGMs, and it can be said that the obtained results are consistent with Watanabe et al. simulation results [25].

3.3. Microhardness

The thickness of the FGMs manufactured using the centrifugal casting method was reduced to 7 mm by hot rolling. Then, microhardness measurements were made on the inner, middle, and outer regions of the specimens at 1 mm intervals. Fig. 8 depicts that the microhardness values of the FGMs increased with increasing distance from the inner to the outer section. The highest hardness value was 73 HV for Al_2O_3 -reinforced FGM at 1 mm below the outer circumference of the FGMs. The microhardness values of the SiC- and B_4C -reinforced FGMs were measured as 70 and 65 HV, respectively. In the middle regions of the FGMs, the microhardness values of

Al_2O_3 - and SiC-reinforced FGMs were measured as 66 HV, whereas that of the B_4C -reinforced FGM was 60 HV. The microhardness values measured at the inner zones of B_4C - and SiC-reinforced FGMs were 53 HV, whereas that of the Al_2O_3 -reinforced FGM was 56 HV. It is noticed that the microhardness variation in the outer and inner regions of B_4C -reinforced FGMs was 22.6%, while the variation in the SiC- and Al_2O_3 -reinforced FGMs were 32% and 30.4%, respectively.

The optical micrographs and SEM images in Figs. 6 and 7 indicate that local agglomerations and non-uniform particle dispersion were formed in the SiC- and Al_2O_3 -reinforced FGMs. The measurements were likely performed in agglomerated regions resulting in higher hardness values. Thus, the higher microhardness values and variations can be attributed to the non-uniform dispersions in the FGM structure. Mallick et al. [8] reported similar results and they concluded that the faster solidification and agglomerations of the reinforcement particles resulted in hardness variations. The lower hardness values obtained at the inner region were due to the dispersion of the particles toward the outer region of the specimens because of centrifugation. Therefore, the higher hardness values in the middle and outer regions were due to the high concentration dispersion of B_4C , Al_2O_3 , and SiC particles from the center to the outer periphery of FGMs caused by the centrifugal acceleration experienced during centrifugal casting.

Table 3 – Impact velocity and thickness values of specimens.

FGMs	Shot no	Impact Velocity (m/s)	Test results	V50 (m/s)	Thickness, (mm)	Density, (g/cm ³)	Areal density, (kg/m ²)
Al6061/8 wt% B_4C	1	760.44	CP1	676.585	25.2	2.66	67.03
	2	714.36	CP2				
	3	664.25	PP1				
	4	567.29	PP2				
Al6061/8 wt% SiC	1	612.16	CP1	523.87	24.6	2.71	66.67
	2	555.82	CP2				
	3	500.88	PP1				
	4	426.62	PP2				
Al6061/8 wt% Al_2O_3	1	607.34	CP1	485.8175	24.8	2.78	68.94
	2	566.45	CP2				
	3	435.23	PP1				
	4	334.25	PP2				

*PP: Penetration, partial, *CP: Penetration, complete.

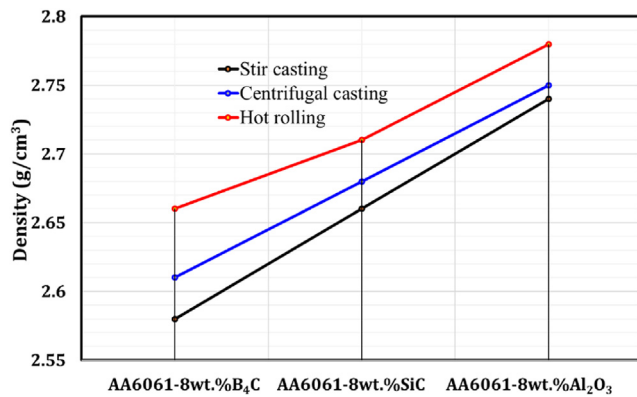


Fig. 5 – Experimental densities of FGMs.

3.4. Tensile strength

Tensile test samples were cut along both the rolling direction (RD) and transverse direction (TD) using a wire EDM after hot rolling. Hot rolling is a secondary deformation process, and it is known that it is an effective method for reducing the volume percent of porosity formation and obtaining a more homogeneous particle distribution in metal matrix composites [31,32]. Hot rolling is widely used in aluminum matrix composites to reduce stir-casting defects by grain refinement and fragmentation of reinforcement particles [33]. Furthermore,

the distribution of the reinforcement particles can be modified after hot deformation processes, and thus excellent mechanical properties are achieved [34]. Therefore, the effects of the rolling and transverse directions on the tensile strength of each sample were also compared. Figs. 9 and 10 depict the tensile test results and percentage elongation rates of the FGMs. The highest tensile strength values both in the RD and TD were obtained with the B₄C-reinforced FGM.

The tensile strength and elongation rate of B₄C-reinforced FGM in the RD were 252.36 MPa and 27.69%, respectively. For TD, the tensile strength and elongation rate of B₄C-reinforced FGM were determined as 227.98 MPa and 22.40%, respectively. The tensile strength in the rolling direction was 10.70% higher than that in the transverse direction. The tensile strengths in the RD of SiC- and Al₂O₃-reinforced FGMs were 184.68 and 139.27 MPa, respectively. Moreover, the tensile strengths of both FGMs in the transverse direction were measured as 158.70 and 127.15 MPa, respectively. The percentage elongations of both FGMs in the rolling and transverse directions were quite close to each other. Therefore, it can be stated that the grain direction had a positive effect on the tensile strength of FGMs. The improved tensile strength in the RD can be attributed to the presence of long grains formed in the hot RD.

Microstructure and fracture surface analyses revealed that B₄C particles were more uniformly dispersed in the FGMs. Therefore, the higher tensile strength values indicate that the homogeneously dispersed B₄C particles form a good

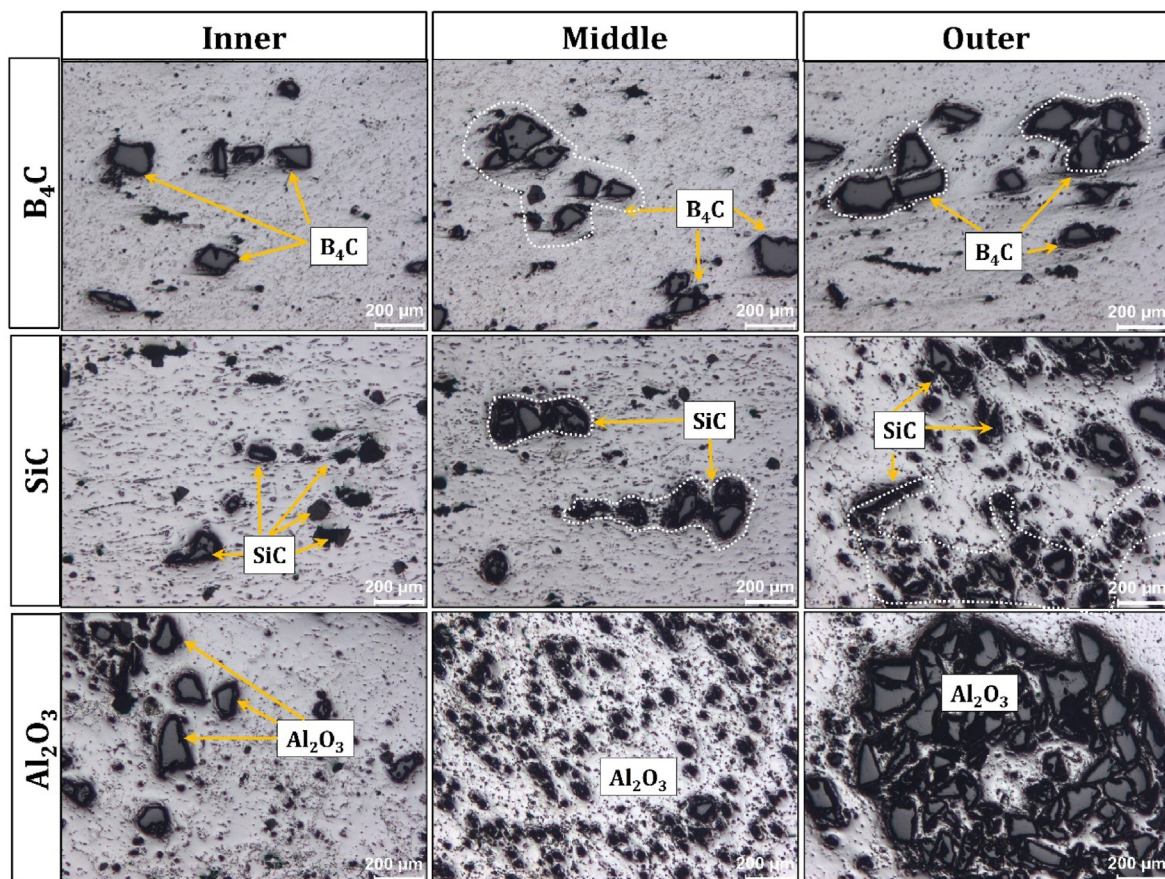


Fig. 6 – Particle dispersions in FGMs.

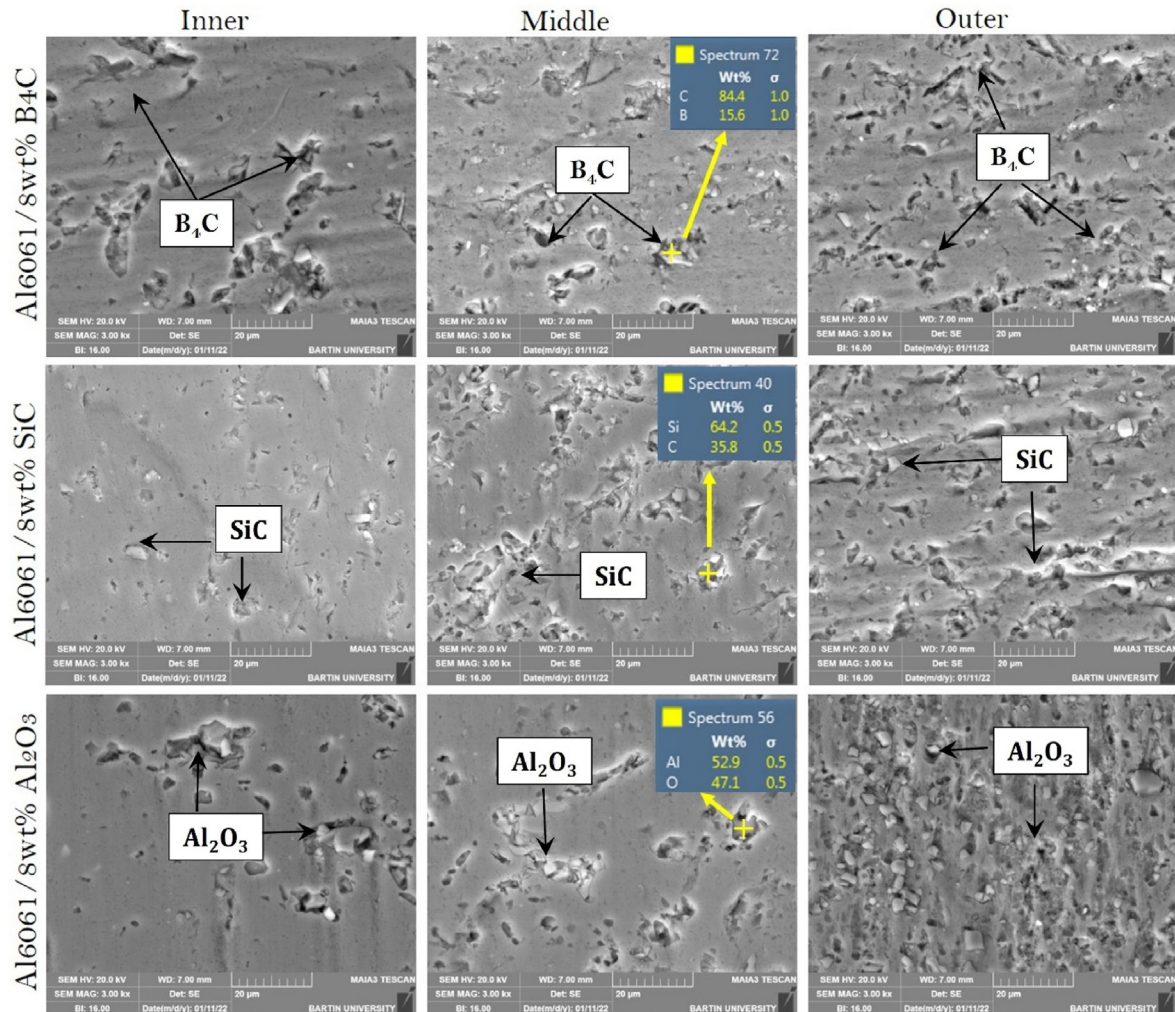


Fig. 7 – SEM micrographs indicating the particle dispersions and interfaces in FGMs.

interfacial bond within the FGM structure through the hot rolling process, preventing dislocation movement during the tensile test and slowing down the specimen fracture. Uniformly dispersed particles in the matrix structure can act as preventative dislocations and restrict their movement. The tensile stress can be transferred to B₄C particles, and the dislocations bypass the particles, creating Orowan loops around the particles. Thus, B₄C particles increase the stress required for deformation. This can be stated that during the hot deformation process, the reinforcement particles enhanced the rate of grain refinement and dislocation generation in the matrix structure by promoting the formation of Orowan loops. On the other hand, the frictional impacts between roll surfaces and the surface of the specimen under non-lubricated conditions produce additional shear strain on the surface of the specimen in the hot rolling process. This additional shear strain generated parallel to the rolling direction has a significant effect on the microstructure of the specimen, resulting in increased dislocation density and work hardening rate [35]. These results are in parallel with the findings of the previous studies [32,36,37].

The presence of local agglomeration in the matrix structure results in the formation of small voids and weak bonding

between the particles in SiC- and Al₂O₃-reinforced FGMs. These defects cause a decrease in the tensile strength of FGMs. Therefore, these findings may be a result of agglomeration and inadequate bonding at the matrix/particle interface [28,38,39]. Hence, it can be stated that the mechanical properties were affected by the uniform dispersion of the reinforcement particles used in the FGM structure.

The fracture surfaces of the tensile test specimens were analyzed using SEM. Figs. 11–13 show the fractographies in the rolling and transverse directions, respectively. The B₄C- and SiC-reinforced FGMs exhibited ductile fracture behavior with fine dimples on the fractured surfaces in the RD (Fig. 10). Meanwhile, the dimple sizes in the TD direction were larger than those along the RD. No crack formation was observed on the fracture surfaces in both directions in B₄C-reinforced FGM. It is noticed that B₄C particles remained embedded on the fracture surfaces, and cracks occurred on the B₄C particles. Therefore, there was a good interfacial bond structure between the particles and matrix structure owing to the presence of the B₄C particles on the fracture surface. The B₄C particles disrupted the dislocation movement and prevented crack formation in the matrix structure. However, microvoids were observed on the fractured surface owing to the increased

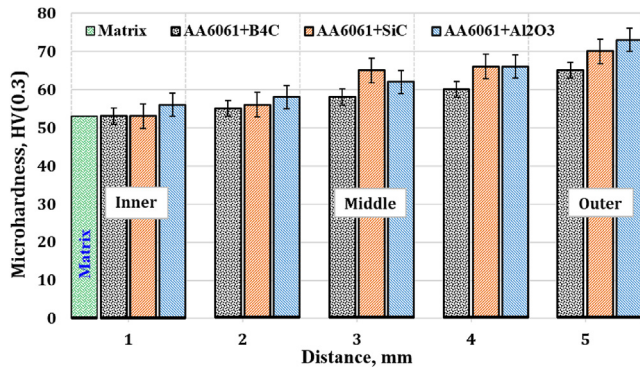


Fig. 8 – Hardness variation of FGMs with increasing distance from inside to outside.

tensile load in the specimens. In the TD tensile specimen, microvoids were integrated with other microvoids and caused larger voids on the fracture surface as can be seen in Fig. 11.

SiC particles remained on the fractured surface of the SiC-reinforced FGM, similar to that observed in the B₄C-reinforced FGM, and cracks occurred on the particles and did not leave the matrix structure as seen in Fig. 12. Local agglomerations were observed on the fractured surface, and these defects in the matrix structure caused a decrease in the tensile strength of the FGM. Owing to the increase in tensile strain, microvoids combined with other microvoids on the fracture surface of the TD sample formed larger voids. However, as shown in Fig. 12, the crack formation did not occur on the fractured surface.

The reason for the low tensile strength of the Al₂O₃-reinforced FGM can be explained by the agglomerations that occurred in the FGM structure. Crack formation and voids were observed on the fracture surfaces of the RD and TD tensile specimens. During the tests, microvoids enlarged owing to the increase in tensile load and the applied load exceeded the maximum tensile strength, leading to crack formation (Fig. 13). Since the ceramic particles were not uniformly distributed in the matrix structure and had weak interfacial bonding, they were easily separated from the matrix structure. Therefore, the Al₂O₃ ceramic particles did not act as crack stoppers and did not contribute positively to the tensile strength.

3.5. Ballistic behaviors of FGMs

The ballistic performances of FGMs manufactured using stir casting and centrifugal casting, and subsequent hot rolling was investigated. Furthermore, the deformation mechanisms of FGMs under ballistic impact were analyzed. The thickness of the FGMs was reduced to 7 mm by hot rolling, and then joined using an adhesive to form a three-layer laminated structure. During the centrifugal casting process, the particles were densely dispersed in the outer region of the FGM. Therefore, the outer region of the FGM was placed in front of every layer, and the softer inner regions were placed at the back. An AA7075-backing plate of 4 mm was placed at the fourth layer of each armor specimen. Subsequently, three different armor FGMs were subjected to ballistic impact tests, and their ballistic resistances were compared. The V50 ballistic speed limits were calculated after four ballistic shots at the speeds listed in Table 3 for each specimen.

Ballistic limit velocity (V_{BL}) is specified as the maximum velocity at which the projectile cannot fully penetrate the target below this velocity in the MIL-STD-662 F standard [40]. According to this standard, it is expected that armor of a given thickness and mechanical properties will always hold the projectile at its specified maximum velocity. The MIL-STD-662 F standard accepts the statistical approaches because of the cost of ballistic tests and the impossibility of precisely maintaining shot velocity. Therefore, ballistic limit protection velocity (V_{50}) is described as the arithmetic average of an equal number of the highest partial penetration and the lowest full penetration velocities. The ballistic protection criteria suggest using at least two partial penetration (PP) velocities and two penetration, complete (CP) velocities, depending on the armor materials and test conditions [41]. V_{50} ballistic limit protection velocities were computed accordingly based on four different velocities for penetration, PP, and penetration, CP shots. V_{50} ballistic limit was calculated using Eq. (2) and the results were presented in Table 3.

$$V_{50} = \frac{CP1 + CP2 + PP1 + PP2}{4} \quad (2)$$

During the ballistic tests, the projectile encountered the first layer rich in ceramic reinforcement particles, then passed to

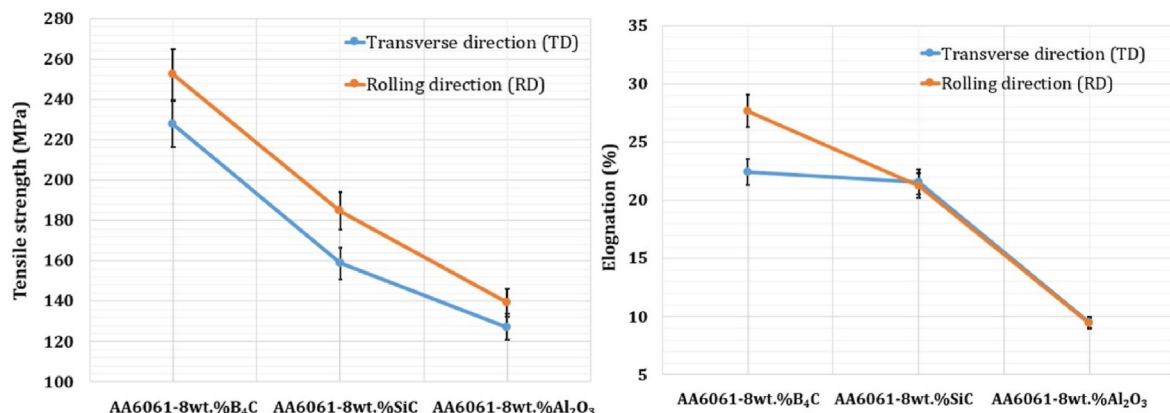


Fig. 9 – Tensile test results of FGMs: (a) Maximum tensile strength and (b) Elongation (%).

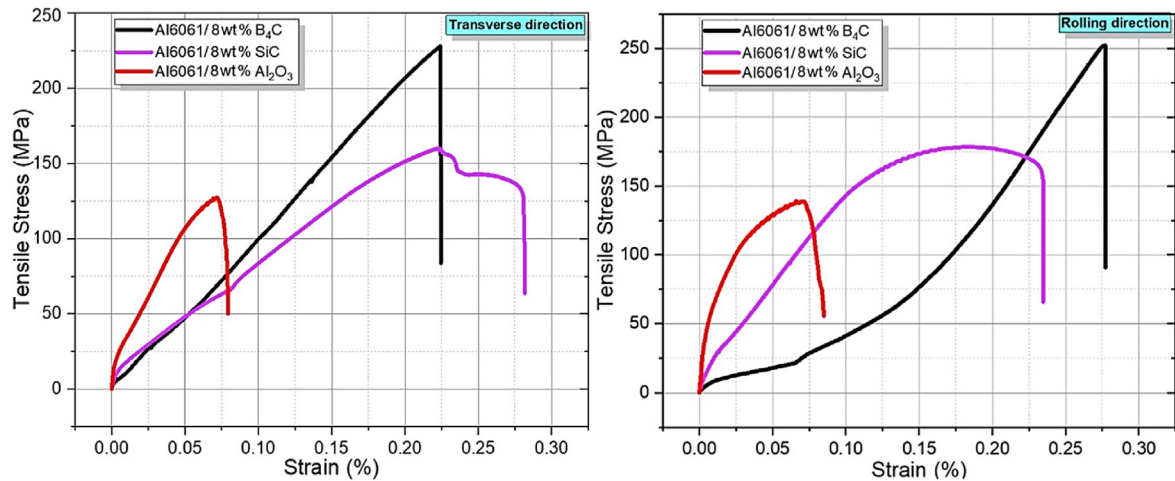


Fig. 10 – Tensile stress and strain curves of FGMs (a) transverse direction (b) rolling direction (%).

the second and third layers in the laminated structure, encountering rich ceramic reinforcements at every layer. Figs. 14–16 show the perforated and partially penetrated FGMs after the ballistic shooting. The first ballistic shot was fired on a 25.2 mm thick B_4C -reinforced FGM at a speed of 760.44 m/s (Fig. 14 (a)). The FGM could not resist the impact of the projectile and was completely perforated. The impact velocity of the projectile was reduced by approximately 8%, a second shot was conducted at 714.36 m/s, and the FGM was completely penetrated again. Tensile stress cracks were generated at the layer interfaces owing to the stress waves that occur during

ballistic impact (Fig. 14). The specimen exhibited ductile behavior in ballistic tests and did not exhibit any breakage or fragmentation behavior. However, the aluminum rear plate placed on the back of the armor material fragmented at the projectile exit point.

The bullet impact speed was gradually reduced, and two shots were fired at impact speeds of 664.25 (Fig. 14 (b)) and 567.29 m/s. The FGM specimen managed to stop the bullet fired at these two impact speeds. The FGM specimen could stop the projectile at 14 mm from the rear surface at an impact speed of 664.25 m/s. The projectile speed was decreased due to

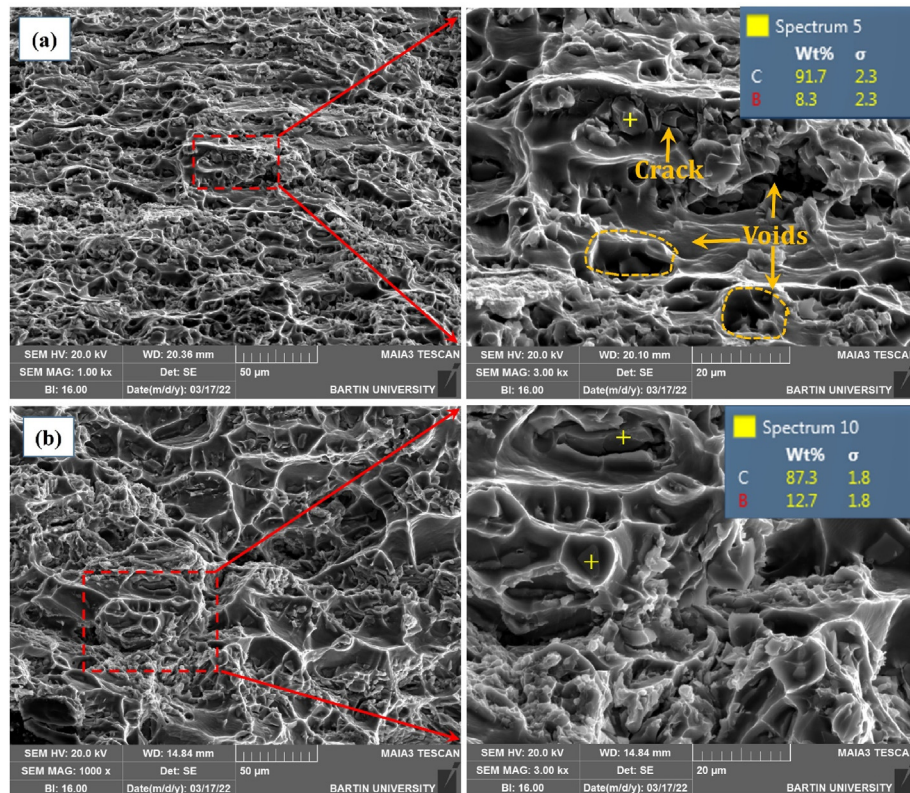


Fig. 11 – Fracture surfaces of B_4C -reinforced FGM: (a) Rolling direction and (b) Traverse direction.

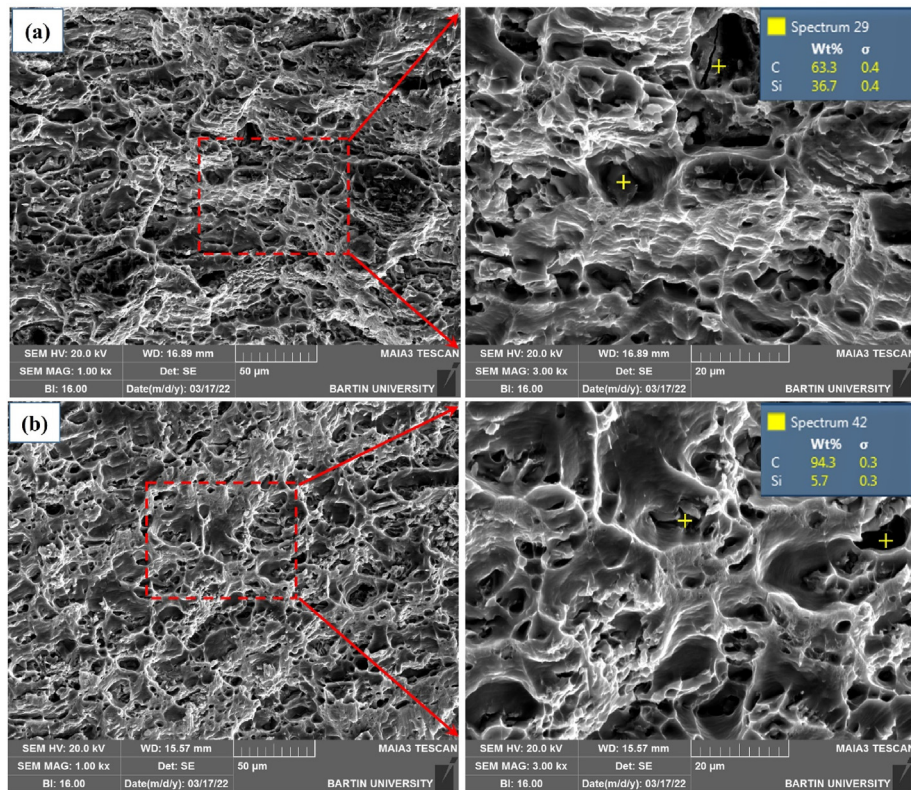


Fig. 12 – Fracture surfaces of SiC-reinforced FGM: (a) Rolling direction and (b) Traverse direction.

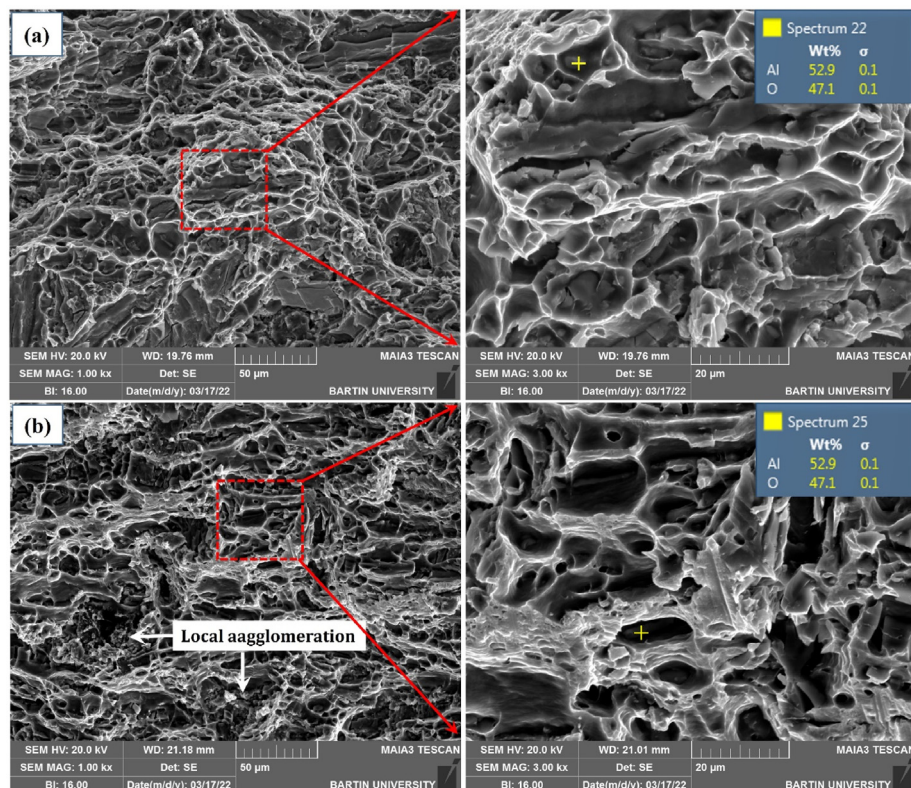


Fig. 13 – Fracture surfaces of Al_2O_3 -reinforced FGM: (a) Rolling direction and (b) Traverse direction.

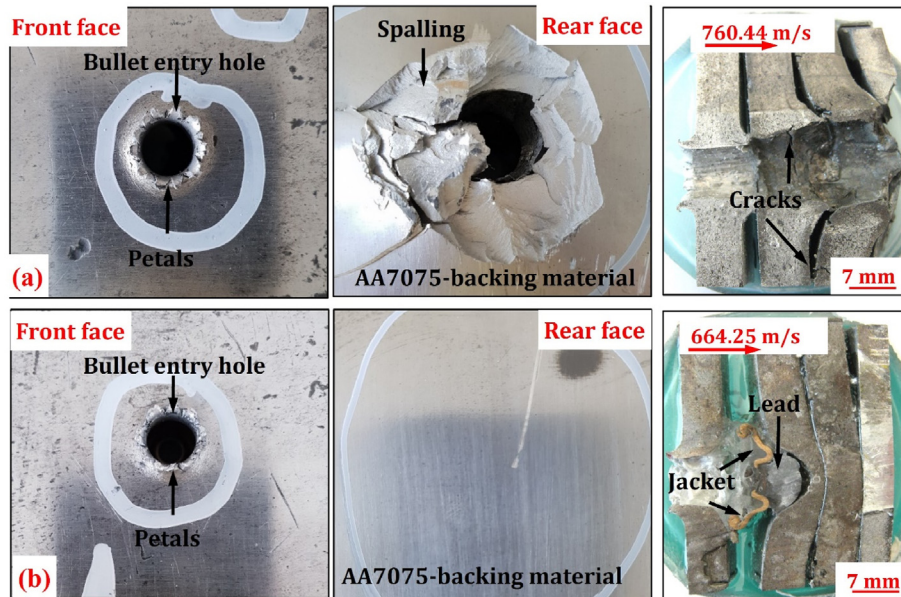


Fig. 14 – Ballistic test results of Al6061/8 wt% B₄C, a) 760.44 m/s, b) 664.25 m/s.

the frictional resistance created by the ceramic particles in the first layer. The pressure wave was transmitted to the second and third layers, and the projectile was stopped before it reached the support plate. Hence, the ballistic limit was 676.58 m/s, which was determined based on the four ballistic shots fired on the B₄C-reinforced laminated FGM. It was observed from the cross-sectional image presented in Fig. 14 that bulging formation occurred in the third layer owing to the pressure wave while bulging formation and cracking did not occur in the aluminum support plate.

The projectile passed the first FGM plate smoothly, forming a hole equal in size to the projectile diameter, at an impact speed of 760.44 m/s. In the second and third FGM layers, the

perforation diameter expanded, and the hole surface roughness increased. This could be attributed to the projectile significantly deforming while its velocity drastically decreased through the second and third layers. The slowed-down and deformed projectile increased the perforation diameter and heat transfer to the specimen. Similar behavior is also observed in Figs. 15 and 16. The stopped projectile causes an increase in the FGM perforation diameter.

Fig. 14 depicts that a solid-state welding formation occurred at the interface between the second and third layers owing to the friction and heat generated by the projectile. Furthermore, it was noticed that the aluminum was melted by the slowing projectile, which then solidified resulting in a

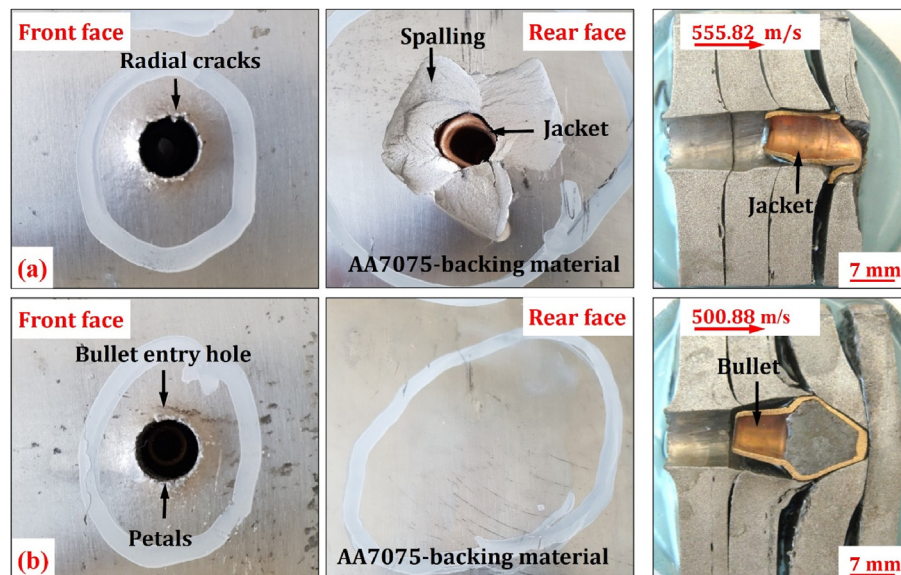


Fig. 15 – Ballistic test results of Al6061/8 wt% SiC reinforced FGMs, a) 555.82 m/s b) 500.88 m/s.



Fig. 16 – Ballistic test results of Al6061/8 wt% Al₂O₃ reinforced FGMs at a) 566.45 m/s b) 435.23 m/s.

rough surface. Also, a similar trend was observed in Figs. 15 and 16. The stopped and deformed projectile resulted in an enlarged FGM perforation diameter.

Similarly, as seen in Figs. 15 and 16 drawn for SiC- and Al₂O₃-reinforced FGMs' ballistic performance, the stopped and deformed projectile caused the perforation diameter to increase. In completely perforated FGMs, the matrix materials were melted and subsequently solidified owing to the decrease in the projectile speed through the hole. Both the hole expansion and matrix structure melting tendencies can be explained as an indication that the projectile has begun to lose its energy.

The first ballistic shot on the 24.6-mm-thick SiC-reinforced laminated FGM armor was fired at a speed of 612.16 m/s, close to the ballistic limit of the B₄C-reinforced FGM. However, the SiC-reinforced FGM could not resist the impact and was completely perforated by the projectile Fig. 15 (a)). The second projectile impact speed value was reduced by approximately 10% compared to the first, which corresponded to a speed of 555.82 m/s. The specimen was completely perforated again. The bullet jacket remained inside the FGM and peeled off owing to the friction between the FGM and the bullet (Fig. 15(a)). The retained bullet jacket underlines the ballistic efficiency of the resistance armor because the stripped lead core can be easily eroded, reducing the abrasive resistance of the bullet. Additionally, a change in the direction between the entry and exit points of the projectile was observed. Owing to the complete FGM perforation, the impact speed was gradually reduced. The third shot was taken at 500.88 m/s. The projectile partially penetrated the FGM and was retained in the third layer with the support of the backplate AA7075 as seen in Fig. 15 (b). A smooth bulging formation occurred on the AA7075-backing plate, which was not damaged. The SiC-reinforced FGM exhibited ductile behavior during all shots, and smooth surfaces were observed throughout the perforation zone.

Petalling and radial crack formation were noticed in the projectile entry region, and fragmentation occurred in the AA7075-backing plate at the projectile exit point. The ballistic limit velocity for the SiC-reinforced FGM was calculated as 523.87 m/s based on the four ballistic shots taken.

The first ballistic shot on the 24.8-mm-thick Al₂O₃-reinforced FGM was taken at 607.34 m/s. The specimen could not resist the projectile at this impact speed (Fig. 16). The projectile speed was reduced by approximately 8%, corresponding to 566.45 m/s; the projectile easily perforated the specimen again as provided in Fig. 16 (a). Subsequently, the projectile impact speed was decreased by approximately 30%, and another shot was conducted at an impact speed of 435.23 m/s. At this setpoint, the Al₂O₃-reinforced FGM stopped the projectile. Subsequently, the ballistic speed limit after four ballistic shots were computed as 485.82 m/s (Fig. 16 (b)). The Al₂O₃-reinforced FGM provided the lowest ballistic protection compared with the B₄C- and SiC-reinforced FGMs. The ballistic results agreed with the microstructure and tensile test results. Therefore, the low ballistic resistance of Al₂O₃-reinforced FGM was because of its inability to achieve homogeneous particle dispersion.

3.6. Specific ballistic energies of FGMs

FGMs exhibited ductile behavior in ballistic shots owing to their gradient structure and have the potential to prevent multiple projectile impacts. The presence of the gradient formation in the matrix structure was effective in altering the propagation and reflection of the stress wave created by the projectile and acted against the crack formation. The ballistic limit velocity (V_{BL}) and specific ballistic energy values were utilized to explain the performance of B₄C-, SiC-, and Al₂O₃-reinforced FGMs manufactured via centrifugal casting and subsequent hot rolling processes. Table 3 lists the areal densities and ballistic limit velocities of the FGMs.

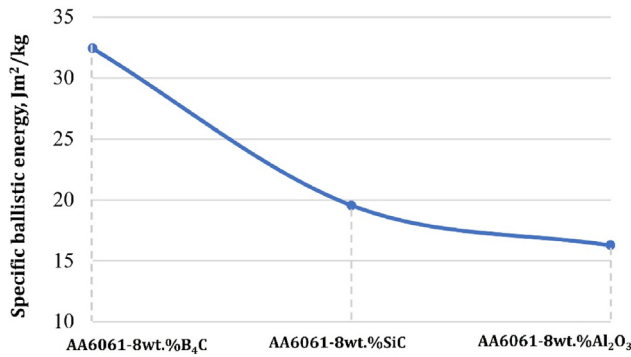


Fig. 17 – The variation of the specific ballistic energy of the FGMs.

The ballistic limit velocity V_{BL} is defined as the velocity at which the projectile cannot fully perforate the target. That is, when the bullet impact speed is lower than the ballistic limit, the bullet generally does not perforate the armor. Therefore, if the ballistic limit velocity and projectile mass m (kg) are known, the ballistic energy E_{BL} of the projectile can be calculated using Eq. (3).

$$E_{BL} = \frac{1}{2} m V_{BL}^2 \quad (3)$$

Then, the specific ballistic energy (SBE) of the FGM is calculated using Eq. (4).

$$SBE \text{ (Jm}^2 \text{ / kg)} = \frac{E_{BL}}{\rho_A} \quad (4)$$

Fig. 17 illustrates the specific ballistic energy changes for the FGMs. As the specific ballistic energy of the samples decreased, the penetration depth increased. Among the FGM samples, the highest specific ballistic energy was observed in the B₄C-reinforced FGM, whereas the lowest value was observed in the Al₂O₃-reinforced FGM.

4. Conclusions

The main findings of the experimental study are summarized as follows.

- The density values were higher in the hot-rolled FGMs compared with the centrifugally cast FGMs. The lowest density value was recorded in B₄C-reinforced FGM owing to the low density of B₄C particles, followed by SiC- and Al₂O₃-reinforced FGMs.
- The outside perimeter of the FGMs had the largest concentration of Al₂O₃ and SiC particles, with a steady reduction toward the interior periphery of the FGMs. Because the higher density Al₂O₃ and SiC reinforcement particles are spread in the specimen's outer perimeter by centrifugal force, the density of the composites rises toward the periphery. A uniform particle dispersion was achieved in B₄C-reinforced FGM, while local agglomerations were observed in the SiC- and Al₂O₃-reinforced FGMs.
- Optical and SEM micrographs demonstrate that the ceramic particles were dispersed from the inner to the

outer periphery of the FGMs during the centrifugal casting process owing to the centrifugal acceleration.

- Higher hardness values were recorded 1 mm below the outer circumference of the FGMs compared with the measurements taken deeper below the surface. The highest measured microhardness value was 73 HV in Al₂O₃-reinforced FGM due to local agglomerations. The microhardness variation in the outer and inner regions of B₄C-reinforced FGMs was 22.6%, while the variations in the SiC- and Al₂O₃-reinforced FGMs were 32% and 30.4%, respectively.
- The tensile strengths in the rolling direction were higher than those measured in the traverse direction for all FGMs. The tensile strength of the FGMs in the rolling direction increased by between 9% and 15% owing to the presence of long grains that are formed in the hot RD.
- The highest tensile strength and percentage elongation were measured in the rolling direction for the B₄C-reinforced FGM as 252.36 MPa and 27.69%, respectively. For TD, the tensile strength and elongation rate of B₄C-reinforced FGM were determined as 227.98 MPa and 22.40%, respectively. The tensile strengths in the RD of SiC- and Al₂O₃-reinforced FGMs were 184.68 and 139.27 MPa, respectively. Moreover, the tensile strengths of both FGMs in the transverse direction were measured as 158.7 and 127.15 MPa, respectively. The local agglomerations in Al₂O₃-reinforced FGMs weakened the interfacial bonding in the structure and reduced the load strain capacity.
- Ductile fracture behavior with fine dimples on the fractured surfaces was observed after tensile tests. The presence of B₄C and SiC particles on the fracture surface indicated good interfacial bonding between the FGM structure and reinforcement particles.
- The best ballistic protection was achieved with the B₄C-reinforced laminated FGM at an impact speed of 664.25 m/s. The first layer of laminated FGM was perforated, but the projectile was stopped at the second layer with a penetration depth of 14 mm. A smooth bulging formation occurred on the rear side of the FGM but no deformation was observed.
- The ballistic protection impact speeds for SiC- and Al₂O₃-reinforced FGMs were 500.88 and 435.23 m/s, respectively.
- The laminated FGMs exhibited ductile behavior during multiple ballistic shots because of their gradient structure. Moreover, petalling with radial cracks was observed at the projectile entry region.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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