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Influence of Rolling and Ageing on Mechanical Properties of AA2195 Based Metal Matrix Composites

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Abstract: The modern Aluminium based composites have a great demand in the field of aerospace applications due to their lightweight, high strength, high stiffness, and superior mechanical properties. The main objective is to fabricate the AA2195 composites through Medium Frequency Induction Furnace (MFIF) with Taguchi L_{16} design of experiments, hot rolling process and heat treatment of composites is done and then compare the mechanical properties of hot rolled and heat treated AA2195 composite with casted composite. It is analyzed the effects of reinforcements like graphite and boron carbide on the mechanical behaviors and microstructure of both AA2195 composites. The microstructures revealed that reinforcements were distributed uniformly throughout the composites. It observed that the elemental investigation on SEM and XRD for both the composites showed that formed intermetallic compounds (IMCs) helped refine the microstructure and further increased the mechanical properties. The hot rolled and heat-treated AA2195 composite fabricated at 8% B_4C and 6% Gr exhibits the more enhanced ultimate tensile strength, hardness, and reduction in density, % elongation compared to the casted composite. The rolling process is used to reduce the porosity of the composite. In contrast, heat treatment enhances the composite's mechanical properties like strength and hardness.

Keywords: Taguchi method, Medium Frequency Induction Furnace (MFIF) casting process, hot rolling process, heat treatment, microstructure and mechanical properties

1. Introduction

In the recent studies of manufacturing applications predominantly in aircraft, aerospace, and naval attention was significantly focused to less weight materials with excellent strength. Hence a lightweight and better efficiency composite could be considered as the greatest option for fulfilling different requirements of the fabrication companies [1]. The composite production has been revealed to be one of the flexible processes and the simplest to improve the material features with unique effectiveness and functionality that could not be observed in a single material [2]. Aluminium Lithium alloys have superior features like high elastic modulus, excellent specific strength & low density. Hence, they are mostly using in aerospace & aeronautical applications. The 3rd-gen AA2195 al-li alloy is excellently used in Aerospace Fuel Tanks, aircraft & launch vehicles [3]. The composite materials were made up of matrix as well as reinforcement. The matrix phase is the principal base material that functions should be enhanced, while the reinforcement materials are predominant with superior properties compared to the matrix phase [4]. The composition of reinforcement acts an important function on the matrix material in the preparation of composites. The proportion fraction of reinforcement in the matrix plays an important function in composite formability. The different types of composites were discussed. Usually, MMCs consist of two or more ingredient parts, frequently metal, and another is the reinforcement. The aim of the development of MMCs is to obtain superior physical and mechanical properties [5]. However, the modern tendency looking towards the production of metal matrix composites is due to their excellent properties compared to the conventional materials, hence the desired aims of many extremely developed engineering

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applications almost rely upon the successful advancement of metal matrix composites for the reason that the lifetime–economy materials can moderate the challenge faced by fabrication firm, particularly automobile, aircraft and space application. Therefore, stir casting method may be the simplest, flexible, less expensive, and easily available method. This method was chosen as the most selected one and referred to by many researchers. [6–9]. This alloy was consequently used for the Super Lightweight External Tank (SLWET), first launched in June 1998. Direct substitution of 2195 for 2219 reduced the tank weight by 3175 kg, weight savings of over 10%. This tremendous result was achieved by exploiting 2195's advantageous combination of higher strength, increased stiffness, and reduced density [10].

Al7075-SiC composites with different weight fractions were fabricated using powder metallurgy. Microstructural analysis, tribological and mechanical features of MMCs were examined. The best mechanical and tribological properties were observed. The dry sliding wear test was evaluated through a pin on the disc equipment. The coefficient of friction and wear loss of samples were examined [11-13]. The stir casting technique manufactured the AA4032 composites. The granite powder was used as weight reinforcement at 0, 3, 6, and 9 %. The AMC mechanical features and microstructural analysis were discovered to be better than the unreinforced alloy [14-18]. Al-TiB2 metal matrix composites were fabricated using the in-situ method, and optimization techniques like the grey relational approach and the Taguchi L9 orthogonal array method were used. The optimized physical and mechanical properties results were discussed [19-22]. Al-SiC - kaoline hybrid metal matrix composite was fabricated by using the powder metallurgy technique. The mechanical behaviour of manufactured hybrid composites was studied. [23-24]. An overview of the fabrication of Hybrid MMCs through various methods and their applications were discussed [25-33]. The Al-Al_2O_3-SiC hybrid composites were manufactured through the stir casting method. The microstructure morphology and mechanical properties of MMCs were studied [34-41]. AA6061-reinforced SiC- Al_2O_3 hybrid metal matrix composites HMMCS were manufactured by using the squeeze casting technique. The microstructural characterization, physical and mechanical properties were investigated. Optimization techniques were used to optimize the process parameters [42-44]. A356- Gr- B_4C composites were manufactured through the two-stage stir casting method. The composite's characterization was done. Mechanical properties were discussed [45-47]. The MMCs were fabricated by using the stir-casting method. The fabrication of Aluminium composites with Jute Ash and SiC Particles was done. The wear and mechanical properties were evaluated [48]. The aluminium-based composite was successfully made-up with the stir casting method. The effect of stir casting variables, namely, stir time, stir speed, and temperature, were studied using Taguchi L9 orthogonal array to design experiments [49]. The mechanical properties and microstructural characterization of aluminium metal matrix composites (MMCs) prepared by liquid metallurgy method reinforcement materials such as nano graphene and Zirconium Oxide particles were discussed [50-51]. Aluminium matrix hybrid composites were manufactured using the Stir Casting technique, consisting of reinforcements such as SiC, fly ash and coconut shell ash. Their tribological and mechanical properties were discussed [52]. The traditional liquid metallurgy method fabricated the AA7075 boron nitride metal matrix composites. Composite microstructural morphology was done. The physical and mechanical properties were evaluated, and the optimization technique was done by response surface methodology [53].

Al6061-SiC composites were manufactured by using the Stir casting technique. For the microstructure analysis, mechanical properties were evaluated. The process variables were optimized by using an optimization technique [54]. Aluminium matrix reinforced with titanium oxide (10, 7.5, 5.0, and 2.5 wt%) and aluminium oxide are equal in proportion and were made up through stir casting technique. However, microstructure analysis and sample mechanical properties were investigated [55-57]. The aluminium-based Al- Al_2O_3-SiC hybrid metal matrix composites were fabricated through the stir casting method. Mechanical properties, microstructure and wear behaviour of the fabricated specimens were examined. 1 wt% of Al_2O_3 and 8 wt% SiC-reinforced AMCs reveal the highest hardness [58]. An overview of mechanical behaviour and fabrication routes of aluminium matrix composite applications were discussed [59]. Cu-based composites with Graphite-Sic (10, 7.5, 5.0, and 2.5 wt%) are fabricated through the stir casting technique. Characterization, corrosion, and mechanical features of these copper matrix MMCs were evaluated. MMCs consisting of 5 wt.% revealed less wear rate and high corrosion resistance [60]. The Aluminium Al_2O_3–TiC-reinforced AMCs were fabricated by stir casting, and learning the influence of reinforcement on the mechanical characteristics was discussed. It was found that reinforced AMCs showed better mechanical properties compared to unreinforced AMCs [61]. The Al–Li alloys of diverse aircraft applications were used in microstructural properties and processing metallurgy; historical progress, mechanical properties, aviation usage, and corrosion of Al–Li alloys were studied [62-63].

The present work has focused on the development of aluminium composites as well as their fabrication methods. It is focused on AA2195 composites via a hot rolling process and heat treatment process. The grain texture characteristics depend on a variety of ageing situations. The optimization of grain structure has been analyzed for enhancing the AA2195 composite mechanical features in a variety of ageing conditions. The essential production strategies are helpful for the success of the AA2195 composites. It signifies that enhancement in the AA2195 composites is most suitable for the performance of future aircraft & aerospace applications. An investigation is done to observe the characterization and mechanical properties of AA2195 alloy with B_4C and Graphite and composites that Medium

Frequency Induction Furnace fabricates. The composites were manufactured by combining particles to increase the wetting behaviour and to get better bonding of both the alloy matrix and Gr-B_4C particulates.

2. Experimentation

Fabrication of AA2195 alloys on 9–10 kg was produced in MFIF under an inert gas environment. For each sample, the selected composition is Al– (5–5.7) Cu, (0.4–0.6) Ag, (0.15–0.2) Zr, (0.4–0.6) Mg, and (0.8–1.6) Li. Later purifying with acetone, the materials are placed in the Graphite Crucible so that pure Aluminium ingots and other materials are placed at the sides and at the bottom of the cruc ible, and lithium is placed in the middle. The melting process is done by maintaining the furnace at 0.001 bar with inert environment conditions. Once Al and other materials were melted, Li material was added into the crucible under an inert atmosphere and manufactured using the MFIF casting method. Sixteen melts of AA2195 were produced by using this technique with varying B_4C and graphite wt % of 2 %, 4 %, 6 % and 8 %, respectively. The liquid metal pouring temperature is maintained at 710 °C. The molten liquid is poured into the mould from the crucible to (210 ×150 × 25) mm 3 rectangular shape size. The cast composites were hot rolled with a 40 % reduction at 480 °C temperature under different heat treatment conditions. Hot-rolling experimental data is given in Table 1. The samples were heated to a temperature of 480 °C then fed into the rolling machine, and the distance between the rollers was adjusted as per the required thickness of the samples. The thickness of the samples will get under several passes of the samples into the rollers. In hot rolling operations, the diameter of the roller is 96 mm, the roller is made with hardened tool steel, and the speed of the roller is 40 rpm. A water displacement technique is employed for estimating the composite density. The Archimedes method explains that a buoyant force pushing up on an object submerged in a fluid equals the fluid weight volume displaced by that object. Micro Vickers hardness is employed to measure the sample hardness. A diamond indenter with size 2.5 microns, a load of 100 gms, is applied on the sample for 25s. The hardness values were measured on samples cross-sections of different samples at different locations by using a Micro Vickers hardness tester, and an average of six hardness values was taken. For the Tensile test, samples were prepared as per ASTM-E8 standards. The sample's microstructure is analyzed using an optical and scanning electron microscope. The experimental setup as shown in Fig. 1 of schematic view of MFIF. The matrix material introduced as AA2195 & the materials for reinforcement are Boron carbide (B_4C) and Graphite particulate grain size is 90nm.

Table 1 - Hot rolling detail of MMC

MMCs	Thickness in mm (in 8 passes)		% of reduction
	Before rolling	After rolling	
AA2195-B_4C-Gr	12	7	41.67

Fig. 1 - Medium frequency induction furnace

AA2195 alloy is selected as a matrix material due to its many applications in various engineering fields, including space applications, aerospace sectors, and automotive. Additionally, this alloy shows good formability, excellent corrosion resistance and high strength. Table 1 exhibits the chemical composition of the AA2195 alloy studied in this. Boron Carbide (B_4C) and Graphite (Gr) are taken as reinforcement materials. Boron carbide (B_4C) is employed as a reinforcement material because of its excellent features, like high hardness, high strength, and lower density. B_4C nanoparticle is used as reinforcing material; its size is 90 nm. The B_4C has less density compared to AA2195. Hence proper mixing of matrix material and reinforcement gives less density composite. The applications of boron carbide are used in wear protection, armor, neutron absorbers, turbines, nozzles, and bearings. Graphite (Gr) is widely used as an engineering material across various applications, such as thrust bearings, piston rings, journal bearings and vanes. Carbon-based seals are used in the shafts of several aircraft jet engines and in the fuel pumps. Natural Gr is mostly employed for batteries, brake linings, refractoriness, steel making, expanded graphite, lubricants, and foundry facings.

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Table 2 - AA2195 alloy chemical composition and as matrix material (weight %)

Elements	Copper	Lithium	Magnesium	Silver	Zirconium	Aluminium
%	4	1	0.4	0.35	0.1	Balance
B_4C	wt.% range 2,4,6 & 8					
Graphite	wt.% range 2,4,6 & 8					

Table 3 - Properties of AA2195, B_4C and Graphite

Name of the material	Density (gms/cm ^{3})	Melting point(°C)	Thermal conductivity (Watts/mt.kelv)	Thermal expansion coefficient (µm/m°C)	Youngs modulus (GPa)
AA2195	2.7	660	130	23	69
B_4C	2.51	2450	40	5	450
Graphite	2.26	3600	61	2.9	15.85

Fig. 2 - Rolling machine

3. Results and Discussions

3.1 Microstructure Analysis

The samples microstructure was examined, and reinforcement particles appeared along the grain boundaries and also observed that particles are uniformly distributed in the matrix phase. After the hot rolling process, the particles were arranged in the direction of rolling compared to the cast composites. The composites displayed refined grains because of the presence of boron carbide and Gr nanoparticles, which gives grain refining. The presence of boron in boron carbide, a famous grain refiner in composites grain refining. The AA2195-B_4C-Gr composites images are shown after hot rolling, as shown in Fig. 3 b. After the rolling process, the microstructure changes were observed. The grain structure was changed in the rolling direction, and the grains were elongated in the rolling direction. After hot rolling, the new generation of new grains appeared at the grain boundaries, and it showed very less porosity in the composites and casted composites also. However, the composites revealed an excellent adhesion between the AA2195 matrix and Gr and B_4C particles, and uniform distribution and refinement of the grains revealed improving composites strength. The AA2195- B_4C Gr MMCs microstructures are shown before the rolling process and after the rolling process in Fig. 3.

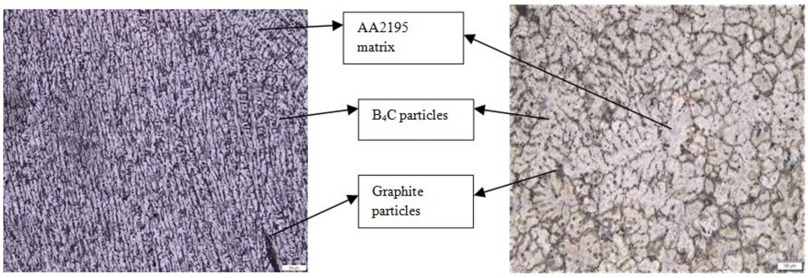
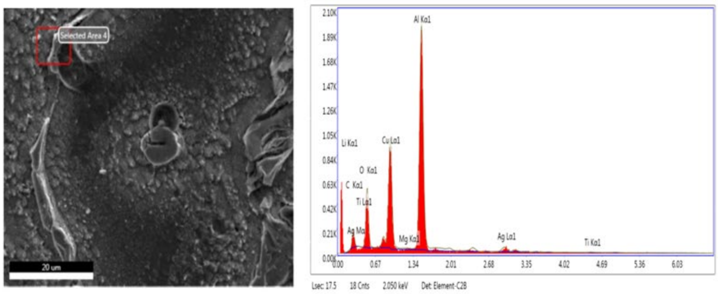


Fig. 3 - (a) Optical image of hot rolled sample after rolling AA2195-B_4C-Gr composites; (b) optical image of casted sample before rolling AA2195-B_4C-Gr composites

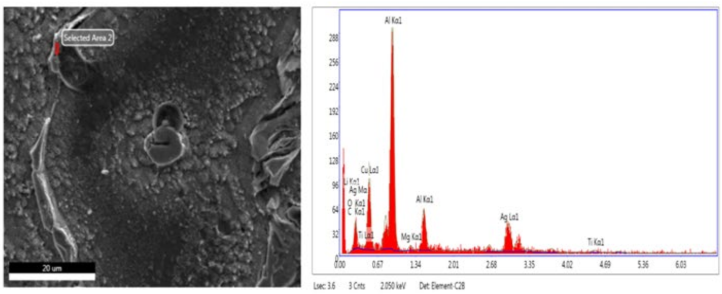
3.2 Scanning Electron Microscope (SEM):

To know the fractured nature, the specimens were investigated using SEM (TESCAN VEGA 3 LMU) at several magnifications. The micrographs of AA2195 composites revealed that the reinforced particulates are distributed uniformly throughout the matrix. A uniformly distributed reinforcement increases the strength and reduces the porosity of the metal matrix composites. There was a strong bond between the AA2195 matrix and reinforcement particles. The EDAX images of cast and rolling composites are given in Fig 4 and 5. These images were revealed that grains distribution different from the base material. The different phase compounds were formed in the material Al-Li, Al-Li-Cu and Al-Li-Cu-Ag. The images of SEM of Composites that had elements nearer to the base material were examined in the EDAX also. The other phase particles were formed in the material, revealing diverse regions. The elongated and coarse grains of MMCs were there in that phase. Mg and Ag's elements were shown less in EDAX analysis in contrast to the base materials. In the EDAX analysis, B_4C and Graphite particles were present in the material also. X-Ray diffraction: The XRD pattern of cast and hot rolled AA2195-B_4C-Gr MMC is observed in Fig, 6 and 7. The pattern of XRD of hot rolled AA2195-B_4C-Gr composite informs about similar peaks corresponding to cast AA2195-B_4C-Gr composite. The existence of Al_3Li phases with variety intensities were proved at 44.67°, 65.06° and 78.18°. The highest Al_3Li phase largest intensity is examined at 44.67°. In addition, the pattern of XRD of AA2195-B_4C-Gr composite reveals different phases of C, B_4C, Al_2Cu, Al, Al_2CuLi and B_4C nano particles.



Element	Weight %	Atomic %
Li K	1.06	1.75
B K	2.13	2.12
C K	2.47	2.54
O K	3.64	3.90
Al K	87.01	86.04
Si K	0.08	0.07
Ag L	0.26	0.21
Cu K	3.05	3.12
Mg K	0.25	0.21
Ti K	0.05	0.04
Total	100%	100%

Fig. 4 - SEM EDAX Spectrum of the casted AA2195-B_4C- Gr composites



Element	Weight %	Atomic %
Li K	1.04	1.50
B K	2.26	2.18
C K	2.38	2.46
O L	3.59	3.68
Al K	86.69	85.87
Si K	0.06	0.08
Ag L	0.32	0.34
Cu K	3.32	3.56
Mg K	0.30	0.27
Ti K	0.04	0.06
Total	100%	100%

Fig. 5 - SEM EDAX Spectrum of the Hot rolling of AA2195-B_4C- Gr composites

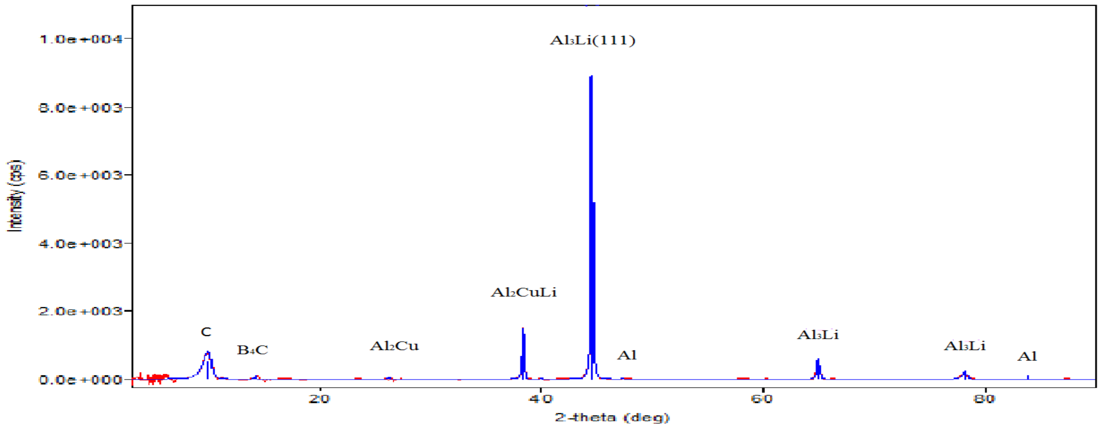


Fig. 6 - XRD pattern of the Casted AA2195-B$_4$C- Gr composites

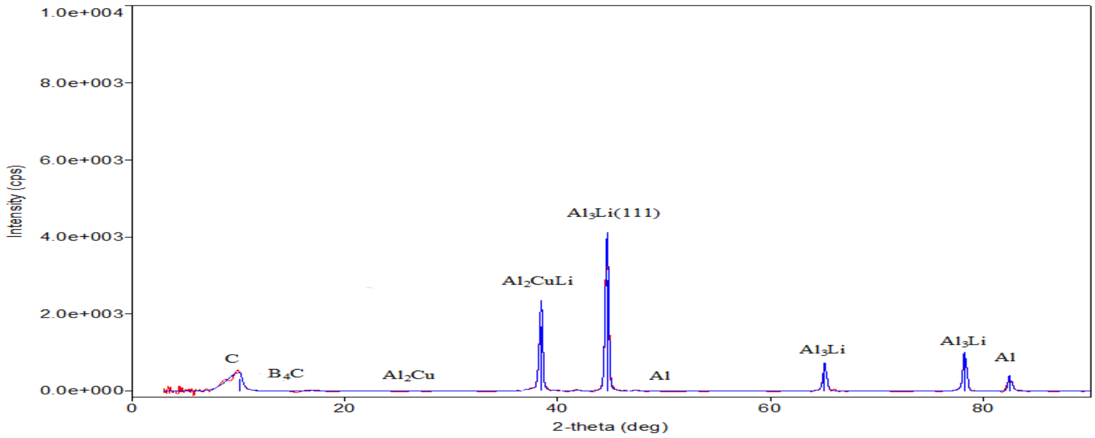


Fig. 7 - XRD pattern of the Hot rolling of AA2195-B$_4$C- Gr composites

3.3 Micro Hardness

The samples are made as per ASTM E384-17 (10 mm×30 mm). The Micro Vickers hardness testing (METCO-ECONOMET VH-1MDX) was done on the specimens by applying a 500-gf load for 10 seconds. The experimental results revealed that the microhardness values are enhanced with the raising in the wt % of reinforcements (B$_4$C and Gr) compared to the base metal. The addition of both reinforcements leads to form less clustering of the ceramic particles, which further improves the hardness of the composites due to their refined microstructure. The influence of Gr and B$_4$C nanoparticles on AA2195 matrix microhardness and AA2195- B$_4$C -Gr composites prior and later rolling and ageing conditions as displayed in Fig. 8; both hot rolled and casted samples were examined for microhardness, the sample microhardness values were reviewed and made average and locating the test indenter at a variety of locations to avoid the indenter locating on high harder B$_4$C reinforcement particles. The graph reveals that microhardness improves with the increasing insertion of B$_4$C and Gr nanoparticles to the AA2195 alloy before and later hot rolling and ageing situations. It was observed that the hardness of AA2195- B$_4$C -Gr Composites increased by up to 49 % after hot rolling and ageing conditions. The hardness improved due to the following factors. Usually, the insertion of harder reinforcement particles into AA2195 enhances matrix hardness. The samples are mounted in mould to measure the hardness at the different locations as shown in Fig.8. While performing the Vickers micro hardness test diamond pyramid indenter is used and as shown in Fig. 9. The microstructure of the samples is shown in Fig.10. The Vickers microhardness machine is used to perform the hardness for composites precisely as shown in Fig.11. The insertion of hard B$_4$C and Gr reinforcement particles into the matrix might diminish the density during the solidification of casted MMCs; this, in turn, enhances the resistance to plastic deformation resulting in improved hardness. The hot rolled and ageing MMCs specimens reveal the best hardness values in comparison to the casted samples due to the following factors. The hot rolling method decreases the voids composition and improves the grain structure and highly homogenous distribution of Gr and B$_4$C nanoparticles in the hot rolling MMCs. Micro hardness values are higher than the casted composites after the heat treatment process performed for all samples are shown in Fig.12. This hardness values shows higher compared to casted composite and for sample 15 shows highest hardness value.

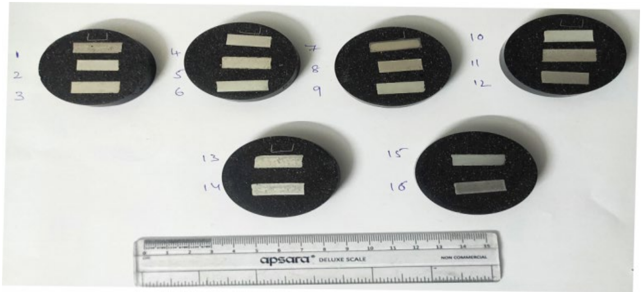


Fig. 8 - Micro hardness of AA2195-B_4C-Gr composites of 16 samples images

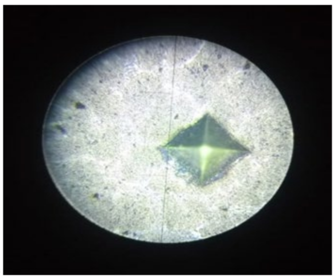


Fig. 9 - Vickers Micro hardness Diamond pyramid Indenter

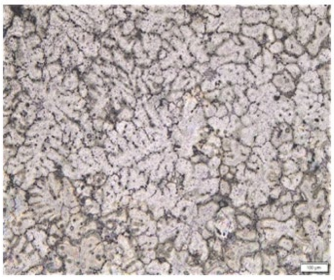


Fig. 10 - Hardness microstructure

Fig. 11 - Vickers Micro hardness machine

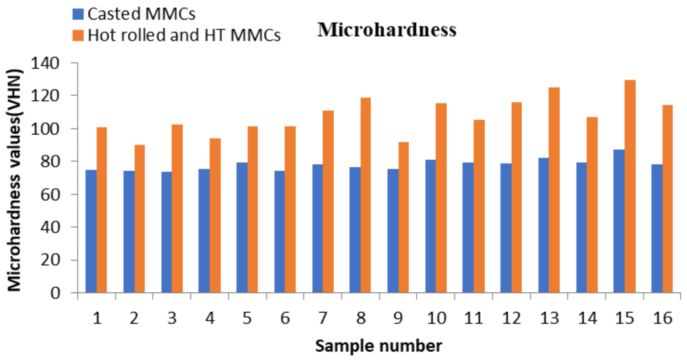


Fig. 12 - Micro hardness variation prior and later hot rolling process

3.4 Ultimate Tensile Strength

The graph displays the improvement in composite strength with an improvement in Gr, B_4C nanoparticle composition up to 8wt%, but more than 8wt% reveals a diminishes in strength before the hot rolling method; this might be because of nanoparticles agglomeration and micro porosities contents due to the application of the hot rolling process and ageing, significant enhancement in the tensile strength of MMCs. The hot rolled and ageing MMC reveal an excellent tensile strength which can be mainly attributed to the microstructure influence changes in the matrix phase, such as porosity reduction, reinforcements particles distributed uniformly and grain refinement in the matrix phase. The various levels that contribute to the enhancement of the tensile strength of MMCs, like excellent adhesion between the matrix phase and reinforcement, boron carbide and Gr particles, were distributed uniformly in the matrix phase and refinement of grain structure. Due to the refining of the grain structure, which gives good strength to the MMCs, smaller grain size enhances the strength of the composites. The mechanical properties were evaluated using Instron UTM at natural environment conditions, % elongation, 0.2% offset yield strength, and ultimate tensile strength. The samples were prepared as per the ASTM-B557 standards, as shown in Fig. 13. The tensile testing machine is used to perform different tests for different samples of composites to evaluate different mechanical properties that are shown in the Fig. 14-16. The variation of the ultimate tensile strength for sample numbers of composites is performed on universal testing machine and the higher the ultimate strengths are observed for heat treated samples compared to casted composites. The sample number 15 observed as the highest ultimate strength that is shown in Fig. 17.

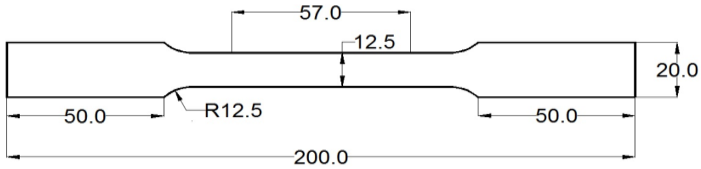


Fig. 13 - ASTM tensile test specimen dimensions

Fig. 14 - Tensile testing machine

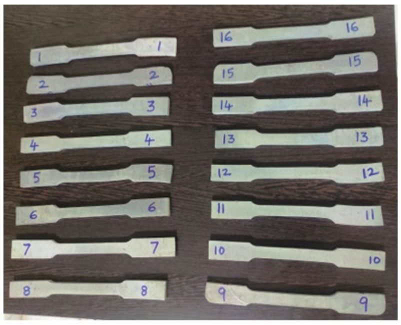


Fig. 15 - Before tensile test 16 samples

Fig. 16 - After tensile test 16 samples

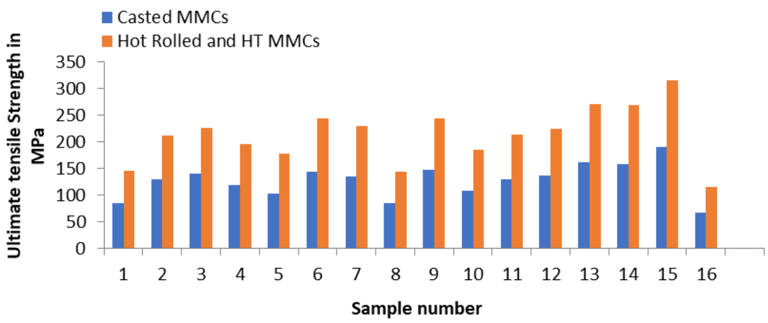


Fig. 17 - Ultimate tensile strength variation with sample number

3.5 Ductility Analysis

As shown in the Fig.18, the changes in ductility of the casted AA2195-B_4C-Gr composites before and later hot-rolling process, the elongation for sample 15 was less compared to other samples, it was examined that the insertion of Gr and B_4C nano-particles into the AA2195 matrix phase leads to diminishes the ductility of the composite. The decrease in composites ductility is due to the existence of hard ceramic boron carbide particles in the soft, ductile matrix phase; the hard ceramic reinforcement particles generate phases as well as some secondary intermetallic phases that resist deformation of matrix on force application and lead to the nucleation of cracks at interfacial zones as well as the existence of possible micro voids attributing to the failure of the matrix material. Because of the existence of boron, grain structure refinement reveals the MMCs ductility. In the matrix phase, the rolling process strengthens the composite by enhancing the hardness which consequently decreases the ductility. After tensile fracture specimen 15 is shown in Fig.19 and 20 for casted sample and hot rolled and hot sample.

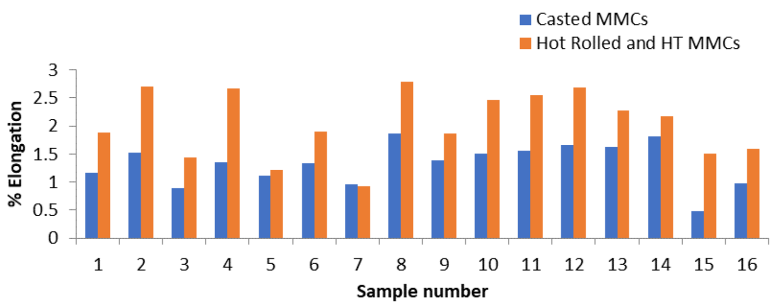


Fig. 18 - Variation of ductility before rolling and after hot rolling & HT MMCs

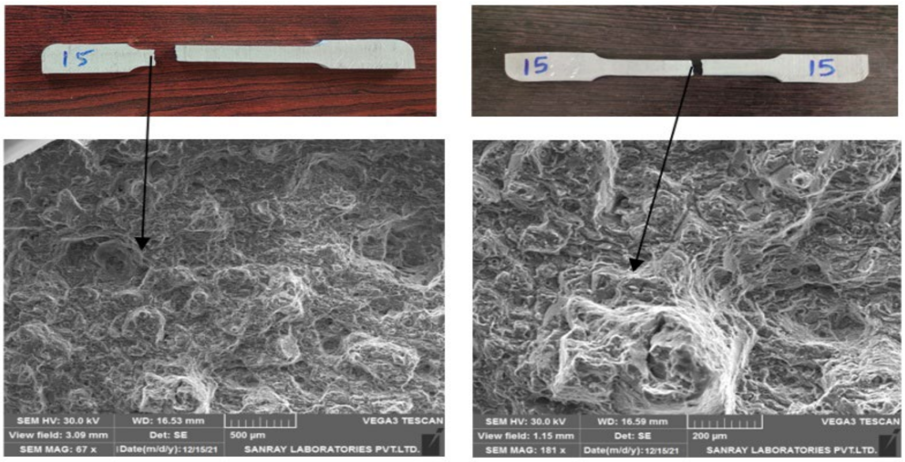


Fig. 19 - Casted AA2195-B_4C-Gr MMCs and Hot Rolled HT AA2195-B_4C-Gr MMCs and tensile fractured surfaces SEM images Casted & Hot Rolled aging AA2195-B_4C-Graphite MMCs

In SEM analysis, AA2195- B_4C -Gr composites were observed with less ductile fracture; this ductile fracture sample reveals a small number of dimples shaped structures and small voids can be observed in the matrix AA2195 phase. In some cases, composite failure occurs due to the small voids observed in the AA2195- B_4C -Gr composites and the presence of small dimples indicating the formation of ductile fracture reveals cleavage fracture due to hard ceramic brittleness surrounding soft matrix phase. It is also observed that the cracks in the matrix phase are large with fracture hard B_4C particles. In SEM analysis, the tensile fracture surfaces of rolled AA2195-B_4C-Gr composites as shown in Fig. 19, it was observed that dimples sizes are finer in the matrix phase and its developed composite when compared with casted composites owing to better plastic deformation. Fractography shows an excellent bonding between matrix phase and reinforcements.

3.6 Density Analysis

A water displacement technique is employed for estimating the composite density. The Archimedes method explains that a buoyant force pushing up on an object submerged in a fluid is equal to the fluid weight volume that is displaced by that object. The effect of reinforcements into AA2195 gives a reduction in the density of hot rolled and heat-treated composite compared to the casted composite due to the reduced porosity and which offers better strength and hardness to the composite. Fig. 21 shows density values for sample 15 was less compared to other samples.

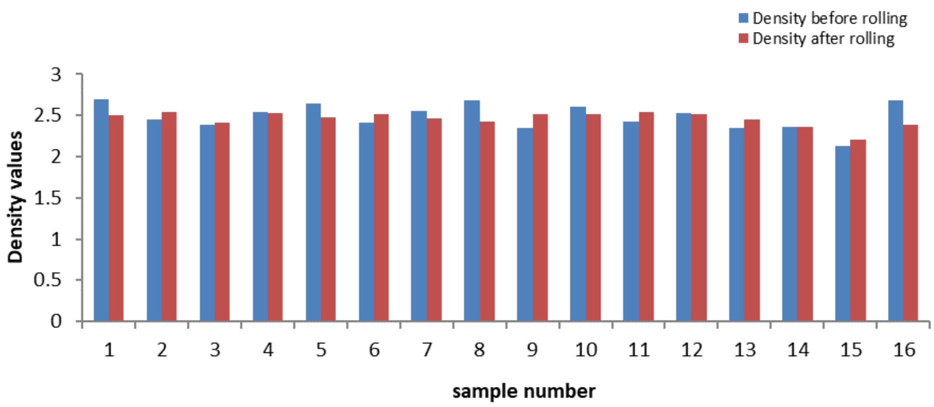


Fig. 21 - Density values before and after rolling of AA2195-B_4C-Gr MMCs with sample number

4. Conclusions

AA2195-B_4C-Gr composites is successfully fabricated using Medium Frequency Induction Melting (MFIM) casting and processed with hot-rolling at 480 °C temperature, and then ageing is done. With the insertion of graphite and B_4C nanoparticles into the matrix phase, the microhardness of AA2195- B_4C -Gr composites are enhanced. The microstructure reveals that uniform distribution of graphite and B_4C nanoparticles, and the fine grain structure is observed in the matrix phase. Then hot rolling process and ageing reveals a rise in the composites' mechanical properties. The tensile test results show that the tensile strength of as casted composites are enhanced with an increase in graphite compositions up to 6 wt % and B_4C particle compositions up to 8 wt % but beyond 6 wt% & 8 % reveals to diminishes composites strength because high porosity and high particles agglomeration and composition are observed whereas in the hot rolled and ageing conditions the ultimate strength values enhanced rapidly with the rise of Gr and B_4C composition due to more homogeneous distribution and less porosity is observed. In the hot rolled composites, ductility is enhanced compared to as-cast composites because of microstructure refinement, and particles are distributed homogeneously and reduced porosity composition. The hot-rolled and heat-treated composites show more hardness & greater strength compared to casted composites. The hot rolled AA2195- B_4C -Gr composite mechanical properties revealed better hardness, tensile strength, reduction in density, and % elongation than casted composites.

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