

# TRIBOLOGICAL STUDY ON HEAT-TREATED ALUMINIUM MATRIX COMPOSITES

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## ABSTRACT

Al 7075 composites are widely used in various industrial applications. The Al 7075 alloy was reinforced with Si<sub>3</sub>N<sub>4</sub> and Al<sub>2</sub>O<sub>3</sub> at different proportions. Composites were fabricated using the stir-casting method. The reinforcements were preheated at a temperature of around 250°C before adding it to the matrix. The casted composite is machined and turned to obtain the final specimen with the desired size. Casted specimens were age hardened at various temperatures ranging from 150°C – 200°C and quenched using water at room temperature to improve their mechanical properties such as hardness and wear characteristics. The aging period varied between 2 to 8 hours. Further, the micro-hardness of As-cast and heat-treated specimens were studied and the wear analysis was done on the specimen with higher hardness.

**Keywords:** Aluminium 7075(Al7075), Silicon nitride (Si<sub>3</sub>N<sub>4</sub>), Alumina (Al<sub>2</sub>O<sub>3</sub>), Stir-casting, hardness, Heat treatment, Quenching, Wear analysis.

## I. INTRODUCTION

A Composite is a combination of two or more constituent materials each having distinct physical and chemical properties, which is composed of two phases namely matrix (continuous phase) and reinforcement (dispersed phase). These composites possess greater properties than their constituents. The aerospace industry demands materials with enhanced properties such as high strength, temperature-withstanding capability, fatigue resistance, wear resistance, etc. That's where composite material comes into play with greater mechanical properties than conventional materials. Aluminium matrix composites reinforced with ceramics which are oxides, carbides, carbonates, nitrides, etc. This proved to display superior mechanical and physical properties that are applicable to the aerospace and automobile industry where wear has a significant effect on the lifespan and failure of the material.

## II. LITERATURE REVIEW

R. Pramod et al. studied the wear characteristics of Al7075 reinforced with Al<sub>2</sub>O<sub>3</sub> with the help of an Artificial Neural Network. Alumina particles of size 150 μm were added in the range of 2% – 6%wt. It was concluded that Aluminium composite with 6% wt. Al<sub>2</sub>O<sub>3</sub> showed excellent wear resistance when compared to the other composite specimens [1]. Avinash Lakshmikanthan et al. conducted research on the mechanical and tribological properties of heat-treated A357 composite reinforced with dual-sized SiC. The size of SiC ranged from 140±10 μm to 30±5μm. Heat treatment of composite is done through aging at varying temperatures such as 160°C, 180°C, and 200°C for 6 hours. It was inferred that all the composite specimens showed superior mechanical properties in contrast to A357 [2]. A. Pramanik et al. studied the influence of reinforcement on metal matrix composite. Al6061 matrix was reinforced with 10%wt. Al<sub>2</sub>O<sub>3</sub>. The size of Al<sub>2</sub>O<sub>3</sub> ranged from 6 to 18μm. From the study, it was proved that wear resistance was improved in all varying aspects such as sliding speed, load, and sliding distance. It was also inferred that wear resistance is drastically increased by means of resisting plastic deformation [3]. E. Rajkeerthi et al. conducted research on heat-treated aluminum matrix composite reinforced with 10%wt. Al<sub>2</sub>O<sub>3</sub> to study its effect on hardness, tensile and compression properties. The aluminum 6000 series is used for the study. Heat treatment was done through quenching and precipitation hardening processes. It was concluded that the precipitation-hardened specimens displayed greater hardness when compared to quenched specimens [4]. P.S. Raghavendra Rao et al. performed a study on the mechanical characteristics of aluminum (LM6) matrix reinforced with silicon nitride. The percentage of silicon nitride ranged from 2 to 10 wt. %. It was found that agglomeration is reduced by a uniform distribution of matrix and reinforcements. It was also inferred that hardness, yield strength, and ultimate tensile were greatly improved when compared to the matrix alloy but with reduced ductility [5].

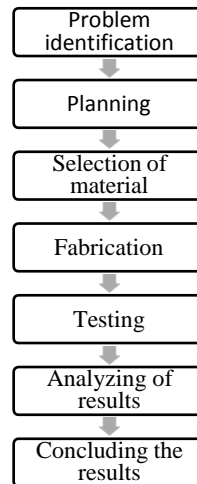
A study on the influence of quenching heat treatment on hardness properties was carried out by HammarIlham Akbar et al. They used AL6061 composite reinforced with Al<sub>2</sub>O<sub>3</sub>. The proportion of Al<sub>2</sub>O<sub>3</sub> was 10 wt.%. Quenching was done with cooling agents such as oil, water, and salt solution (Brine). It was found that the cooling rate has a great effect on hardness characteristics. It was also found that brine quenching with a higher cooling rate produces higher hardness and distortion [6]. S. Arun Kumar et al. fabricated an Al7075 composite reinforced with Si<sub>3</sub>N<sub>4</sub> through stir casting to study the effect of porosity. The reinforcements were added in the proportion of 4%, 8%, and 12%. The specimens were heat treated using a muffle furnace at various temperatures such as 150oC, 250oC, 350oC, 450oC, and 550oC for 5 hours. It was inferred that porosity resulted in a reduction of mechanical properties to a greater extent which can be reduced through heat treatment [7]. Jitendra M. Mistry et al. conducted a tribological study on heat-treated aluminum composite reinforced with Si<sub>3</sub>N<sub>4</sub>. Al7075 is used for the matrix phase of the composite. The proportion of reinforcements was 4%, 8%, and 12%. Fabrication was done through electromagnetic stir casting. It was inferred that wear rate was inversely proportional to sliding velocity and directly proportional to sliding distance and load. Reduction in wear loss was found with the increase in Si<sub>3</sub>N<sub>4</sub> wt.% [8]. Fazludheen Chemmala et al. conducted computer analysis on Al7075 reinforced with Si<sub>3</sub>N<sub>4</sub> to study its mechanical characteristics such as Hardness, Tensile, etc. The proportion of reinforcement added varied from 2%, 4%, and 6%. A study was also conducted on the fabrication of aluminum composites through stir casting. From the study, a considerable increase in mechanical properties was noticed due to the addition of Si<sub>3</sub>N<sub>4</sub> reinforcement [9]. Ravikumar Nagula et al. utilized the Taguchi method in the process of analyzing the wear characteristics of hybrid aluminum composites. Si<sub>3</sub>N<sub>4</sub>, Sea snail shells, and Rice husk ash were used as reinforcements. The proportion of Si<sub>3</sub>N<sub>4</sub> and sea snail shells was varied as 2, 4, and 6% wt., while Rice husk ash percentage was kept constant at 5%wt. It was concluded that sliding speed, load, and percentage of reinforcements had a considerable effect on the coefficient of friction [10].

Fly ash is regarded as a good reinforcement for aluminium since it boosts the mechanical characteristics of the metal while also being very inexpensive. Conclusion: As the weight percentage of fly ash in aluminium composite increases, tensile strength, compressive strength, and hardness all improve. In order to turn industrial waste into industrial wealth, fly ash aluminium composites should be used in industry [11]. Due to its inexpensive initial cost, great foundry castability, and strong mechanical and machining qualities, ZA-27 alloy is now preferred. The ZA27 alloy/graphite particulate composite in this instance has a particle size range of 90-150 um and a composition of 0-5%. It is determined that as the amount of graphite particles in the alloy rises, there is a drop in hardness and an increase in ductility, UTS, and compressive strength after heat treatment at 280°C for 1 to 4 hours [12]. Here, AA606 matrix material and 1-5% MoS<sub>2</sub> reinforcement material are used to create a metal matrix composite. It is then heated for 1 hour at 520°C, quenched in water, artificially aged for 12 hours at 180°C, and then cooled with air. 4% MoS<sub>2</sub> reinforced composites had much higher yield and tensile strengths than other materials, but their percentage of elongation property was lower. Additionally, it is noted that after heat treatment, the reinforcement particles are evenly dispersed [13]. Here, a 4-weight percent SiC alloy reinforced with particles with an average size of 650 nm has been studied. The solution is treated at 540C for 6 hours as part of the age hardening process, which is then followed by water quenching and aging at varying temperatures of 175 C, 200 C, and 225 C for soaking durations of 3, 6 h, and 9 h. SiC is added to the alloy to boost its hardness, but it does not affect the material's wear mechanism. The rate of wear is reduced as the hardness increases [14]. 2-10 wt% of TiC was found in the AMMCs under study. The 2 m/s sliding speed, 2 km sliding distance, and 20 N normal load were used in the wear experiments. The wear rate was noticeably lower for the composite material compared to the matrix material, and the wear resistance of the composites increased with increasing weight percentage of TiC particles. The mechanical characteristics of the TiC-reinforced composite specimens, such as hardness, tensile strength, and percentage elongation qualities, are superior to those of the AA7075 matrix material in both cases [15].

Investigated in this article is the friction and wear behaviour of heat-treated Al 6061 alloy and Al 6061 SiC-graphite. The cast 6061 alloy and its composites underwent a solutionizing process for one hour at a temperature of 803 K, followed by a water quench. After being quenched, the samples were aged artificially at a temperature of 448 K for varying lengths of time between 4 and 8 hours. The hardness result demonstrates that the composites' hardness rose as the weight fraction of graphite particles decreased. Increased reinforcing has a positive impact on the metal matrix composites' wear behaviour by reducing friction and increasing wear resistance [16]. Here, Al, Ni, and Al<sub>2</sub>O<sub>3</sub> powders were combined in different ratios to create dense coatings by low-temperature cold spraying. Aluminides were created using two different post-deposition processes: resistance spot welding and furnace heating. The hardness of the coatings increased to 205.4 HV0.3. All three coatings had equivalent microhardness, with the highest value coming in at 358.4 HV0.3 [17]. In this study, the high-temperature age-hardening behaviour of an aluminum-lithium alloy reinforced with silicon carbide particulates is reported and contrasted with that of a matrix material that has undergone a comparable thermomechanical treatment. According to the DSC and aging results shown here, the addition of SiCp does not seem to alter the matrix's general precipitation process, although strength is preserved for longer periods of time and at higher levels [18]. Here, a basic matrix of A356 alloy is employed, to which Al<sub>2</sub>O<sub>3</sub> and RHA particulates (1Wt%, 2Wt%, 3Wt%, 4Wt% & 5Wt%) are added in equal amounts as reinforcements and corrosion resistance of the generated hybrid composites. The density of

hybrid composites made from A356 alloy reduces when RHA and Al<sub>2</sub>O<sub>3</sub> particles in the alloy matrix rise. The heat treatment has a significant impact on the hybrid composites' corrosion resistance [19]. Stir cast Al 6082-SiC-Gr (Al-SiC-Gr) hybrid composites' two-body abrasive wear behaviour was investigated and compared to that of its matrix alloy and SiC reinforced composites. Wear improvement of Al-SiC-Gr composites at greater load and sliding distance was 16.4% and 27% in as cast and T6 heat treated condition, respectively. Due to the creation of a graphitic coating, which functions as a self-lubricant in Al-SiC-Gr composites, the addition of graphite has been found to be advantageous. improved wear resistance with anti-aging therapy. This might be the result of intermetallic precipitates forming throughout the aging process [20].

### III. METHODOLOGY



### IV. EXPERIMENTATION

#### IV. i. Stir casting

A mechanical stirrer is used in the stir-casting process to create a vortex that mixes the reinforcement with the matrix material. Due to its low cost, suitability for mass production, simplicity, nearly net shaping, and ease of composite structure control, it is an appropriate procedure for producing metal matrix composites.

The stir-casting equipment includes a furnace, a feeder for reinforcement, and a mechanical stirrer. The ingredients are heated and melted in the furnace. At the bottom of the furnace an opening port is placed for instant pouring, it is needed to prevent the solid particles from settling in the bottom of the crucible after stirring, in order to create the vortex that facilitates the mixing of the reinforcement materials added to the melted matrix, a mechanical stirrer is used. The impeller blade and the stirring rod make up a stirrer. The geometry and number of blades in the impeller might vary. With an axial flow pattern in the crucible with less power consumption. The reinforcing powder is fed into the melt using a feeder that is also linked to the furnace. The blended slurry is then poured into a permanent mould.

#### IV. ii. Schematic of stir casting

The graphic illustrates the various phases involved in the stir-casting process. The matrix material is added and retained in the bottom pouring furnace, during this time the matrix starts to melt. In order to remove moisture, contaminants, etc., simultaneously the reinforcements are warmed at a specific temperature in a different furnace. After the matrix material is melted at a certain temperature, mechanical stirring is started and creates a vortex, after which the feeder is included in the setup to feed reinforcements at a constant rate into the center of the vortex. The stirring process is then continued for some time. The liquid mixture is then put into a mould and let to cool down and solidify naturally. Additionally, post-casting procedures like heat treatment, machining, testing, and inspection have been carried out.

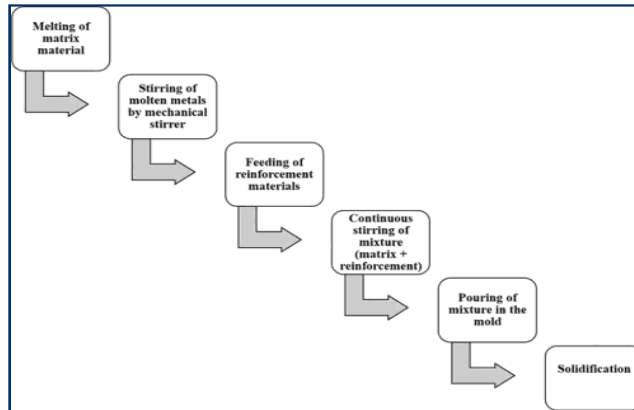


Fig. 1: Schematic of the casting process



Fig.2



Fig.3

Fig.2, Fig3: Casting process

**IV. iii. Preparation of specimen**

The moulded material is cut into pieces according to the required number of specimens which are required for all the testing procedures. The appropriate material should be compatible with the lathe and the desired specifications. Once the material is placed in the lathe, it is secured using a chuck or a collet. A Centre lathe is used for the process. The next step is to set the cutting tool at the correct angle and position, which is determined by the desired shape and size of the specimen. The cutting tool is then brought into contact with the material, and the lathe is turned on. The cutting tool is used to remove the excess material from the specimen, gradually shaping it into the desired form. Careful attention must be paid to the speed and feed of the lathe, as well as the depth of cut, to ensure that the specimen is shaped accurately and smoothly. Finally, the specimen is removed from the lathe and inspected for any defects or imperfections. If the specimen is perfect then the specimen is ready to be tested. The samples were 10 mm in diameter and 30 mm in length.



Fig. 4: Cut specimen



Fig. 5: Turning



Fig.6: Finishing



#### IV. iv. Hardness Testing (Vickers Hardness)

Vickers hardness test is a method used to measure the hardness of a material. It involves indenting the surface of the material with a diamond indenter in the shape of a square-based pyramid with a 136-degree angle between opposite faces. The hardness is determined by measuring the diagonal length of the indentation left on the material's surface. To perform a Vickers hardness test, the sample is prepared by polishing it to a mirror-like finish. The material is then placed on the stage of the Vickers hardness apparatus, and the load is applied to the indenter. The load is typically between 1 and 120 kilograms-force (KGF), depending on the material being tested.

The indenter is held in place for a specified period, usually between 10 and 15 seconds, to allow the material to deform. After the load is removed, the indentation is measured under a microscope to determine the length of the diagonals. The Vickers hardness number (HV) is calculated using the formula  $HV = 1.8544P/d^2$ , where P is the applied load in kgf and d is the mean diagonal length of the indentation in millimeters. The Vickers hardness test is a versatile and widely used method for measuring the hardness of metals, ceramics, and other materials. It is particularly useful for measuring the hardness of thin coatings and small parts, as well as for comparing the hardness of different materials.

Table. 1: Hardness of Al7075 alloy and composite specimens.

SPECIMEN	SPECIMEN COMPOSITION	HARDNESSVALUE
1	Al7075	73
2	Al7075+5%silicon nitride	81
3	Al7075+5%alumina	79
4	Al7075+2.5%silicon nitride+ 2.5%alumina	84



Fig.7: Vickers apparatus

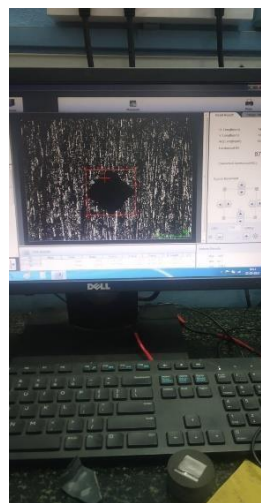


Fig.8: Dimond indentation

#### IV. v. Heat Treatment

Here, the muffle furnace was utilized for the heat treatment procedure. The fabricated composites were subjected to heat treatment at different levels of temperatures and time intervals. The specimens are wrapped in aluminium foil and placed inside a ceramic bowl to prevent the formation of an oxide layer on the specimen surface before being put in the furnace. Later the specimens were placed inside the furnace for heat treatment. The aging treatment was conducted at three distinct temperatures (150°, 175° and 200°), and varying lengths of time (between 2 and 8 hours). After which the specimens were taken out and quenched in the quenching medium. Water kept at room temperature was used as the quenching medium. After being aged, the specimens were polished, and Vickers' hardness test was conducted and the test results were obtained to determine the impact of heat treatment on composites.



Fig. 9: Muffle furnace



Fig. 10: Specimen inside the furnace

#### IV. vi. Hardness Testing After Heat Treatment

Heat treatment processes can significantly alter the properties of a material, including its hardness. Therefore, it is important to perform hardness testing after the heat treatment process to ensure that the material meets the required specifications. Overall, hardness testing is an important step in ensuring that heat-treated materials meet the required specifications for their intended applications.

Table 2: Hardness of heat-treated Al7075 alloy and composite specimens at 150°C

S.No.	Composition	Aged at2hrs	Aged at4hrs	Aged at6hrs	Aged at8hrs
		(VHN)	(VHN)	(VHN)	(VHN)
1	Al7075	78	84.67	91.33	97.3
2	Al7075 + 5%Si3N4	88	93.67	96	103
3	Al7075 + 5%Al2O3	87.33	92	99.7	97.33
4	Al7075 + 2.5%Si3N4 + 2.5%Al2O3	93	95.33	99.67	101

Table 2 shows the hardness values of the specimens subjected to aging treatment at 150 °C. From the results, it is evident that the composite specimens respond faster to aging treatment than alloys. This effect is due to the presence of secondary reinforcement particles such as silicon nitride and alumina particles in the matrix that acts as nucleation sites for the formation of precipitates during aging. Therefore, a higher percentage of precipitate particles can be formed in the composite specimens than in the Al7075 alloy. Al7075 + 5% Si3N4 & Al7075 + 2.5%Si3N4 + 2.5%Al2O3 samples showed higher hardness among the analyzed specimens of about 103 & 101 HV after aging treatment. The formed precipitates also act as barriers to dislocation motion and thus contribute to the hardening of the alloy.

Table 3: Hardness of heat-treated Al7075 alloy and composite specimens at 175°C

S.No.	Composition	Aged at2hrs	Aged at4hrs	Aged at6hrs	Aged at8hrs
		(VHN)	(VHN)	(VHN)	(VHN)
1	Al7075	91	93.67	96.3	98
2	Al7075 + 5%Si3N4	105.3	107	111.67	114.3
3	Al7075 + 5%Al2O3	97.6	102	108.7	112.3
4	Al7075 + 2.5%Si3N4 + 2.5%Al2O3	115.67	116.3	118	119.67

The hardness values after aging the samples at 175 °C are shown in Table 3. The reading shows that when Al7075 composites are aged at 175 °C, the rate of precipitation in the matrix is faster as compared to aging at 150 °C. Al7075 + 5%Si3N4 samples show a hardness value of about 88 HV when aged at 150 °C for 2 hours, whereas it shows a hardness of

about 105.3 HV when aging is done at 175 °C. Similar observations are noticed in analyzed samples in all the composite samples. The effect of temperature during aging is not significant in Al7075 alloy in comparison to Al7075 composites. The maximum hardness achieved for Al7075 alloys after aging at 175 °C is 98 HV. Al7075 + 2.5%Si<sub>3</sub>N<sub>4</sub> + 2.5%Al<sub>2</sub>O<sub>3</sub> showed a maximum hardness of about 119.6 HV after aging at 175 °C for 8 hours. The presence of hybrid reinforcements like alumina & silicon nitride aid in the formation of precipitates during aging.

Table 4: Hardness of heat-treated Al7075 alloy and composite specimens at 200°C

S.No.	Composition	Aged at2hrs (VHN)	Aged at4hrs (VHN)	Aged at6hrs (VHN)	Aged at8hrs (VHN)
1	Al7075	94	97.33	108	10.67
2	Al7075 + 5%Si <sub>3</sub> N <sub>4</sub>	109.7	112	116.67	113.33
3	Al7075 + 5%Al <sub>2</sub> O <sub>3</sub>	102	107.7	118.33	112.66
4	Al7075 + 2.5%Si <sub>3</sub> N <sub>4</sub> + 2.5%Al <sub>2</sub> O <sub>3</sub>	118.67	119	123.7	120.33

From Table 4, the peak hardness achieved for both Al7075 alloy and its composites is after aging for 6 hours at 200 °C. The hardness values start to decrease when aging is done beyond 6 hours, leading to over aging phenomenon. The aging was not noticed in the 150°C and 175°C due to the lower temperature Therefore the aging time duration has to be restricted to 6 hours when aging is done at 200°C to achieve maximum hardness values. From the results observed, it can be concluded that Al7075 + 2.5%Si<sub>3</sub>N<sub>4</sub> + 2.5%Al<sub>2</sub>O<sub>3</sub> composite shows a maximum hardness of 123.7 HV when aging heat treatment is done at 200 °C for 6 hours, This aging temperature of 200 °C for 6 hours is the optimum aging cycle for both Al 7075 alloy and silicon nitride, alumina reinforced composites and hybrid composites resulted in superior hardness value when compared to the other composites.

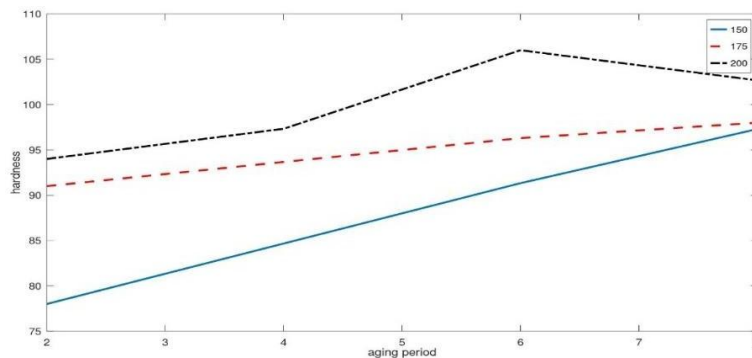


Fig. 11: Comparison of hardness values for Al7075 alloy at different aging duration

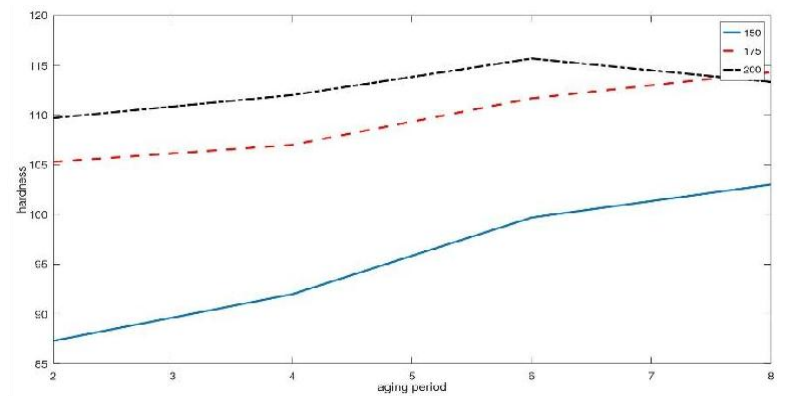


Fig. 12: Comparison of hardness values for Al7075 + 5%Si<sub>3</sub>N<sub>4</sub> alloy at different aging duration

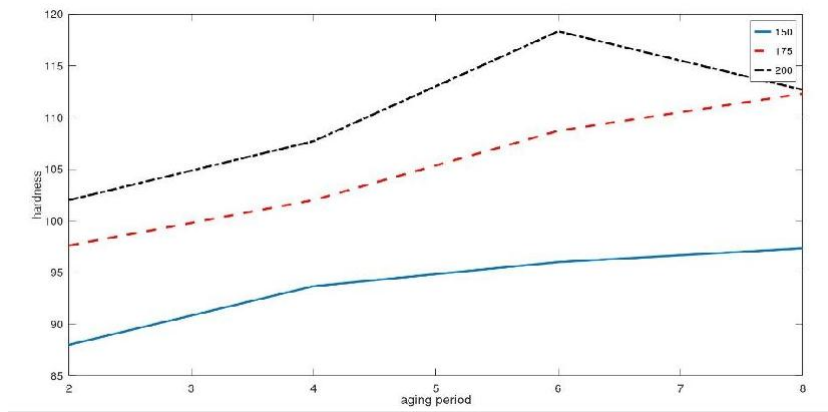


Fig. 13: Comparison of hardness values for Al7075 + 5%Al<sub>2</sub>O<sub>3</sub> alloy at different aging duration

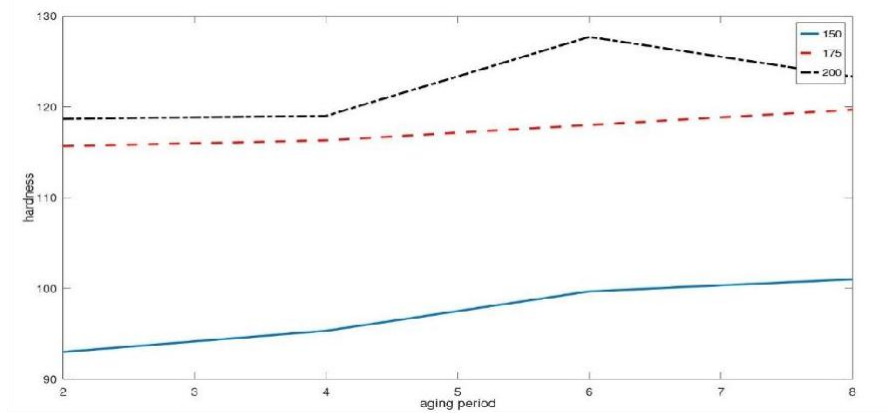


Fig. 14: Comparison of hardness values for Al7075 + 2.5%Si<sub>3</sub>N<sub>4</sub> + 2.5%Al<sub>2</sub>O<sub>3</sub> alloy at different aging duration

**IV. vii. Wear Test**

A wear test on a pin-on-wear disc apparatus is a method used to evaluate the wear resistance of materials. The wear test is carried out at 20 N load with a sliding distance of 1000m and 300 rpm. It is well known that hardness is directly proportional to wear resistance (i.e. higher the hardness, the higher the wear resistance). Since the hybrid composite (Al7075 + 2.5%Si<sub>3</sub>N<sub>4</sub> + 2.5%Al<sub>2</sub>O<sub>3</sub>) portrays superiority in terms of hardness, its wear characteristics were evaluated specifically. The wear studies of the aged specimen for Al7075 + 2.5%Si<sub>3</sub>N<sub>4</sub> + 2.5%Al<sub>2</sub>O<sub>3</sub> sample is shown in Fig 15.

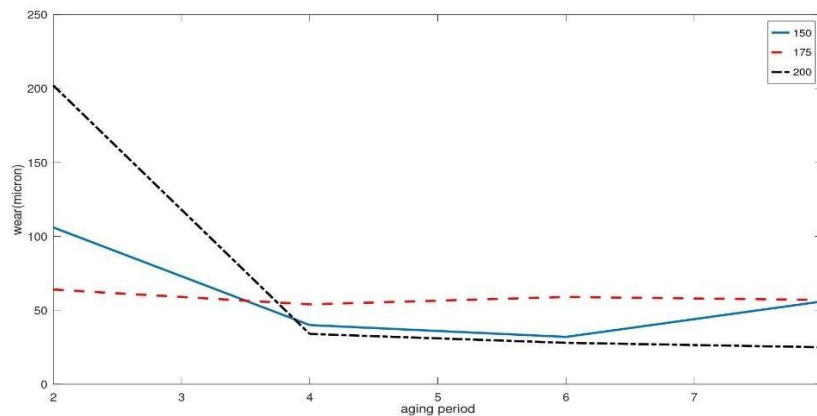


Fig. 15: Wear loss of Al7075 + 2.5%Si<sub>3</sub>N<sub>4</sub> + 2.5%Al<sub>2</sub>O<sub>3</sub>



## VI. CONCLUSION

The hardness of Al7075 composite specimens reinforced with silicon nitride and alumina possesses higher hardness, Compared with Al7075 alloy this is due to the presence of hard ceramic reinforcements in the matrix. The optimum cycle for heat treatment of Al7075 hybrid composites is aging at 200 °C for 6 hours. The rate of precipitation during aging is significantly higher in Al7075 composites in comparison with Al 7075 alloy and the hybrid composite with 2.5% of silicon nitride and 2.5 % alumina reinforced Al 7075 composite exhibited a higher response to aging treatment and resulted in maximum hardness of about 123.7 HV.

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