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Technical Note

Influence of forging on the hardness and tensile properties of Al7075/TiC composites

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Abstract

This study offers a thorough examination of the mechanical characteristics shown by as-cast and hot-forged Al7075-TiC alloy composites. Optical micrographs are used to verify the different characteristics of these composites. The process of hot forging has been shown to improve the dispersion and orientation of TiC particles inside the matrix, hence preserving the structural integrity of the interface between the matrix and the reinforcement. The observed relationship between the augmentation of TiC reinforcement and the diminishment of the mean grain size is described to the mechanisms of nucleation and dynamic re-crystallization. It is worth mentioning that hot-forged composites routinely demonstrate refined microstructures, which in turn lead to enhanced mechanical characteristics. The process of stir casting followed by hot forging of Al7075-TiC composites has improved mechanical properties, indicating their potential appropriateness for high-performance applications.

1. Introduction

Aluminum and its alloys are highly sought-after materials in engineering fields like aerospace, automotive, marine, and construction. This is because aluminum and its alloys have great mechanical properties like ductility, formability, malleability, and strength. Researchers are looking into ways to improve their mechanical properties and meet changing engineering needs through secondary processing to make them work better. Metal Matrix Composites (MMCs) were made when researchers looked into how to add reinforcing elements to the aluminum matrix [1, 2]. When added to aluminum alloys, titanium carbide (TiC) has stood out because it increases both mechanical strength and ductility. This reinforcement also makes the tribological properties better, lowering the coefficients of sliding resistance and friction. Using techniques like powder metallurgy and liquid metallurgy, TiC-reinforced MMCs with different microstructures can be made. This makes it possible to study their engineering uses in depth [3, 4]. This study focuses on making a composite out of an aluminum alloy 7075 matrix that is only strengthened by TiC

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particles. This will be done through liquid metallurgy and hot forging, which will also improve the mechanical properties of the composite. Characterization methods like microscopy give information about the microstructure, morphology, and phase composition, which is very important for understanding processing properties. To figure out if a composite is suitable, its hardness, tensile strength, tribological properties, and thermal properties are all looked at. Aluminum is the most commonly used matrix material for MMCs, as it offers several desirable attributes, including low density, excellent thermal and electrical conductivity, precipitation hardening capability, corrosion resistance, and high damping capacity. Moreover, it offers an extensive range of mechanical properties, depending on its chemical composition. Al-based MMCs are usually strengthened with ceramic particulates, such as $Al2O3$, SiC, B, $AlB2$, $TiB2$, BN, $SiO2$, AlN, and others. Various fabrication methods, predominantly based on casting or powder metallurgy, are available for creating nano-size (or micro-size) particle/metal composites [8, 9]. However, achieving uniform dispersion of particles in liquid metal can be challenging. Furthermore, micro-level porosity, a common casting defect, can pose difficulties in creating micro-level geometries [10].

The mechanical properties and microstructure of MMCs have been improved by methods like forging and extruding. Because it can be bent without breaking, forging is an especially good way to make things. This method improves the load-bearing capacity of MMCs by realigning the grain structures and strategically placing reinforcements. Forging also makes it easier to make parts because it cuts down on waste and costs and lets you change the way a material works [5-12]. Wang and Chen [13] provide their results in their detailed review, which delves into the mechanical properties of aluminum matrix composites. The authors go into extensive length about various production procedures, microstructural characteristics, and mechanical behaviors associated with the usage of these composites. This study emphasizes the importance of secondary processing techniques, such as forging and extrusion, in the process of tailoring mechanical properties to specific application requirements. By evaluating a wide range of studies, the authors give a complete assessment of the criteria influencing the enhancement of strength, ductility, and other mechanical characteristics in secondary processed aluminum composites. As a result, they can convey information in a clear and succinct way.

This review is an excellent resource for academics and engineers who want to maximize the mechanical performance of aluminum-based materials. Zhan and Zhang [14] investigate how equal channel angular pressing (ECAP) affects the microstructure and mechanical properties of SiC particle-reinforced aluminum composites. According to the study's findings, secondary processing by ECAP results in considerable improvements in mechanical properties. These advantages include enhanced strength and hardness. An analysis of the material's microstructure reveals a refined grain structure as well as SiC particles that are equally distributed throughout the aluminum matrix. This research demonstrates the use of ECAP as a secondary processing method for altering the properties of aluminum composites. Furthermore, it provides insights into the mechanisms responsible for the observed improvements in mechanical behavior. Jia and his colleagues [15] investigated the influence of the forging process on TiC-reinforced aluminum composites in their study. The researchers are examining the microstructural changes generated by the forging process and linking those changes with improvements in the material's mechanical properties. According to the researchers, forging enhances the dispersion of TiC particles, resulting in better tensile strength and hardness, as demonstrated by a number of mechanical tests and in-depth micrograph studies.

This research sheds light on the complex connection between secondary processing and microstructural development, providing critical insights into the fabrication of high-performance aluminum composites. Zhang and his colleagues investigate [16] the effect of in situ equal channel angular pressing (ECAP) on Al-TiB2 composites. According to the study's findings, secondary processing with ECAP results in finer microstructures, greater particle dispersion, and enhanced mechanical properties. The microstructural changes generated by ECAP boost the tensile strength and hardness of the composites significantly. By investigating the relationship between microstructure and mechanical behavior, this research demonstrates the potential of secondary processing approaches for changing the properties of aluminum-based composites. This association was investigated in the research. The mechanical properties of aluminum matrix composites reinforced with Al2O3 particles are the major focus of Li and colleagues' study [17]. The study introduces a novel extrusion process with the goal of increasing the mechanical properties of these composites. The authors show that further processing, in this instance extrusion, improves the material's hardness, ductility, and strength. An analysis of the material's microstructure indicates that it has a refined grain structure and uniformly dispersed Al2O3 particles. This research highlights the relevance of secondary processing techniques for modifying the mechanical properties of aluminum composites to meet the needs of a specific application. Huang et al. [18] explore the mechanical characteristics of Al-SiC composites produced via semi-solid stirring and extrusion. The research shows how secondary processing may improve the mechanical properties of these composites. The authors show enhanced strength and hardness by examining the microstructural changes caused by semi-solid stirring and extrusion. The study underlines the importance of secondary processing in enhancing the characteristics of aluminum-based composites for high-performance engineering applications. Tao and colleagues [19] investigate the effects of extrusion on Al-TiB2 composites in situ. The research focuses on the effect of secondary processing on the microstructure and mechanical characteristics of composites. The researchers demonstrate a link between improved particle dispersion and increased tensile strength and hardness using extensive microstructural and mechanical investigation [20, 21]. This study adds to our understanding of the relationship between secondary processing and the mechanical behavior of aluminum composites. In the past few years, people have become more interested in MMCs, which has led to more research into secondary processing methods like forging. This method is good for industries that need high-performance materials because it can improve mechanical properties and microstructure. For practical applications, it is important to have a deep understanding of how MMC behaves during secondary processing, especially forging. Forging is a good way to make MMC because it lets you fine-tune the microstructure and mechanical properties by controlling things like temperature and rate of deformation. Because of this, MMCs are perfect for a wide range of uses, from high-stress parts to parts that don't wear out easily. The objective of the current study is to manufacture aluminum alloy composites reinforced with TiC using liquid metallurgy and forging techniques, and afterwards assess their mechanical characteristics.

2. Materials and Methods

The matrix was made of an aluminum alloy made of 7075 aluminums. This alloy has a high ratio of strength to density, which makes them a popular choice for a wide range of uses. For this study, powdered particles of titanium carbide (TiC) were chosen to be used as reinforcement. The TiC particles (30-40 microns) were made by M/s Metallizing Jodhpur, Rajasthan. In 3 wt.% steps, a maximum weight percentage of 9 wt.% was used for TiC to make sure that everything was the same. TiC was chosen as the reinforcement material because it has unique properties that could help improve the properties of the composite. Fig. 1 and Fig. 2 show scanning electron micrographs and energy-dispersive X-ray spectroscopy (EDAX) patterns of TiC particles.

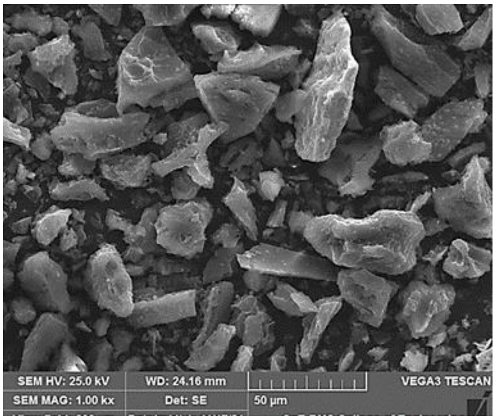


Fig. 1. SEM of TiC particles

At 770°C, an electrical resistance furnace was used to melt the aluminum 7075 alloy. To make a controlled vortex in the molten aluminum alloy, a mechanical stirrer covered with ceramic was used. In this changing environment, heated, already-mixed TiC particles were added slowly while the mixture was constantly stirred. Before adding the TiC particles, they were heated in a muffle furnace at 200°C for one hour to make sure they were evenly spread out. From 0 to 9 wt.%, the weight fraction of titanium carbide (TiC) particles was changed in a planned way by 3 wt.%. TiC was always used as a reinforcement in all composite recipes. The method of preparation was used to make sure that the TiC reinforcement particles were spread out evenly in the aluminum matrix. To get rid of any trapped gases, degassing tablets, which are easy to find on the market, were added to the molten mixture.

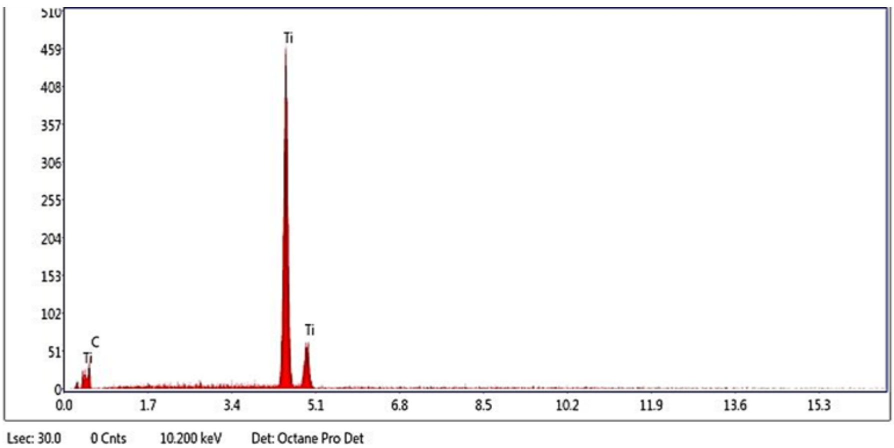


Fig. 2. EDS of TiC particles

The treated molten mixture was then poured into 200 mm long and 80 mm wide metal molds that had been heated. This picture shows what the material looks like after the casting and processing steps. The height and diameter of both the cast matrix alloys and the cast composites were machined to be 80 mm. The 80 mm diameter was for the cast matrix alloys. The muffle furnace was heated to 550 degrees Celsius, and billets that had been machined were put inside. At M/s Fitwel forgings Pvt. Ltd. in Tumkur, Karnataka, India, heated billets were forged in an open die using a one-ton hydraulic hammer. Before the casting process, the cylinder-shaped billets were heated for 30 minutes at 580+3°C to get them ready. The machined billets that had been heated were then forged according to the process parameters with deformation ratio of 6:1. The microhardness tests were done with a Vickers microhardness tester, a 100-gram load, and a 10-second dwell time. In line with ASTM A370 standards, tensile tests were done with a TUE-C-400 universal testing machine.

3. Results and Discussion

3.1 Microstructural Analysis

Fig. 3 (a-d) shows optical micrographs that show the microstructure of Al7075 alloy composites that have been made stronger with TiC particles. The micrographs show that very small pieces of TiC are spread out across the matrix alloy. Even though the cast micrographs show that there are some clusters of TiC particles, the hot-forged Al7075-TiC composite shows that the synthesized TiC particles are more evenly spread out and can be moved to different places. After the hot forging process, the TiC particles are aligned in the direction that the metal is flowing, which is an important thing to notice.

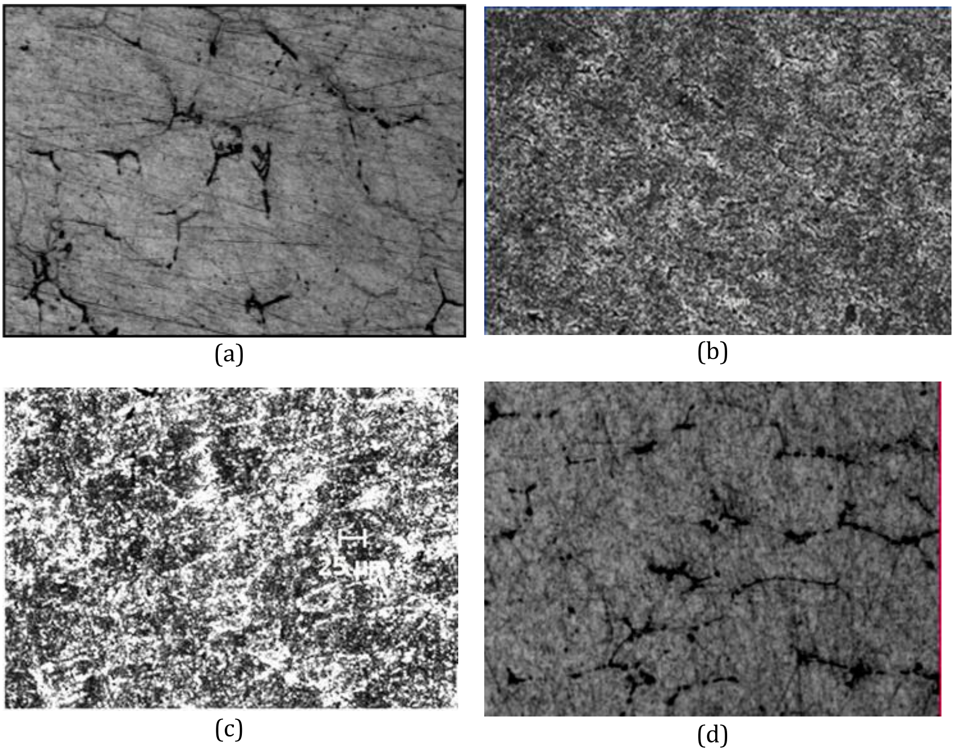


Fig. 3. Optical Micrographs of (a) As-cast Al7075 alloy (b) Forged Al7075 alloy (c) Al7075-9 wt.% TiC Composites(d) Forged Al7075-9 wt.% TiC Composites

Even after hot forging, there is no evidence that the link between the matrix alloy and the TiC reinforcement has lost its structural integrity. Figure shows some micrographs that show this to be true. When looked at through a microscope, the titanium carbide (TiC) particles that are made are said to be between 25 and 50 micrometers in size. After seeing the particles in question, this conclusion was made. Hot forging helps spread out TiC particles that have clumped together. This reduces the number of places where there are no particles at all. Figure 1.1 shows that the porosity is getting smaller, which is the most important thing. At the same time, the microstructure is getting denser and smoother.

3.2 Grain Size Analysis

Fig. 4 shows the size distribution of the grains in composites made of Al7075 alloy and TiC particles. These composites were made using the stir-casting and hot-forging methods, respectively. When the number of synthetic reinforcements in the matrix alloy goes up, there is a clear pattern that shows the grain size of the composites that are made drops by a large amount. This is true whether you look at the as-cast or hot-forged state. When hot-forged composites are compared to their as-cast counterparts, it is clear that the grain refinement is higher in all of the cases that were looked at. No matter what happens, this is always true. Figure shows that the average grain size of the Al7075-TiC composite decreases by 51% when it is as-cast, and then it decreases by 55% when it is hot forged. This is a very important find. Compared to the grain size of the matrix alloy in its as-cast state, the average grain size reduction for the Al7075-TiC composite in its as-cast state is 49% and in its hot-forged state it is 59%. This is because when the matrix alloy is hot-forged, the average grain size is cut by 59%.

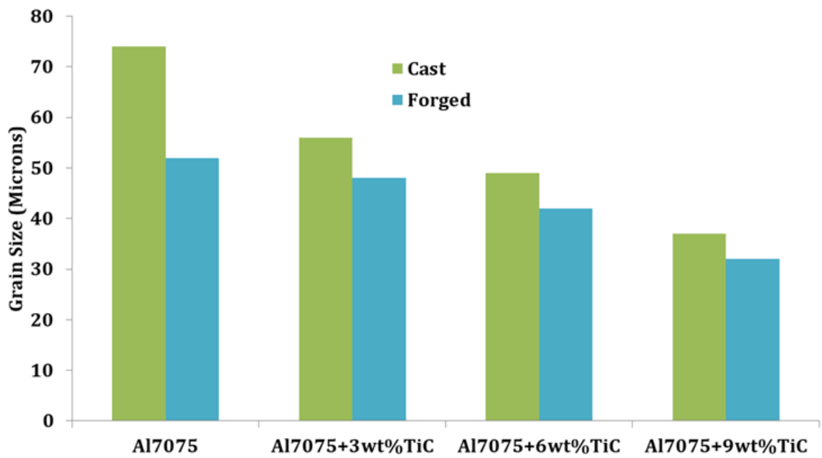


Fig. 4. Variation of grain size with TiC reinforcement for cast and forged composites

Adding ceramic particles to the molten aluminum alloy is what caused the granules to get smaller. During the phase of solidification, these ceramic particles act as places where new crystals can form. Also, micrographs show that the microstructure of cast composites is not as refined as the microstructure of hot-forged composites, which is more refined. The use of thermo-mechanical processing, which causes a lot of plastic deformation and a big drop in particle size, could be to blame for the observed refinement. The micrograph displays a fine and homogeneous dispersion of reinforced particles within the matrix alloy. Following the forging process, TiC particles are orientated in the direction of the metal flow during hot forging.

3.3 Micro-Hardness

Fig. 5 shows the differences in hardness that happen when TiC reinforcement is added to cast and forged composites. When stiff reinforcements are added to a matrix alloy that is normally soft and flexible, the matrix material's hardness increases by a lot. This is what happens when composites made of Al7075 are stir-cast and then hot-forged after being strengthened with TiC. When stiff reinforcing materials are added to a matrix alloy, the total hardness of the alloy goes up [22, 23]. There are a number of important reasons that led to this change. Most of the time, thermal mismatch is caused by a big difference between the matrix alloy without reinforcement and the reinforced phase in the coefficient of thermal expansion. Both the matrix alloy and the reinforced phase have this difference [24, 25].

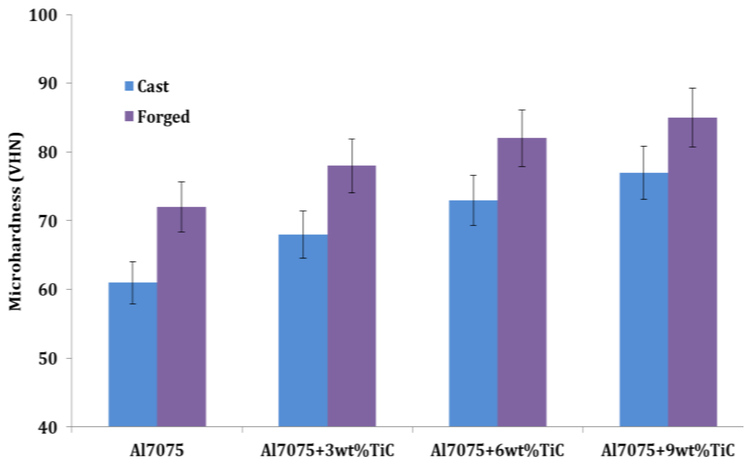


Fig. 5. Variation of hardness with TiC reinforcement for cast and forged

The different rates of expansion of the different materials contribute to the development of residual stresses, which lead to a hardening of the composite in the end. Also, the increased hardness that may be seen in these composites may be due to the uniform dispersion and microscopic particle size of the reinforcement, as well as the successful integration of the unreinforced alloy with the reinforcement [26, 27]. The increased hardness of the material is due to how the composite parts fit together and how the reinforcing particles are now more evenly spread out. When the pictures from optical and scanning electron microscopy (SEM) are looked at in great detail, it is clear that the composite material's porosity has been greatly reduced. This can be blamed on the in-situ processing method that was used.

This research shows that both the average and absolute values of hardness are higher for secondary processed composites than for primary processed composites. There are two main things that cause these things to happen. In composites that are processed a second time, the amount of grain refinement is much higher, which makes the material much harder. During the next steps, any tiny flaws that may have been caused by the way the first casting was done are often fixed. This makes the material more uniform and structurally strong. The improvement in hardness, which came from a higher resistance to plastic deformation, might be related to the fact that the average grain size got smaller as the product was being made. Because of this drop, the number of dislocations is successfully brought down. After hot forging, the hardness of stir-cast Al7075 composites that had TiC added to them went up. This could be due to a number of different things. Because of how these processes work together, the composites have better mechanical properties that make them good for applications that need to be more durable [28].

3.4 Ultimate Tensile Strength

Fig. 6 shows a comparison study of UTS. This analysis shows how the tensile strength of Al7075 alloy composites that have gone through primary processing is different from those that have gone through secondary processing. After the TiC particles made these composites stronger, they were heated up and put through a process called "hot forging." This evaluation shows that the tensile strength of composites is much higher than that of unreinforced versions of the same material during both the first and second stages of processing. Also, it has been shown that adding TiC reinforcement significantly increases the ultimate tensile strength (UTS). When the Al7075-10wt% TiC composites were first processed, their properties got better by 65%. When they were then processed again, their properties got better by 88%. Most of the reason why the composite material has a higher ultimate tensile strength is because rigid TiC particles are mixed into the matrix [29, 30]. This is because the mechanical properties of the composite material are better. The above-mentioned reinforcing process has led to the emergence of a number of factors that, when taken together, are to blame for the increase in UTS that has been seen.

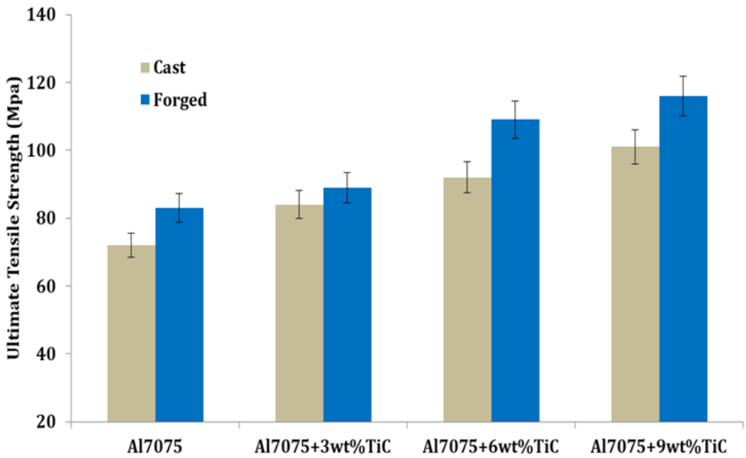


Fig. 6. Variation of UTS with TiC reinforcement for cast and forged composites

3.5 Ductility

Fig.7 shows the ductility of the composites. Most of the loss of ductility that happens when the reinforcement concentration goes up is due to the presence of hard TiC particles in the Al7075 composite. These particles encourage the formation of brittle phases within the matrix. Experiments have shown this to be true. Al7075 composites that have been hot-forged after being strengthened with TiC particles and going through the process described above can show the effect mentioned above. The presence of intrinsically fragile phases, as well as any secondary or intermetallic phases that may be present, makes spots in the material more likely to start cracking early, which makes the material as a whole less flexible [31]. On the other hand, using secondary processing has an effect that is the exact opposite of the first. It makes the material more flexible. During the hot forging process, a lot of grain refinement and re-crystallization takes place. This is why this happens. The process described above helps to strengthen the bond between the matrix and the reinforcement at the interface. This, in turn, makes the material more flexible. The increased interfacial contacts play a big role in spreading out stress and stopping cracks from spreading, which improves the material's ability to bend without breaking [32]. When compared to the ductility of the main processed base alloy, the ductility of the

Al7075-9wt%TiC composite in its secondary processed state is 18% lower, and the ductility of the base alloy in its primary processed state is 9% lower.

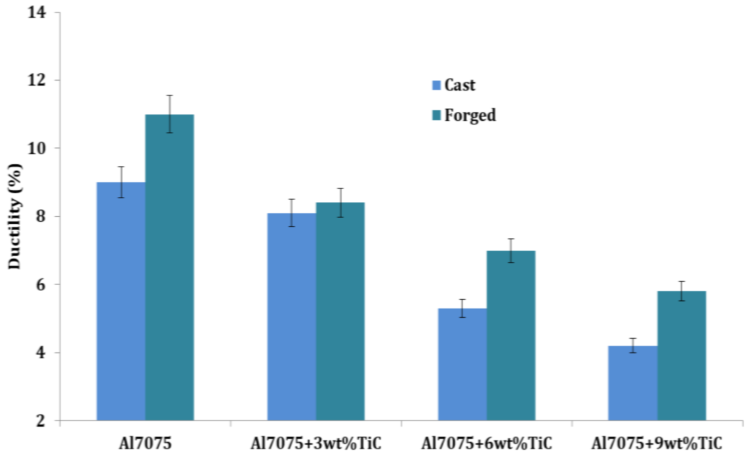
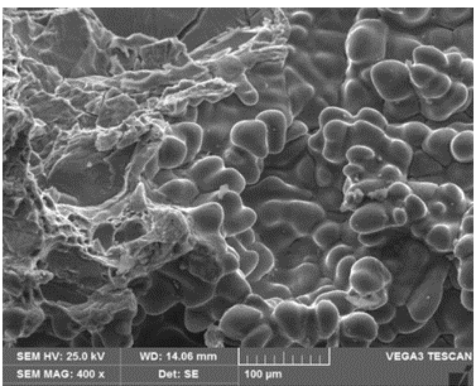


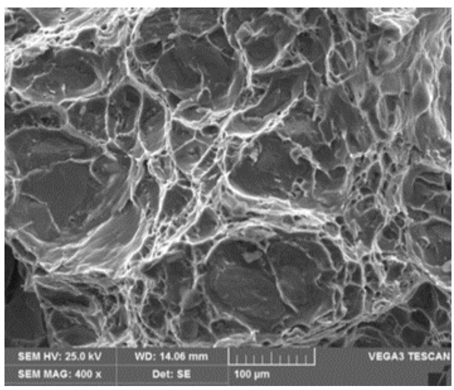
Fig. 7. Variation of ductility with TiC reinforcement for cast and forged composites

3.6 Fractured Surface Analysis

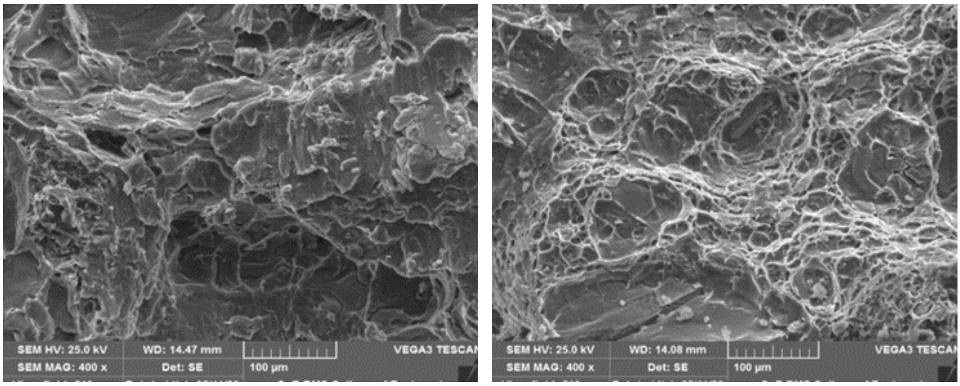
Fig.8 (a-d) shows scanning electron micrographs of the broken surfaces of tensile specimens made from Al7075 alloy composites that have been through both primary and secondary processing. These composites have been forged in a hot environment and have TiC particles embedded in them to make them stronger. The pictures we talked about before give us a lot of information about how the materials break, which helps us understand the underlying mechanisms that determine how the materials fail. After looking at the micrographs, especially Fig.8, in more detail, it becomes clear that the sample has shallow dimples and trim bands. These things point to the fact that there was plastic deformation right before the building fell down. Fig.8 shows that both primary and secondary treated Al7075 alloy and Al7075-TiC composites show clear signs of particle breaking. The fact that the above-mentioned discovery was made shows how strong and long-lasting the bond between the matrix alloy and the TiC reinforcement is. This bond is a side effect of the way the composite material is made and the benefits of the strategy for reinforcing integration [33, 34]. Al7075 alloy shows ductile fracture in nature.



(a)



(b)



(c) (d)

Fig. 8. Fractured SEM Micrographs of (a) As-cast Al7075 alloy (b) Forged Al7075 alloy (c) Al7075-9 wt.% TiC Composites(d) Forged Al7075-9 wt.% TiC Composites

The hot forging makes the Al7075 alloy fracture as ductile and brittle in nature. Also, interfacial fractures can be seen in certain places, as shown in Fig.8. Based on what was seen, one could figure out that the composite material breaks in a complicated way. This process involves the formation of voids and their subsequent filling, as well as the breaking of TiC particles that are embedded in the matrix alloy. The complicated interactions between the different ways that composites can break show how complicated the failure mechanisms [35, 36]. When the way the matrix alloy and composites break is compared to how the matrix alloy breaks, it is clear that there is a big difference between the two. The very even distribution of larger voids in the matrix alloy, which is one of the things that makes it unique, suggests that it breaks in a ductile way. On the other hand, there is evidence that there are fewer voids in the composites, which suggests that they break in a way that is ductile at the microscopic level but brittle at the macroscopic level [37, 38]. The addition of stiff TiC reinforcement makes the composite stronger, but it also makes it more likely to show brittle fracture characteristics because it has a higher tendency to do so. The brittle fracture behaviour is observed in the case of Al7075 alloy with TiC reinforced composites. The presence of TiC particles makes the soft matrix as brittle by reducing the ductility [39, 40].

4. Conclusion

Al7075 alloy with 3, 6 and 9 wt.% of TiC particles composites were developed by conventional stir process. An influence of combined effect of TiC particles weight percentages and hot forging effect on grain size, micro-Vickers hardness and ultimate tensile strength were investigated. The optical micrographs corroborate the microstructural investigation of as-cast and hot-forged Al7075-TiC alloy composites, which demonstrate unique properties. Micrographs of optical microscope indicated the distribution of titanium carbide particles in the Al7075 alloy composites. Hot forging improves particle dispersion and alignment while keeping matrix-reinforcement links intact. Hot forging disperses agglomerated TiC particles and hence reduces porosity. Because of nucleation and dynamic recrystallization, increasing TiC reinforcement corresponds with lower average grain sizes. Hot-forged composites have consistently refined microstructures, resulting in better characteristics. The use of thermo-mechanical processing, which causes a lot of plastic deformation and a big drop in particle size, could be to blame for the observed refinement. The hot forging of as cast Al7075 and 3, 6 and 9 wt.% of TiC composites impacted in the reduction of grain size. As the weight percentage of TiC content increased from 3 to 9 wt.% in the matrix, the micro hardness of prepared composites was enhanced. The hardness of as cast Al7075 alloy was 60 VHN, with the 9 wt.% of TiC particles and hot forging combined effect it was 85 VHN. An improvement of 41.66% was obtained with the addition of 9 wt. % of TiC and hot forging. Further, an ultimate strength of Al7075 alloy increased with hot forging and reinforcement of TiC particles. The ultimate strength of as cast Al7075 alloy was 72 MPa, with an incorporation of 9 wt. % of TiC and hot forging, it was 118 MPa. An improvement of 63.88% was obtained with hot forging and TiC particles inclusion. The Al7075-TiC composites with hot forging exhibited superior hardness and tensile properties as compared to the as cast alloy and composites. Various fracture mechanisms were observed in the Al7075-TiC composites. Al7075 alloy represented ductile mode of fracture, while Al7075 with TiC composites were exhibited brittle and ductile mode fracture surface behaviors.

References

[1] Pankaj RJ, Sridhar BR, Nagaral M, Jayasheel IH. Evaluation of mechanical properties of B4C and graphite particulates reinforced A356 alloy hybrid composites. Materials Today: Proceedings, 2017;4 (9):9972-9976. https://doi.org/10.1016/j.matpr.2017.06.304

[2] Satish BB, Samuel D, Bharath V, Madeva N, Aravinda T, Vijee K, Virupaxi A. Development and mechanical characterization of Al6061-Al2O3-Graphene hybrid metal matrix composites. Journal of Composites Science, 2021;5 (6):155. https://doi.org/10.3390/jcs5060155

[3] Veeresh Kumar GB, Gude V, Mandadi SV, Jayarami KR, Nagaral M, Naresh K. Effects of addition of titanium diboride and graphite particulate reinforcements on physical, mechanical and tribological properties of Al6061 Alloy based hybrid metal matrix composites. Advances in Materials and Processing Technologies, 2022; 8 (2):2259-2276. https://doi.org/10.1080/2374068X.2021.1904370

[4] Jayasheel IH, Prasad TB, Nagaral M, Pankaj J, Auradi V. Microstructure and dry sliding wear behaviour of Al2219-TiC composites. Materials Today: Proceedings, 2017; 4 (10):11004-11009. https://doi.org/10.1016/j.matpr.2017.08.058

[5] Ashby MF, Shercliff HR, Cebon D. Materials: Engineering, Science, Processing and Design. Butterworth-Heinemann, 2019.

[6] Gu D, Shen YL, Jiang QC, Peng XJ, Li XL. Fatigue behaviors and microstructure of TiCp/Al composites at elevated temperatures. Journal of Alloys and Compounds, 2017; 695:2237-2244.

[7] Suryanarayana C. Mechanical alloying and milling. Progress in Materials Science, 2001;46(1-2):1-184. https://doi.org/10.1016/S0079-6425(99)00010-9

[8] Jiang F, Wei D, Zhang D, Sun S. Tribological behavior of TiC reinforced Al composites at elevated temperature. Wear, 2014; 315(1-2):118-125.

[9] Polmear IJ. Light Alloys: From Traditional Alloys to Nanocrystals. 3rd ed. Oxford: Elsevier Butterworth-Heinemann, 2006.

[10] Lu L, Shen Y, Chen X, Qian L, Lu K. Ultrahigh strength and high electrical conductivity in copper." Science, 2004;304(5669):422-426. https://doi.org/10.1126/science.1092905

[11] Patil JA, Bhate N. Effect of spray parameters on microstructure and hardness of in situ Al6061-10% TiC composite coatings. Surface and Coatings Technology, 2012;207:483-490.

[12] Bhagat RB, Mohan TP. In-situ cast composites: a review. Journal of Minerals & Materials Characterization & Engineering, 2006; 5(2):145-154.

[13] Wang Y, Chen D. Mechanical properties of aluminum matrix composites: A review. Journal of Materials Science & Technology, 2019;35(12):2703-2718.

[14] Zhan J, Zhang Y. Microstructure and mechanical properties of SiCp/Al composites processed by equal channel angular pressing. Materials Science and Engineering: A, 2018; 737: 93-100.
[15] Jia H. Effect of forging process on microstructure and mechanical properties of TiC/Al composites. Materials Science and Engineering: A, 2020;770:138541.
[16] Zhang Y. Microstructure and mechanical properties of in situ Al-TiB2 composites processed by equal channel angular pressing. Journal of Alloys and Compounds, 2019; 770:444-450.
[17] Li C. Enhanced mechanical properties of aluminum matrix composites reinforced with Al2O3 particles through a novel extrusion process. Materials Science and Engineering: A, 2018;713:180-189.
[18] Huang H. Mechanical properties of Al-SiC composites fabricated by semi-solid stirring and extrusion. Journal of Alloys and Compounds, 2020; 826: 154171.
[19] Tao X. Effects of extrusion on microstructure and mechanical properties of in situ Al-TiB2 composites. Materials Science and Engineering: A, 2018; 736:106-115.
[20] Gopal Krishna UB, Vasudeva B, Virupaxi A, Nagaral N. Effect of percentage variation on wear behaviour of tungsten carbide and cobalt reinforced Al7075 matrix composites synthesized by melt stirring method. Journal of Bio-and Tribo-Corrosion, 2021;7 (3):89. https://doi.org/10.1007/s40735-021-00528-1
[21] Vasanth Kumar HS, Kempaiah UN, Madeva N, Revanna K. Investigations on mechanical behaviour of micro B4C particles reinforced Al6061 alloy metal composites. Indian Journal of Science and Technology, 2021;14 (22):1855-1863. https://doi.org/10.17485/IJST/v14i22.736
[22] Zeeshan A, Muthuraman V, Rathnakumar P, Gurusamy P, Madeva N. Studies on mechanical properties of 3 wt% of 40 and 90 µm size B4C particulates reinforced A356 alloy composites. Materials Today: Proceedings, 2022; 52:494-499. https://doi.org/10.1016/j.matpr.2021.09.260
[23] Raj Kumar, Deshpande RG, Gopinath B, Jayasheel H, Madeva N, Auradi V. Mechanical fractography and worn surface analysis of nanographite and ZrO2-reinforced Al7075 alloy aerospace metal composites. Journal of Failure Analysis and Prevention, 2021;21:525-536. https://doi.org/10.1007/s11668-020-01092-5
[24] Nagaraj N, Mahendra KV, Madeva N. Microstructure and evaluation of mechanical properties of Al-7Si-fly ash composites, Materials Today: Proceedings, 2018;5 (1):3109-3116. https://doi.org/10.1016/j.matpr.2018.01.116
[25] Krishna D, Prashanth L, Madeva N, Rakesh M, Hanumantharayagouda MB. Microstructure and mechanical behavior of B4C particulates reinforced ZA27 alloy composites. Materials Today: Proceedings, 2017;4,8: 7546-7553. https://doi.org/10.1016/j.matpr.2017.07.086
[26] Manjunatha TH, Yadavalli B, Madeva N, Venkataramana V, Jayasheel IH. Investigations on mechanical behavior of Al7075-nano B4C composites, IOP Conference Series: Materials Science and Engineering, 2018; 376 (1):012091. https://doi.org/10.1088/1757-899X/376/1/012091
[27] Anjan Kumar BH, Chaithra PC, Ragavendra C, Chandrasekhar SB, Latha SB, Madeva N, Suresh R. Synthesis and mechanical characterization of Si3N4 reinforced copper-tin matrix composites, Journal of the Mechanical Behavior of Materials, 2021;30 (1):199-206. https://doi.org/10.1515/jmbm-2021-0020
[28] Pankaj RJ, Madeva N, Shivakumar R, Jayasheel IH. Impact of boron carbide and graphite dual particulates addition on wear behavior of A356 alloy metal matrix composites, Journal of Metals, Materials and Minerals, 2020;30 (4):106-112. https://doi.org/10.55713/jmmm.v30i4.642
[29] Rashmi PS, Mahesh TS, Zeeshan A, Veeresha G, Madeva N. Studies on mechanical behaviour and tensile fractography of boron carbide particles reinforced Al8081 alloy

advanced metal composites, Materials Today: Proceedings, 2022;52:2115-2120. https://doi.org/10.1016/j.matpr.2021.12.397

[30] Anjan Babu VA, Saravanan R, Raviprakash M, Madeva N, Nithin K. Microstructural characterization and wear behavior of 12 wt% of boron carbide reinforced Al2030 alloy composites. Materials Today: Proceedings, 2022; 52: 439-444. https://doi.org/10.1016/j.matpr.2021.09.098

[31] Rashmi PS, Hemanth RT, Madeva N, Nithin K, Auradi V. Effect of B4C particles addition on the mechanical, tensile fracture and wear behavior of Al7075 alloy composites. Journal of Bio-and Tribo-Corrosion, 2024;10 (2). https://doi.org/10.1007/s40735-024-00841-5

[32] Pathalinga GP, Chittappa HC, Nagaral M, Auradi V. Influence of B4C Reinforcement Particles with Varying Sizes on the Tensile Failure and Fractography of LM29 Alloy Composites, Journal of Failure Analysis and Prevention, 2020;20 (6):2078-2086. https://doi.org/10.1007/s11668-020-01021-6

[33] Madeva N, Auradi V, Kori SA, Veena S. Mechanical characterization and wear behavior of nano TiO2 particulates reinforced Al7075 alloy composites. Mechanics of Advanced Composite Structures, 2020;7(1):71-78.

[34] Bharath V, Santhrusht SA, Nagaral M, Virupaxi A, Kori SA. Characterization and Mechanical Properties of 2014 Aluminum Alloy Reinforced with Al2O3p Composite Produced by Two-Stage Stir Casting Route. Journal of The Institution of Engineers (India): Series C, 2018;100;277-282. https://doi.org/10.1007/s40032-018-0442-x

[35] Ananthakrishna S, Madeva N, Chandrashekar A, Meshel QA, Ravikiran KB, Nithin K, Virupaxi A, Saiful I, Ranga RC, Abdul R, Mohammad AK, Channa KN. Influence of graphite particles on the mechanical and wear characterization of Al6082 alloy composites. ACS Omega, 2023;8(30):26828-26836. https://doi.org/10.1021/acsomega.3c01313

[36] Subhashchandra SG, Mahadev S, Madeva N, Shashidhar S, Auradi V. Microstructural evolution and mechanical behavior of 90 micron sized B4C particulates reinforced Al2219 alloy composites. Materials Today: Proceedings, 2021;45:7138-7142. https://doi.org/10.1016/j.matpr.2021.02.026

[37] Raksha MS, Madeva N, Satish BB, Chandrashekar A, Mohammad SK, Mohammed OAW, Saiful I, Vivek B, Rohini KP, Mohammad AK, Abdul R. Impact of boron carbide particles and weight percentage on the mechanical and wear characterization of Al2011 alloy metal composites. ACS Omega, 2023;8(26):23763-23771. https://doi.org/10.1021/acsomega.3c02065

[38] Shashidhar S, Vijaya Kumar P, Shantharaja M, Nagaral M, Shivananda BK. Processing, microstructure and tensile behavior of nano B4C particulates reinforced Al2219 alloy composites. Materials Today: Proceedings, 2018;5(11):25158-25164. https://doi.org/10.1016/j.matpr.2018.10.317

[39] Shantharaj P, Prashanth AS, Madeva N, Bharath V, Auradi V, Dharshan K. Microstructure, tensile and compression behavior of B4C particles reinforced Al7075 matrix composites. Materials Today: Proceedings, 2022;52:1135-1139. https://doi.org/10.1016/j.matpr.2021.11.008

[40] Chandrasekhar GL, Vijayakumar Y, Nagaral M, Rajesh A, Manjunath K, Kaviti RVP, Auradi V. Synthesis and tensile behavior of Al7475-nano B4C particles reinforced composites at elevated temperatures. Materials Physics and Mechanics, 2024;52(3):44-57.