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Impact of Zirconium Inclusion on Microstructure and Mechanical Performance of Stir Cast AA6061 Reinforced with B_4C and SiC Hybrid Particles

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Research Article

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Abstract

The investigation is reported on the processing of AA6061 Hybrid Metal Matrix Composites (AHMMCs) with B4C, SiC, and Zr as reinforcing particles by the stir casting method. The AA6061 alloy was selected as the matrix material due to its excellent balance of strength, corrosion resistance, weldability and light weight, and the B4C and SiC ceramic reinforcements were added to improve the mechanical properties. The effect of the addition of Zr3, 5, 7, and 9 wt.% on the microstructure, ultimate tensile strength (UTS) and hardness of hybrid composites has been studied systematically. SEM analysis along with EDS graph verified the presence and even distribution of reinforcement particles in the AA6061 matrix. The microstructural study revealed better particle dispersion and a stronger matrix/reinforcement interface with the increase of Zr content. The mechanical results revealed an ever-increasing improvement in the strength and hardness as the Zr content increased. The composite containing 9 wt. % Zr yielded the maximum UTS of 246.47 MPa and hardness of 55.58 BHN, which were significantly higher with reference to lower Zr-added composites. The improvement in mechanical properties was attributed to the combined effects of ceramic reinforcement strengthening, grain refinement, enhanced load transfer efficiency, dislocation strengthening, and restricted plastic deformation. The hybrid reinforcement approach provided synergistic strengthening by combining the high hardness of B_4C, the stiffness contribution of SiC, and the grain-refinement ability of Zr. The developed AA6061 + B_4C + SiC+Zr hybrid composite exhibits promising potential for lightweight structural applications requiring enhanced strength and hardness.

1. Introduction

Aluminium matrix composites (AMCs) have considerable research interest owing to their combined properties of low density, high specific strength, stiffness, wear resistance, and dimensional stability, which make them suitable for defence, aerospace, structural, and automobile applications. [1–3]. Unlike conventional aluminium alloys, AMCs provide superior mechanical performance by adding hard ceramic reinforcements into an aluminium matrix. [4]. The reinforcement particles act as load-bearing phases and enhance the resistance against plastic deformation, thereby improving tensile strength, hardness, and wear behaviour. [5]. AA6061 is one of the most widely used matrix materials for developing particulate-reinforced composites owing to its excellent corrosion resistance, weldability, machinability, and heat-treatable characteristics. The moderate strength and hardness of unreinforced AA6061 limit its applications. So, researchers have extensively investigated the development of AA6061-based MMCs using ceramic reinforcements such as SiC, B_4C, aluminium oxide (Al_2O_3), titanium carbide (TiC), and hybrid reinforcement combinations. [6].

Stir casting is an economical and industrially viable fabrication method for particulate-reinforced AMCs [7]. The process offers advantages such as easy processing, low production cost, and allows large-scale manufacturing and customization of reinforcement materials. However, obtaining a homogeneous distribution of particles, better wettability and strong interfacial bonding is still a challenge in stir casting [8]. Improper dispersion, particle agglomeration and porosity formation can seriously degrade the

microstructure and mechanical properties of the resulting composites. SiC is a widely used ceramic reinforcement in AMCs because of its high hardness, elastic modulus, thermal stability and good wettability with aluminium alloys [9]. Studies on AA6061 + SiC composites have shown that the addition of SiC particles improved UTS, hardness and wear resistance of composites due to enhanced load transfer and barriers to dislocation movement. The presence of uniformly dispersed SiC particles also leads to grain refinement and strengthens the aluminium matrix. B4C has emerged as an important reinforcement material, as it has excellent chemical stability, high hardness and stiffness, and low density [10].

AA6061 + B_4C composites fabricated through stir casting demonstrated improved hardness and tensile behaviour owing to effective load transfer between the aluminium matrix and hard B_4C particles [11]. The enhanced mechanical behaviour was linked with homogeneous particle distribution, improved interfacial bonding, and resistance to dislocation movement. Previous works have also inferred that proper processing conditions are essential for improving B_4C wettability and avoiding particle agglomeration during composite fabrication [12]. Hybrid reinforcement strategies have recently received significant attention because different ceramic particles provide multiple strengthening mechanisms compared with single-reinforcement systems. AA6061 hybrid composites reinforced with SiC and ZrO_2 exhibited improved hardness and tensile strength due to synergistic strengthening effects and enhanced microstructural characteristics. Similarly, hybrid AA6061 composites containing SiC and TiB_2 showed enhanced mechanical behaviour due to enhanced interfacial bonding, grain refinement, and effective stress transfer between matrix and reinforcement phases. Recent works have also extended hybrid reinforcement concepts to higher-strength aluminium alloys such as AA7075 and AA2024. AA7075-based composites reinforced with SiC demonstrate improved tensile strength and hardness due to homogeneous particle dispersion and stronger interfaces.

The improvement was largely credited to refinement of grains and minimisation of defects during processing of the composite. Likewise, hybrid Al2O3/Si3N4/ TiC reinforcement systems in aluminium alloys have demonstrated remarkable enhancement in UTS and hardness by means of combined strengthening mechanisms including Orowan and Hall–Petch strengthening. The addition of Zr has additionally been investigated for strengthening of aluminium composites as it can refine the grains, enhance thermal stability and mechanical properties [13]. Previous reports on Al6061 + ZrO_2 composites fabricated through stir casting showed improved UTS and hardness with increasing zirconium-based reinforcement addition, which was attributed to uniform particle distribution and strengthening of the aluminium matrix. Although several works have investigated AA6061 composites reinforced with individual ceramic particles such as SiC, B_4C, and Zr-based reinforcements, minimal investigations have focused on the combined effect of SiC, B_4C, and Zr addition on microstructural behaviour and mechanical properties. The synergistic contribution of high-hardness B_4C, stiffness-enhancing SiC, and grain-refining Zr can provide a balanced improvement in mechanical properties. Therefore, the present work aims to fabricate AA6061 + B_4C + SiC+Zr hybrid composites through stir casting and systematically investigate the effect of Zr addition on microstructure, UTS, and hardness behaviour. The relationship

between reinforcement contribution, interfacial bonding, and strengthening mechanisms is established to develop high-performance lightweight AMCs suitable for advanced engineering applications.

2. Materials and Methods

2.1 Matrix and reinforcement details

AA6061 is used as the metal matrix, and it was supplied as an ingot from Metal Source Pvt. Ltd., Coimbatore. Boron carbide (B_4C), Silicon carbide (SiC) and Zirconium (Zr) were supplied with 3 wt. %, 5% wt. % and 3 to 9 wt. %, respectively. Al6061 is selected as the matrix material due to its low density, and the hybrid reinforcements are SiC, B_4C, and elemental Zr. SiC and B_4C provide high hardness, stiffness and wear resistance, whereas Zr improves metallic reinforcement and microstructuring. Density, Young's modulus, thermal conductivity and coefficient of thermal expansion (CTE) differences contribute to load transfer, residual stresses, and the total strengthening. Its density is ~ 3.21 g/cm3 and the Young's modulus is 400–450 GPa, B4C has a density of ~ 2.51 g/cm3 and a modulus ranging from 440 to 460 GPa, Zr has a density of 6.52 g/cm3 and a modulus of ~ 88 GPa compared to Al6061 with density of ~ 2.70 g/cm3 and a modulus of 69–70 GPa. Also, particle size, shape and purity play an important role in affecting dispersion, interfacial bonding and the performance of the composite.

2.2 Stir casting route for producing aluminium composites

Stir casting was considered for this manufacturing route due to its simplicity, low cost and the efficiency of the production of aluminium hybrid composites with improved material properties. The aluminium matrix material was preheated to 400°C in a muffle furnace to remove moisture or impurities, if any.

Table 1
Matrix and reinforcement used for different samples

Sample	Matrix material	Reinforcement added
1	AA6061	3 wt.% B_4C + 5 wt.% SiC + 3 wt.% Zr
2	AA6061	3 wt.% B_4C + 5 wt.% SiC + 5 wt.% Zr
3	AA6061	3 wt.% B_4C + 5 wt.% SiC + 7 wt.% Zr
4	AA6061	3 wt.% B_4C + 5 wt.% SiC + 9 wt.% Zr

The reinforcement particles were preheated (7000C) before being added to the molten aluminium. The preheated particles were gradually introduced into the molten AA6061, while continuously stirring the mixture using a mechanical stirrer for 30 minutes until the reinforcement was uniformly dispersed in the matrix. Table 1 summarizes the matrix and reinforcement combinations employed in this study. The stirring action produced a vortex, which aided in the homogeneous distribution of reinforcement agents throughout the aluminium matrix. The molten metal is subsequently transferred into the corresponding

dies and permitted to solidify. After solidification, the specimens were removed from the mould and further characterized mechanically, tribologically, and microstructurally.

2.3 Microstructure examination of aluminium composites

Scanning Electron Microscopy (SEM) uses a focused beam of high-energy electrons to generate signals from the surface of solid specimens, typically producing a two-dimensional image of a designated surface area. SEM can also probe specific points on a sample, which is useful for qualitatively assessing chemical composition. SEM with Energy Dispersive X-ray Analysis (EDAX) was done on each sample to ensure the uniform dispersion of reinforcement and its presence within the aluminium matrix. A sample of 10 $\times$ 10 mm was cut to examine the microstructural features.

2.4 Examination of tensile and hardness properties of aluminium composites

Tensile strength is an important parameter in determining a material's usability. The tensile test was carried out as per ASTM E8 standard [14]. The stir-cast cylindrical rods were machined into dumbbell-shaped specimens and mounted on a universal testing machine, where tensile load was applied until fracture and the corresponding values were recorded. Each specimen had a thickness of 6 mm and a gauge length of 100 mm. Three tests were conducted for every composite specimen to ensure accuracy. The hardness of the composites was assessed on the Brinell hardness scale following ASTM standards. Specimens were prepared with smooth, flat, parallel surfaces, and indentation was performed with a load of 1000 kgf for 10 seconds. Each specimen was tested at three locations, and the average hardness value was determined.

3. Results and Discussion

3.1 Microstructural analysis of developed composites

The SEM analysis was performed to investigate the distribution of reinforcements within the AA6061 matrix. The fabricated composites consist of AA6061 as the matrix material with constant additions of B_4C and SiC by 3 wt. % and 5 wt. %, respectively. On the other hand, Zr content was varied from 3 wt. % to 9 wt. % for Samples 1 to 4, respectively. The SEM images show (Fig. 1) that the ceramic reinforcements are distributed throughout the AA6061 matrix, with noticeable variations in particle dispersion and interfacial characteristics with increasing Zr addition. As shown in Fig. 1 (a-b), sample 1 containing 3 wt. % Zr reveals a relatively uniform distribution of reinforcement particles; however, minor particle clustering is observed owing to limited interaction between the ceramic particles and matrix.

With increasing Zr content in Sample 2, improved reinforcement dispersion and reduced agglomeration are observed, indicating increased wettability between the reinforcement particles and the AA6061 matrix, as shown in Fig. 1(c-d). Figure 1 (e-f) reveals further microstructural refinement, where the reinforcement particles appear more uniformly distributed with improved interfacial bonding.

The detection of Zr promotes stronger interaction between matrix and reinforcement, which in turn contributes to grain refinement. The maximum addition of Zr exhibits the highest refinement effect among the investigated composites and is shown in Fig. 1 (g-h). The SEM morphology indicates a compact microstructure with uniform reinforcement distribution; however, localized Zr-rich regions may appear owing to the increased Zr concentration. The EDS spectra of B4C, SiC, amd Zr additions show the presence of Al as matrix element, with B, C, Si, and Zr elements. The intensity of Zr signal, as can be seen from figure increases gradually from Sample to Sample, indicating the existence of zirconium in the composite material. In summary, SEM with EDS results reveal that with the increase in Zr content, the distribution of reinforcement becomes more uniform, the interfacial bonding between the reinforcement and matrix strengthens and the microstructure features of AA6061 hybrid composites change.

3.2 Mechanical performance of fabricated composites

Table 2 displays the UTS and BHN of AA6061 hybrid composites reinforced with a constant amount of B_4C and SiC with varying Zr content. The results indicate that both UTS and hardness are enhanced continuously with increasing Zr addition.

Table 2
Ultimate tensile strength and Brinell hardness of the fabricated composites (present work)

Sample	UTS (MPa)	BHN
1	191.59 ±4.38	46.78±4.38
2	213.02 ±7.53	49.35±2.69
3	233.49 ±6.70	50.72±1.49
4	246.47 ±3.93	55.58±1.23

Figure 2 (a-b) shows that the composite contains 3 wt. % Zr results in a UTS and a hardness of 191.59 MPa and 46.78 BHN, respectively. The addition of 9 wt. % Zr enhanced the UTS to 246.47 MPa and hardness to 55.58 BHN. This improvement can be attributed to the combined strengthening effects of ceramic reinforcements and Zr inclusion, including grain refinement, load transfer strengthening, and enhanced resistance to plastic deformation [15–17]. The presence of hard ceramic SiC particles improves the load-bearing capability of the AA6061 matrix, while Zr promotes the formation of stable intermetallic phases and prevents grain growth during processing. [18,19]. As observed in SEM images, increasing Zr content, enhanced particle distribution and stronger interfacial bonding contribute to improved mechanical properties. The microstructural features observed support the UTS and hardness

results obtained in Table 2, where higher Zr addition resulted in superior strength and hardness characteristics.

Table 3 compares the mechanical properties of the present work with previously reported Aluminium Matrix Composites (AMCs).

Table 3
Comparison of the ultimate tensile strength and hardness of the present AA6061/B_4C/SiC/Zr hybrid composite with previously reported aluminium matrix composites.

Ref	Matrix	Reinforcement	UTS (MPa)	Hardness
[20]	AA6061	5 wt. % SiC and 2 wt.% ZrO_2	96.1	53.6 RHN
[21]	AA6061	4 wt. % SiC	157	85 VHN
[22]	AA6061	3 wt.% ZrO_2	110	80 VHN
[12]	AA6061	5 wt. % B_4C	162	102.1 VHN
[23]	AA6061	9 wt. % B_4C	185.4	151.4 HV
[24]	AA6061	5 wt. % SiC and 2 wt.% TiB_2	112.8	68.4 VHN
[25]	AA2219	1 wt.% Al_2O_3, 1 wt.% Si_3N_4 and 0.5 wt. % TiC.	117	-
[26]	AA7075	10 wt.% MXT	82.57	127.87 HV
[27]	AA7075	2.5 wt. % SiC	205	80 HV
Present work	AA6061	3 wt.% B_4C + 5 wt.% SiC + 9 wt.% Zr	246.47	55.58

The reported works show UTS values ranging from 82.57 to 205 MPa, depending on the matrix alloy and reinforcement combination. The present work yielded a maximum UTS of 246.47 MPa with 3 wt. % of B_4C, 5 wt. % of SiC, and 9 wt. % of Zr addition, which is higher than most previously reported AA6061 composites. The enhanced performance is attributed to the synergistic strengthening effect of hybrid ceramic reinforcement and Zr addition, which improves load transfer efficiency, matrix strengthening, and resistance to deformation. The obtained hardness value of 55.58 BHN also confirms the improved mechanical response of the developed composite with respect to AA6061 hybrid composites.

4. Conclusion

- AA6061 reinforced with B_4C, SiC, and variable Zr contents were successfully fabricated through the stir casting process. The SEM with EDS analysis confirmed the existence of reinforcements in the AA6061 matrix.

- The microstructural investigation showed that increasing Zr addition enhanced the reinforcement distribution and improved the interaction between the AA6061 and reinforcement particles. The presence of evenly distributed hard phases contributed to enhanced mechanical performance.
- The mechanical properties of the hybrid composites enhanced progressively with increasing Zr content. The UTS increased from 191.59 MPa for 3 wt. % Zr inclusion to 246.47 MPa for 9 wt.% Zr addition, while hardness increased from 46.78 BHN to 55.58 BHN. The superior mechanical performance of the 9 wt. % Zr composite was attributed to strengthening mechanisms.
- Compared with previously reported articles, AA6061 composites reinforced with individual SiC, B_4C, TiB_2, and Zr-based reinforcements, the present hybrid composite exhibited enhanced tensile strength owing to the synergistic contribution of multiple reinforcements.
- The combination of SiC, B_4C and Zr provides a balanced strengthening effect, where B_4C contributes high hardness, SiC improves stiffness and wear resistance, and Zr promotes microstructural refinement.
- The developed AA6061 + B_4C + SiC+Zr hybrid composite with optimised reinforcement content can be considered a potential candidate for lightweight engineering applications requiring high specific strength with improved hardness.

Declarations

Declarations of competing interest

The author(s) declare that there are no conflicts concerning the research work, authorship, and publication.

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Author Contribution

1. R.A. conceptualized and designed the study, supervised the research, performed formal analysis, and wrote the original manuscript draft. 2.L.N. conducted the stir casting fabrication of the composite samples and performed the tensile and hardness testing, and prepared Figures 1–3. 3. K.V. carried out the SEM and EDS microstructural characterization and prepared the corresponding figures and tables.

Data availability:

Data sharing will not apply to this work.

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Figures

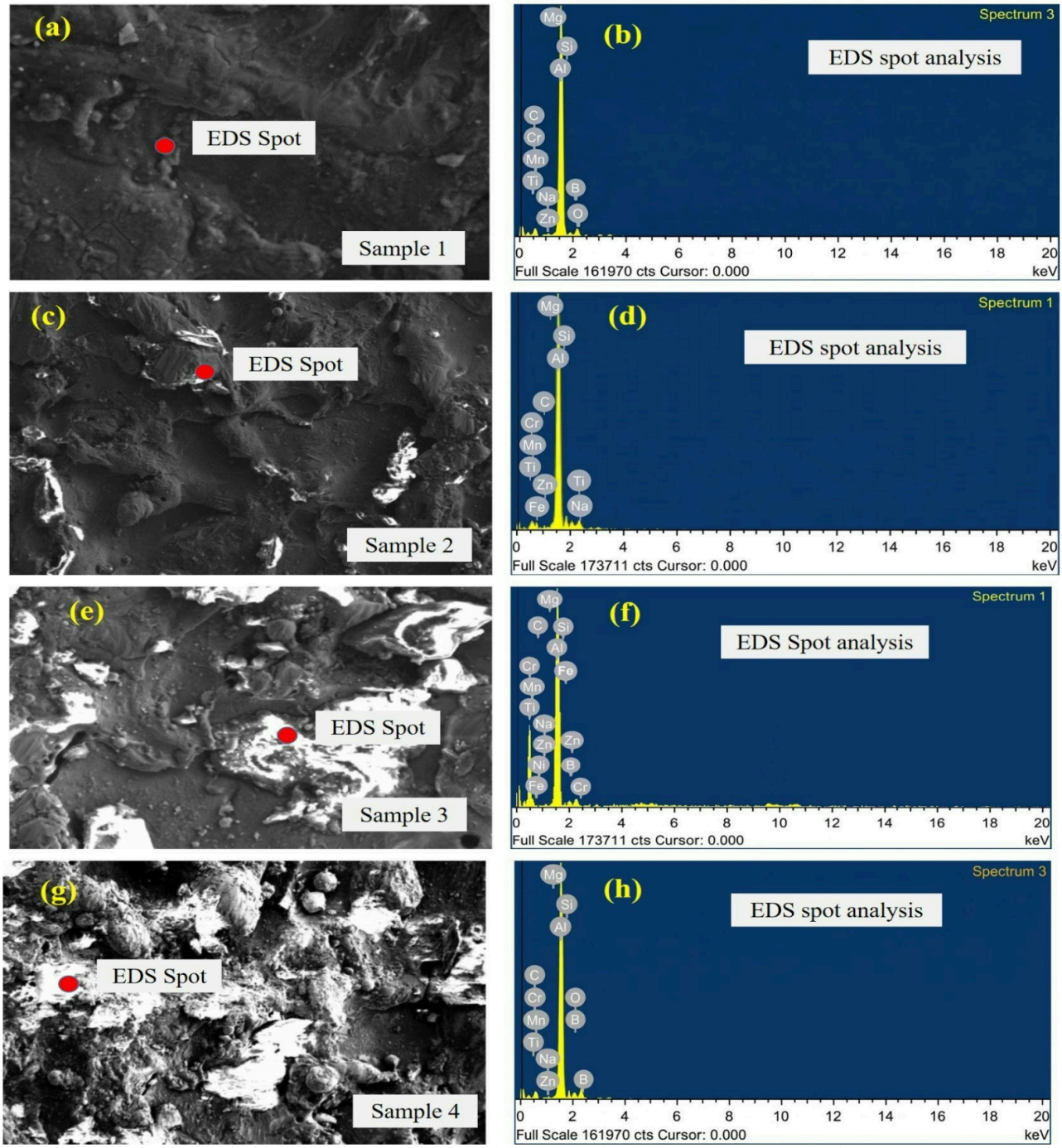


Figure 1

SEM with EDS examination of fabricated hybrid composites **(a-b)** AA6061+ 3 wt.% B_4C + 5 wt.% SiC + 3 wt.% Zr **(c-d)** AA6061+ 3 wt.% B_4C + 5 wt.% SiC + 5 wt.% Zr **(e-f)** AA6061+ 3 wt.% B_4C + 5 wt.% SiC + 7 wt.% Zr **(g-h)** AA6061+ 3 wt.% B_4C + 5 wt.% SiC + 9 wt.% Zr

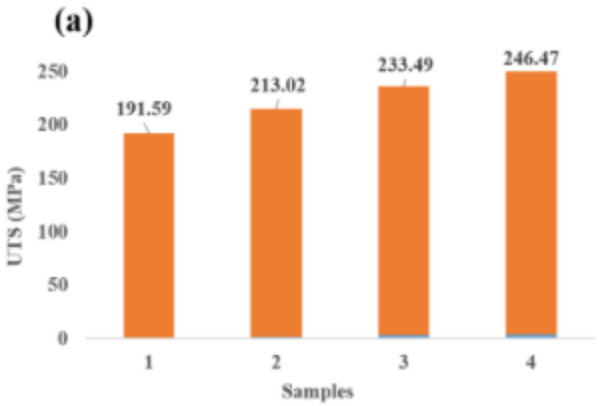


Figure 2

Ultimate tensile strength (UTS) of the developed AA6061/B4C/SiC/Zr hybrid composites as a function of Zr content.

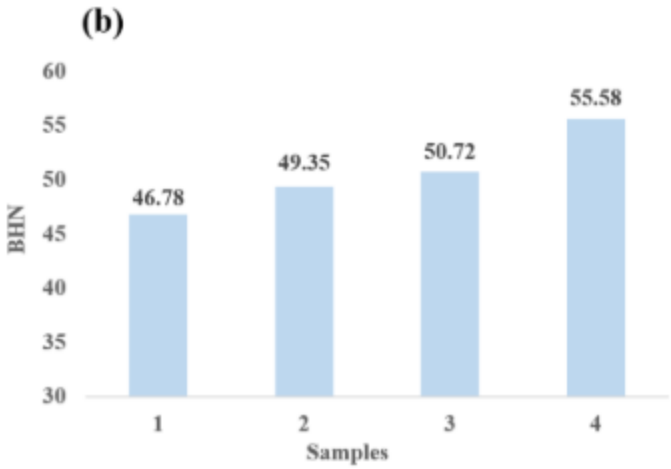


Figure 3

Brinell hardness (BHN) of the developed AA6061/B4C/SiC/Zr hybrid composites as a function of Zr content.