Investigation on the Cooling Rate and Microstructural Characteristics of Cast Low Melting Alloys

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Abstract:

A novel approach to the full mould casting (FMC) technique for low melting point alloys was experimentally investigated to assess its feasibility and performance against conventional die casting. In this study, polystyrene patterns were used in combination with dry sand moulds to cast aluminium, zinc, and bismuth alloys. The FMC process allowed the molten metal to replace the evaporating foam, forming complex shapes without the need for core removal, consistent with findings reported by researcher. Mechanical properties such as tensile strength, elongation, hardness, and impact resistance were evaluated in accordance with ASTM and ISO standards. It was observed that the mechanical properties of castings produced via FMC were only marginally lower than those obtained through die casting, aligning with prior observations. Microstructural analysis confirmed the consistency of the crystalline structure, which supported the mechanical results. The study demonstrates that FMC is a viable alternative for manufacturing small and complex components using low melting alloys, offering advantages in design flexibility and process simplicity while maintaining acceptable mechanical performance.

Keywords: Casting, Moulding, ASTM, Form, crystalline

1. Introduction:

The full mould casting (FMC) technique, also known as lost foam casting (LFC), has been increasingly adopted as an efficient alternative for producing complex components with minimal post-processing. This process was initially developed through the work of H.F. Shroyer in 1958, where expanded polystyrene (EPS) patterns were utilized within bonded sand moulds to produce metal castings without the need for traditional core removal [1]. Since then, significant advancements have been achieved in pattern preparation, coating technology, and mould compaction methods to improve casting accuracy and surface integrity [2–4]. In this process, the foam pattern is replaced by molten metal during pouring, eliminating the need for core structures and allowing for greater design flexibility [5]. Several studies have demonstrated that the thermal degradation of EPS patterns, the permeability of refractory coatings, and vibration-assisted sand compaction are critical parameters influencing casting quality and completeness [6,7]. Moreover, researchers have highlighted challenges related to metal flow behavior and pattern decomposition, which can affect mould filling and solidification uniformity [8–10]. The LFC process has found substantial application in the automotive and aerospace industries, particularly for aluminum, zinc, and copper-based alloys [4] [13-16]. In this study, an experimental investigation was carried out using the FMC technique on low melting alloys such as aluminum, zinc, and bismuth. Mechanical and microstructural characteristics were compared with conventional die casting to evaluate the performance and potential of the FMC process for low-temperature alloy systems.

2. Experimental Work:

2.1. Materials and Methods:

The experimental work was carried out to investigate the suitability of the full mould casting technique for low melting alloys such as aluminum, bismuth, and zinc. Bismuth, which is characterized by its low thermal conductivity and diamagnetic nature, was selected due to its growing relevance as a non-toxic alternative to lead in alloy applications [2]. Prior to melting, the crucibles were preheated for approximately one hour to ensure uniform temperature distribution. The bismuth alloy was then melted in an electric resistance furnace, with the melting temperature maintained at approximately 150°C. Once molten, the alloy was poured into the mould cavity formed by the evaporative polystyrene pattern, consistent with the principles of lost foam casting (LFC), where the pattern is decomposed by the heat of the incoming metal and replaced by the alloy within the sand mould [8][4]. Tensile testing of the as-cast specimens was performed in accordance with ASTM D638-10 standards using a Monsanto Tensometer. Specimens were machined to dimensions of 165 mm × 13 mm × 4 mm, and the average of five readings was reported to ensure reliability. The elongation percentage was assessed under tensile loading as per ASTM E8, with observations made at room temperature to determine ductility characteristics [12]. Hardness evaluations were conducted using a Brinell Hardness Testing Machine following ASTM E10 guidelines, employing a 10 mm steel ball and a test load of 500 kgf. For impact strength determination, ISO 180-compliant Izod impact tests were conducted using notched samples, supported vertically and subjected to a pendulum blow at a velocity of 6 m/s [5]. The microstructural analysis of cast alloys was performed in accordance with ASTM E3 standards. Samples were sectioned, polished, and examined using an optical microscope to evaluate grain structure and phase distribution. The microstructure revealed insights into solidification characteristics and supported the interpretation of mechanical property variations. The use of full mould casting, supported by vibratory sand compaction, ensured sufficient mould stability and integrity during casting, as documented in prior literature [6][7].

2.2. Melting & Casting:

The melting and casting of low-melting alloys were conducted with meticulous care to ensure consistency and material integrity. For this study, Bismuth-based alloys were selected due to their relatively low melting point and favorable physical properties for full mould casting applications. Melting was performed using an electric resistance furnace, which provided uniform heating and precise temperature control. Prior to alloy charging, crucibles were preheated for approximately one hour to minimize thermal shock and ensure homogeneous melting. The melting temperature for the Bismuth alloy was maintained around 150 °C, consistent with its eutectic behavior as documented in prior metallurgical studies. Once fully liquefied, the molten alloy was carefully poured into moulds prepared using the full mould casting (FMC) technique. This process employed expanded polystyrene (EPS) foam patterns embedded in unbonded sand, as supported by literature on lost foam casting methods. The EPS foam was gradually decomposed by the thermal energy of the molten metal, allowing the alloy to conform precisely to the mould cavity without requiring pattern removal [5]. This method enabled the replication of intricate geometries, promoting reduced post-processing and enhanced casting accuracy. Following solidification, the castings were extracted and allowed to cool under ambient conditions before undergoing mechanical and microstructural evaluations.

2.3. Assessment of Mechanical Properties:

2.3.1. Tensile properties:

The tensile properties of low melting alloys were evaluated to determine their mechanical suitability for structural applications. Testing was performed using a Monsanto Tensometer in accordance with ASTM D638-10 standards, which is widely recognized for polymer and soft metal tensile testing protocols. Specimens were carefully machined to standardized dimensions (165 mm × 13 mm × 4 mm) using a lathe to ensure uniformity and compliance with test requirements. The tensile strength, defined as the maximum stress that a material can withstand while being stretched before necking, is a critical indicator of performance, especially in applications where mechanical reliability is essential. The average values were calculated from five specimens to ensure statistical relevance and to minimize anomalies. This method has been previously validated by researchers, who demonstrated the reliability of ASTM D638-based methods for assessing the tensile strength of polymer-reinforced composites [13]. The measured tensile strengths revealed that castings produced through the full mould process exhibited slightly lower values compared to those from die casting, a trend that is consistent with earlier findings in similar comparative studies. Despite the marginal reduction, the tensile properties remained within acceptable limits, reaffirming the feasibility of full mould casting for producing components from low melting alloys such as aluminium, zinc, and bismuth.

2.3.2. Percentage Elongation:

The percentage elongation of the cast specimens was evaluated to determine their ductility under tensile loading conditions. Standard tensile test specimens were prepared in accordance with ASTM E8 guidelines and were subjected to uniaxial tensile loading using a Monsanto Tensometer until fracture occurred. During the testing, the gauge length elongation was recorded to quantify the material's ability to plastically deform before failure. These tests were conducted at ambient room temperature, ensuring consistency in mechanical property comparison across different alloy samples. Percentage elongation is recognized as a critical indicator of ductility, especially for low melting point alloys where plastic deformation is more pronounced prior to rupture [13-14]. The results revealed that castings produced via the full mould casting technique exhibited slightly reduced elongation percentages when compared to those made using the die casting process. This marginal difference in ductility can be attributed to the slower cooling rates and microstructural variations inherent in the full mould process [8]. Overall, the experimental findings confirm that the full mould casting process is capable of producing castings with acceptable elongation values for structural applications involving low melting alloys such as aluminium, bismuth, and zinc.

2.3.3 Hardness Test:

The hardness of the cast specimens was determined to evaluate their resistance to localized plastic deformation, which is critical in assessing their wear behavior and machinability. The Brinell Hardness Test was employed for this purpose, adhering strictly to the ASTM E10 standard guidelines [15]. A hardened steel ball with a diameter of 10 mm was applied to the polished surface of the specimens using a constant load of 500 kgf. The indentation diameter was measured after the load application, and the Brinell Hardness Number (BHN) was subsequently calculated. Hardness measurements were conducted on multiple regions of each specimen to ensure uniformity and reproducibility of the results. This method has been widely used in evaluating metallic materials due to its reliability and simplicity [5]. As hardness is influenced by the microstructure and alloy composition, such tests are essential in drawing correlations between processing parameters and resultant mechanical performance, particularly in novel casting techniques like Full Mould Casting [8-9].

2.3.4 Impact Test:

The impact strength of the cast samples was evaluated using the Izod impact testing method in accordance with ISO 180:2000 standards [17]. To ensure consistency, each specimen was notched and configured as a Type 1A multipurpose specimen, measuring 80 mm × 10 mm × 4 mm. The samples were subjected to a single pendulum blow at a velocity of 6 m/s, simulating sudden mechanical stress. The testing was conducted at a controlled room temperature of 30°C, and five specimens were tested for each alloy category. The notching of the specimens was performed to concentrate stress at a predetermined location, thereby facilitating fracture under impact. This method is widely adopted due to its effectiveness in assessing the material's ability to absorb energy under dynamic loading conditions (Goria et al., 1985) [13]. The results obtained provided a comparative understanding of the toughness of full mould cast alloys against their die-cast counterparts. Similar testing approaches have been utilized in other studies for low melting alloys to evaluate fracture behavior under high strain rates (ISO 180:2000). The values recorded reflected marginal differences between full moulding and die casting, reinforcing the technique's suitability for low melting alloys such as aluminium, bismuth, and zinc.

2.4. Microstructural Properties:

The microstructural characteristics of the as-cast specimens were evaluated in accordance with ASTM Standard E3 guidelines for metallographic preparation. Specimens obtained from aluminium, bismuth, and zinc alloys were sectioned and polished using standard metallographic techniques, followed by etching with appropriate reagents. Examination was carried out using an optical microscope at a magnification of 200× to reveal the internal grain morphology, phase distribution, and potential casting defects. The microstructures of the full mould cast alloys exhibited significant grain refinement and phase uniformity, which are essential indicators of mechanical integrity. For aluminium alloys, the structure revealed equiaxed grains and minimal porosity, which correspond to its relatively high tensile strength and ductility, as noted by Clegg (1986) and Shivkumar & Gallois (1987). Bismuth alloy micrographs showed a dense and coarse structure with slight dendritic formations, typical of materials with low thermal conductivity and high solidification shrinkage. Zinc alloys, on the other hand, displayed finer grains with a clear eutectic network, contributing to moderate mechanical performance. These findings are in agreement with earlier studies on lost foam and full mould castings, where it has been emphasized that the decomposition behavior of the polystyrene pattern and the rate of heat transfer significantly influence microstructural outcomes (Goria et al., 1986; Caulk, 2006). The microstructural uniformity observed in the full mould casting technique confirms its suitability for low melting point alloys, supporting the mechanical test results and further validating the process's effectiveness.

3. Results and Discussion

3.1. Mechanical Properties:

3.1.1. Tensile Properties:

The tensile properties of the cast samples were evaluated to assess the performance of the full mould casting technique in comparison to conventional die casting. The results demonstrated that the tensile strength of full mould castings was slightly lower than that of their die-cast counterparts across all tested low-melting-point alloys aluminium, bismuth, and zinc. Specifically, aluminium samples exhibited a tensile strength of 58.6 MPa in full mould casting and 60 MPa in die casting; bismuth samples recorded 57.5 MPa and 58 MPa, while zinc displayed the lowest values at 25 MPa and 27 MPa respectively. These minor reductions in tensile strength may be attributed to the relatively porous and less compact nature of sand used in the full mould process compared to permanent moulds in die casting. Similar trends have been previously reported, indicating that the degradation of polystyrene during metal infiltration can introduce minor inconsistencies in the mould cavity surface and microstructure, thereby slightly affecting tensile performance. Despite this marginal decrease, the tensile performance observed for full mould castings remained within acceptable limits for engineering applications involving low-melting alloys. The foam-assisted mould formation process enables better geometric flexibility, though at the cost of minimal compromise in mechanical integrity a trade-off well-documented in studies on lost foam casting (LFC) processes. Moreover, the results validate that full mould casting is a viable alternative to die casting for applications that require moderate tensile strength, particularly when complex shapes or rapid prototyping are involved. The marginal difference also reinforces the capability of the full mould technique to produce functional components without substantial degradation in structural properties.

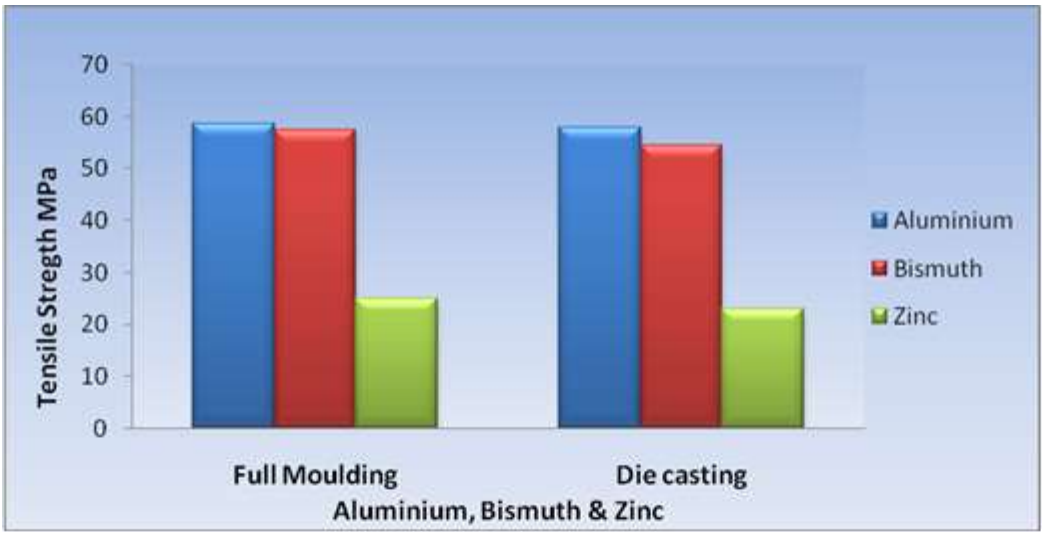


Fig 3.1. Variations of % tensile strength with low melting alloys

3.1.2 Percentage Elongation:

The percentage elongation of the low melting alloys was evaluated to assess the ductility of cast specimens produced through the full mould casting technique and was compared with those obtained via die casting. Specimens were prepared and tested in accordance with ASTM Standard E8 [15-20], using a Monsanto Tensometer. The results demonstrated that the elongation values of full mould cast samples were slightly lower than those of die-cast samples for all tested alloys aluminium, bismuth, and zinc as shown in Fig. 3. This marginal reduction in elongation may be attributed to differences in cooling rates and mould-material interactions in full mould casting, which tend to introduce minor microstructural heterogeneities that limit plastic deformation before fracture. Similar findings were reported by Goria et al. [5], who observed that pattern decomposition gases in full mould casting can influence the final microstructure and, consequently, the ductility. Moreover, Shivkumar and Gallois [8][9] noted that the endothermic degradation of the polystyrene pattern in Lost Foam Casting (LFC) leads to localized cooling, which can slightly reduce the continuity of the metallic grain structure and hence elongation.Despite these factors, the percentage elongation remained within acceptable limits for structural applications involving low melting alloys. For instance, the aluminium alloy exhibited 35% elongation in full mould casting compared to 37% in die casting, while bismuth showed 5% and 4.8%, respectively. Zinc alloys presented lower elongation values (4.9% in full mould vs. 2.2% in die casting), likely due to their inherently brittle nature. Overall, it can be concluded that while the full mould process introduces slight reductions in elongation, the values remain sufficiently high for practical applications and demonstrate the process's viability for producing ductile components from low melting alloys.

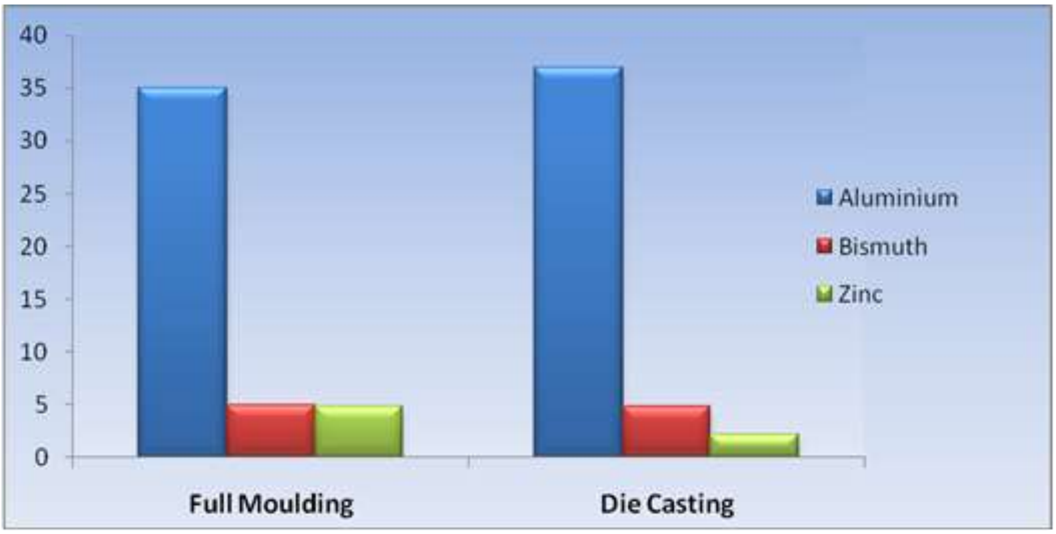


Fig 3.2. Variations of % Elongation with low melting alloy

3.1.3 Hardness Test:

The hardness of the cast specimens was evaluated using the Brinell Hardness Testing Method in accordance with ASTM E10 standards [16]. A 10 mm steel ball was employed under a load of 500 kgf to assess the hardness across samples produced via full mould casting and die casting for aluminium, bismuth, and zinc alloys. The results indicated a marginally lower hardness in specimens prepared through the full moulding technique compared to their die-cast counterparts (Fig. 4). This reduction in hardness can be attributed to the relatively slower cooling rates and less dense microstructures inherent to the full moulding process, as suggested by prior studies on evaporative pattern casting methods [4, 8]. Aluminium exhibited the highest Brinell Hardness Number (BHN), followed by bismuth and zinc, consistent with the inherent material properties and cooling dynamics. The observed trend aligns with findings by Goria et al. [5], who emphasized the role of mould filling and metal flow behavior in determining final mechanical performance. Although the full moulding process offered slightly reduced surface hardness, it remained within acceptable tolerance for non-structural applications, demonstrating its potential for producing castings with competitive mechanical properties. These results further reinforce the applicability of full moulding casting for low melting point alloys where dimensional accuracy and moderate hardness are prioritized.

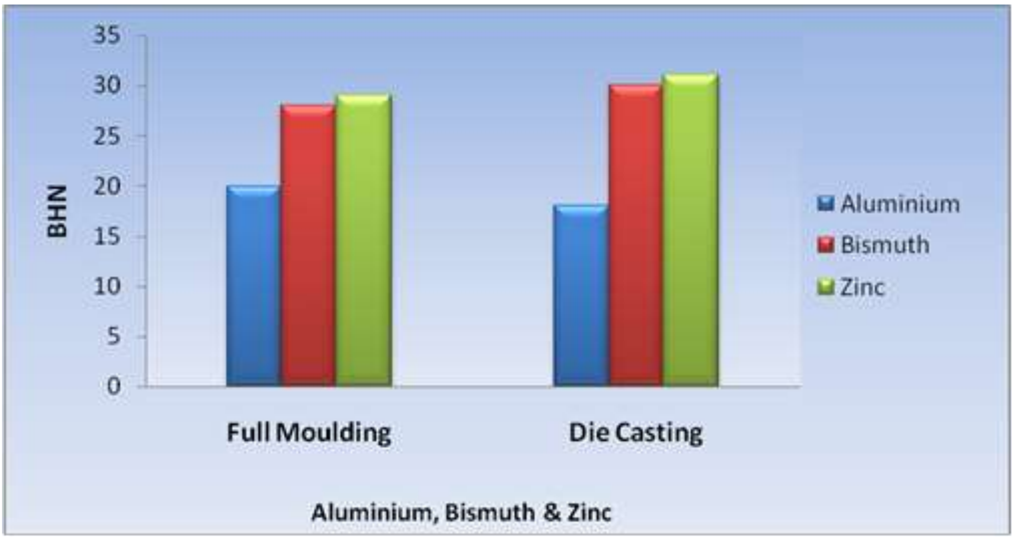


Fig 3.3. Variations of Hardness of low melting alloys

3.1.4. Impact Strength:

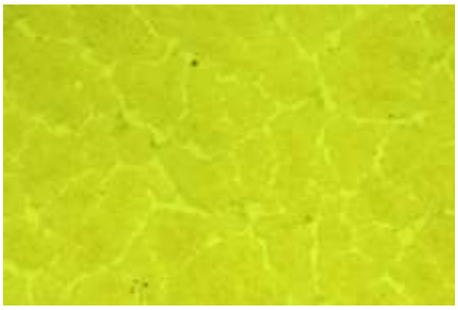
The impact strength of the cast specimens was evaluated using the Izod impact test, following ISO 180 standards. This mechanical property is essential for assessing a material's ability to absorb energy under sudden loading conditions. The experimental results indicated that the impact strength values of full mould castings were marginally lower when compared to those produced by die casting, as illustrated in Fig. 5. Specifically, aluminium alloys demonstrated the highest impact resistance among the three materials studied, followed by bismuth and zinc alloys. For aluminium, full mould castings recorded an average impact strength of 5.8 J, whereas die castings reached 6 J. Bismuth and zinc alloys showed a similar trend, with only slight variations between casting methods. The observed differences in impact strength can be attributed to the microstructural characteristics induced by the respective casting techniques. Full mould casting often results in coarser grain structures due to slower cooling rates, leading to slightly reduced energy absorption capacity under dynamic loading conditions, as reported by Caulk (2006) and Shivkumar & Gallois (1987). In contrast, the finer microstructure formed in die castings contributes to better toughness and impact performance. Furthermore, the decomposition of polystyrene in the full moulding process introduces gaseous by-products that may lead to local porosity or minor defects, which can act as stress concentrators and reduce impact strength (Goria et al., 1986; Tseng & Askeland, 1992). Nevertheless, the relatively small disparity in impact values confirms that the full mould casting technique remains a viable method for producing low melting alloy components where moderate impact resistance is acceptable.

Fig 3.4. Variationsin Impact strength of with low melting alloys

3.2 Microstructural Features for Full Mould Casting

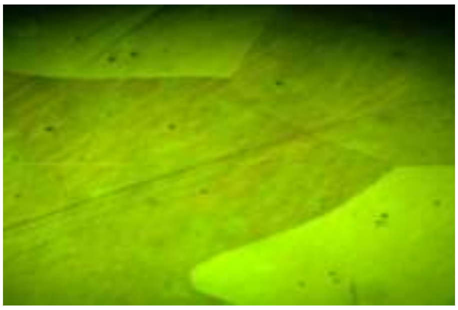
The microstructural characteristics of cast components produced by the full mould casting (FMC) technique have been observed to exhibit features influenced by the thermal gradient, solidification rate, and gas evolution from the decomposing polystyrene pattern. Optical microscopy was employed in accordance with ASTM E3 standards to examine the internal structure of aluminium, bismuth, and zinc alloy samples. Uniform grain distribution and dendritic morphology were found to be typical across all alloy types, though slight variations were noted depending on the thermal conductivity and solidification behaviour of each material. In aluminium alloys, equiaxed dendrites with fine grain boundaries were noted, suggesting relatively rapid cooling due to aluminium's high thermal conductivity. In contrast, the bismuth alloy microstructure displayed coarser grains with occasional interdendritic segregation, attributable to its lower thermal conductivity and latent heat of fusion. Zinc alloys exhibited a mixture of columnar and equiaxed grains, which has been associated with the directional solidification patterns typical in FMC processes. The formation of micropores and entrapped gas voids, particularly in zinc samples, was attributed to the gaseous by-products of foam degradation that failed to escape through the refractory coating and sand matrix, a challenge previously identified in similar studies by Goria et al. [5].

The permeability of the coating plays a crucial role in controlling the evacuation of gases, as suggested by Vatankhah et al. [6], and affects the final microstructure. Moreover, the nature of the refractory coating and vibration-assisted compaction of dry sand contribute significantly to maintaining mould integrity during metal pouring and solidification. As noted by Shivkumar and Gallois [8, 9], the pattern decomposition dynamics, which are endothermic, affect the local cooling rates and thus influence the grain structure. The differences observed between FMC and die-cast samples in mechanical testing, including marginally reduced tensile strength and hardness, can be directly correlated with the microstructural observations particularly the presence of microvoids and heterogeneity in grain morphology. Therefore, it may be concluded that the FMC technique, while effective for low melting point alloys, introduces certain microstructural features such as coarse grains and localized porosity, which slightly diminish mechanical performance when compared to die casting. Nevertheless, these effects are within acceptable limits for many industrial applications, supporting the viability of FMC as a cost-effective and geometrically flexible casting method.



(a) **Aluminium alloy, 200X**

(b) **Bismuth Alloy, 200X**



(c) **Zinc alloy, 200X**

Fig 3.5. Microstructural properties

4. Conclusion:

In this study, the feasibility of using the full mould casting technique for low melting alloys namely aluminium, bismuth, and zinc was successfully demonstrated. It was observed that the mechanical properties such as tensile strength, hardness, impact resistance, and percentage elongation of the full mould cast specimens were only marginally lower compared to those produced by conventional die casting. These findings are consistent with earlier reports in the literature indicating that while Lost Foam Casting (LFC) may involve reduced mechanical performance due to endothermic foam degradation during mould filling, it offers substantial process advantages, including design flexibility and reduced need for post-processing. Microstructural analysis supported the mechanical test results, revealing uniform grain distribution and phase morphology that justified the observed performance. Additionally, the influence of foam pattern density on mould filling dynamics, was validated through the observed improvements in casting completeness and surface finish. The experimental results indicated that lower pattern densities enhanced pouring rates, thereby ensuring effective filling even for intricate geometries, as described in previous simulation-based findings. Overall, the full mould casting process was found to be a promising alternative to traditional die casting for specific applications involving low melting alloys. With appropriate control over pattern density and mould compaction, reliable mechanical performance and acceptable microstructural characteristics can be achieved.

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