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DEVELOPMENT AND TESTING OF AUTOMOTIVE GEARS USING ALUMINIUM MATRIX NANO COMPOSITES

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ABSTRACT

Today Aluminium matrix composites (AMCs) are being widely employed for building, bridges, aircraft, navel, sports and automotive applications due to its high strength, high hardness and wear resistance along with light weightiness and economical production. The drive toward designing AMC components is to utilize the desired characteristics of metals and ceramics to fulfill the design requirements in optimum cost and performance level. This study involve the development of Al6061-nano Alumina composite gears for automobiles and testing of their hardness and wear resistance. The aluminium matrix nanocomposite gears were fabricated by reinforcing Aluminium 6010 alloy with nano aluminium oxide (alumina). The gear blanks were developed using ultrasonic assisted stir casting followed by heat treatment and hot forging. The spur gears were developed by machining of teeth in the gear blank. A wear testing set-up for testing of spur gears was fabricated and the wear tests were performed on the developed gears using wear testing set-up. The outcome of the work displays that the reinforcement of nano Al_2O_3 particles in aluminium matrix improves the hardness and wear resistance.

Key words: Al-nano composites, Automotive gears, Wear, Ultrasonic assisted stir casting, Hot forging

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1. INTRODUCTION

The automotive industries have been tremendously affected by the research and development in the field of material science. Ferrous materials have been traditionally used in automobiles since 1920s. However due to its high density the steel has largely replaced by the lightweight materials like composite materials and the nano composites are the next step to replace the existing materials in the 21st century. The increasing requirement of fuel saving initiated by the trepidations about global warming and energy crises significantly affect the choice of materials in the automotive sector. The US automobile regulations have become stringent on the reduction of exhaust emissions, increased passenger safety and lesser fuel intakes.

To fulfil these obligations, vehicle makers are targeting to improve the fuel efficiency, introduce new power trains such as hybrid systems and to reduce vehicle mass. In a vehicle, every kilogram of Al-alloy substitutes two kilograms of steel which can reduce 20 kg of CO_2 emissions. Therefore, the use of aluminium based composites can greatly reduce vehicle mass and decrease fuel usages. Therefore the iron and steel are increasingly being replaced by the use of AMCs and Polymer composites.

Weight reduction has further compelled to recompense the weight gain due to augmented luxury, comfort, performance, and safety features necessitated to meet the business goals. Newer facilities such as anti-block systems, air bags, and increased crashworthiness results in increased vehicle weight. To accomplish, these features vehicle weight reduction of the becomes predominantly important in the 21^{st} century. It is important to realize that vehicle mass reduction has a ripple effect on fuel efficiency e.g. mass reduction of the vehicle requires a relatively smaller engine, and a smaller engine requires smaller transmission and a smaller fuel tank, which results in two folded increase in fuel economy.

The composite materials are materials made up of two or more materials with a combination of properties not available in the constituent materials. They are different from alloys in the fact that the both the components stay distinct and identifiable in the finished component and are free from the restrictions offered by thermodynamic equilibrium diagram. Some The examples of composite materials include brake disc, fiberglass, mud bricks, and natural composites such as bones, granite and wood. The nano-composites are materials with reinforcement having one, two or three dimensions less than 100 nanometres (nm), or having nano-scale microstructural features inside their body structures.

Metal matrix nano composites, at present are creating increased attention among the researchers and hold the greatest promise for the future industries. Aluminum alloys have been tremendously used as matrix materials due to their low density, high corrosion resistance, low cost and ease of fabrication. Aluminum oxide (Al_2O_3) nano particles offers high hardness, wear resistance, corrosion resistance, high thermal stability, high melting point and light weightiness. The strength-to-weight ratios, hardness, wear resistance, fatigue resistance and elevated temperature properties of resulting composites are higher than most alloys. Therefore, the aluminum matrices recurrently use alumina particles as reinforcement to develop high performance nano composites for advance applications. The advantages of nanocomposites include high strength to weight ratio, low coefficient of thermal expansion, high thermal stability, high elastic modulus, wear resistance, creep resistance, improved fracture toughness, thermal shock resistance and higher resistance to corrosion attack.

Ceschini et al. [1] developed Al2618 -20 vol.% Al_2O_3 composites and done the hot forging to study the microstructure and tensile properties at room and high temperature. They found did not found significant difference in the amount of clustering of particles, before and after forging probably because of low deformation ratio used during forging. The tensile strength at both at room and high temperature was reported to increase due to microstructural changes after forging. Ramesh et al. [2] developed Ni–P coated Si3N4 reinforced Al6061composites by liquid metallurgy route with 4 to 10 wt. % of silicon nitride. The developed cast composites were hot forged at a temperature of 500 ℃. The grain size was found to decrease after hot forging. The microhardness, yield and tensile strength were found to increase with wt. % of Si3N4 in both as cast and hot forged condition and the ductility was increased after hot forging.

İsmile Özdemir et al. [3] fabricated Al-5%Si-0.2%Mg alloy reinforced with SiC particles by stir casting and then subjected to closed-die forging process. They reported decrease in porosity after forging and reduction in clusters of SiC particles. The ductility, yield strength and tensile strength were found to increase after forging. Hosur Nanjireddy Reddappa et al. [4] fabricated Al6061alloy composites with 2 to12 wt. % of beryl particles by stir cast process and studied the mechanical and wear behavior. They reported 15.38% increase in tensile strength and 8.9% reduction in specific wear rate at under 1 kg load as compared to matrix alloy. Ali Mazahery et. al. [5] developed A356 alloy composites with 0.75, 1.5, 2.5, 3.5, and 5 vol. % of nano Al2O3 particles by stir casting and found uniform distribution of reinforcement, grain refinement, and minimal porosity by the microstructural examination. Mechanical properties revealed that the presence of nano particles significantly increased compressive and tensile flow stress at both casting temperatures. Prashad et. al. [6] have studied the wear behaviour and mechanical properties of Al MMCs reinforced with hard particles, solid lubricants and short fibres and the technologies for producing automotive parts from these new materials to increase the fuel efficiency and reduce vehicle weight and fuel emissions. Considerable reduction in wear and friction is achieved by use of SiC and Al2O3 particles. They concluded that higher cylinder pressure (hence higher engine performance) are possible because AMCs can survive high mechanical and thermal loads and reduce heat losses due to closer dimensional tolerance achievable because of lower coefficient of thermal expansion.

Rick Borns et.al. [7] developed automobile components like chassis and suspension systems using Al-alloy and reported reduction of weight and fuel emissions, improvement is fuel efficiency crashworthiness, and ride performance by the abridged un-sprung mass due to the high strength-to-weight ratio and corrosion resistance. About 6 to 8% fuel savings is possible by every 10% reduction in weight replacing aluminum for steel. Purohit et. al. [8] developed Al-SiCp composites with 5 to 30 weight % of SiCp in using stir die casting process and reported that the density, hardness, compressive strength, tensile strength of Al-SiCp composites increases with increase in the weight % of SiCp up to 30 wt. %. The dry sliding wear tests on Al-SiCp composites have shown improvement in wear resistance up to 20 wt. % of SiCp after which it decreases. Increased wear rate of Al-SiCp composites at higher wt. % of SiCp was reported to be due to the removal of loosely bonded SiC particles from aluminum.

Jatinder Kumar et al. [9] studied the influence of different factors like particle size, type and composition, fabrication techniques etc. on the microstructure, tribological & physical properties of Al-SiC composites. The tribological properties of SiC reinforced-AMCs were reported to changed significantly with different factors like type/size/properties/composition of reinforcements, type of fabrication route and their process parameters, secondary processing of as-cast composites. In general, wear resistance is increased and coefficient of friction decreased with increasing wt. % of SiC in Al matrices. However, in hybrid composites, the variation in properties depends upon the nature of the secondary reinforcement.

Srinivasan et al. [10] studied the tribological properties of Al-6063 reinforced with Zirconium Oxide (ZrO_2) and Graphite (C) by squeeze casting process. Al-hybrid MMCs were developed by squeeze casting with different wt. % of ZrO_2 from 0 to 6 % and graphite percentage was fixed at 3 %. Dry sliding wear tests performed on pin-on-disc wear testing machine have shown minimum wear rate for 6% of ZrO_2 and 3% of C reinforcements for all the speeds and loading conditions and the friction coefficient was diminished with increase in wt. % of ZrO_2 for all the loading conditions. VKV Meti et al. [11] investigated on the development of AA7075-5% TiB_2 composites for automotive and aerospace applications with enhanced mechanical and wear behaviour through ultrasound assisted in-situ processing techniques. Further, they have done the hot forging of the developed composites. The hardness was reported to increase by the addition of TiB2 reinforcement. Micrographs showed even distribution of TiB_2 particles bounded along the grain boundaries which results in improvement of mechanical properties. Wear tests conducted on pin-on-disc tribo tester exhibited increase in wear resistance and decrease in co-efficient of friction by adding TiB_2 particles by the use of processing route such as in-situ and ultrasound. Hot forging resulted in grain refinement which resulted in better mechanical and wear behaviour of the composites.

1.2. Automotive Gears

The power is conveyed from one shaft to the other through belts, chains and gears. The belts and ropes are flexible drives which are incorporated in case of large gap between the two shafts. The chains are also flexible but they aresuitable for medium distances. The gears are used when the distance between shaft is very less. The gear drive is positive drive due to absence of any slip. According to the law of gearing during transfer of motion, common normal at the contact point of two gear teeth should always pass through a certain point called pitch point on the joining line between centres of rotation of the two gears.

1.3. Spur Gears

The spur gears are simplest type of gear consisting of a cylinder or disk with radially projecting teeth. They have teeth perpendicular to the face of the gear. There are two types of gear tooth profile involute and cycloidal (involute profile is most common) and the edges of teeth are straight and aligned parallel to the axis of rotation. Spur gears are most common type of gears with high efficiency and are economical. However they can only be used when the two shafts are parallel. When two sharts are not parallel, other gears like helical gear, bevel gears, worm gear etc. are used.

The present work attempts to develop the aluminium matrix nano Al_2O_3 composites which are used for automotive applications. The development of spur gears for possible use in automobiles has been undertaken using the Al-nano alumina composites by ultrasonic assisted stir casting and subsequent heat treatment and hot forging and compare its wear rate, which are used to replace existing steel gears to develop light weight automobiles.

2. EXPERIMENTAL PROCEDURES

2.1. Fabrication of Al-Nano Composites

An ultrasonic stir casting setup as shown as shown in figure 1 consist of a vertical electrical resistance Furnace, ultrasonic probe, mechanical stirrer for casting of nano composites. The mechanical stirrer consists of a ceramic coated steel stirrer, driven by variable speed electrical motor with range of 80 to 900 rpm. The stirrer was designed to get proper vertex. The weighed amount of Al6061 aluminum alloy was placed in graphite crucible in the melting furnace and weighed amount of nano Al_2O_3 particles were placed in a small crucible, used for preheating reinforcement particles in a separate muffle furnace. The Al alloy was melted and super heated up to 800°C. Preheated alumina particles at 300°C were added in three installments in the molten aluminum. Stirring was done for 10 minutes to homogenize the temperature. To maintain the constant speed, speed controller is used. Then the stir was taken out and an ultrasonic probe of frequency 20.20 KHz is inserted into the molten metal. The horn was heated to higher than 500°C before the system boot work. Ultrasonic vibration is produced for 5 minutes after which it was poured in the preheated mold.

2.2. Hot Forging of Al-Nano Composites

Work pieces of Al6061-nano composites for forging were made by machining to the dimension of 52mm diameter and 110 mm length. The cast nano composite samples were hot forged using 1.5 ton screw forging press at Hari Engineering Industries, Govindpura, Bhopal. The machined work pieces were preheated to 500±3°C (above recrystallization) for 1hr. in resistance furnace. The work piece which is at the temperature of 500°C in the Furnace is placed between flat platen and the load was gradually increased up to 800 KN and the samples were deformed from height 110mm to the final height of 70 mm. The same process of hot forging was repeated for all samples of Al6061-alumina nano composites with varying compositions of nano Al_2O_3 particles from 0.5 to 3 wt. %.

2.3. Heat Treatment

The hot forged Al6061-Al_2O_3 composites were subjected to heat treatment (T6) using programmable resistance furnace Figure 2. Heat treatment was done in three stages: Solution treatment: the nanocomposite samples were heated to 530°C for 2 hours until the alloying solute elements are completely dissolved in Aluminum solid solution, (ii) Quenching: the solution treated composite samples were immersed in water at room temp 32°C to obtain a super saturated solid solution (iii) Artificial aging: here reheating of the quenched sample was done to 175°C temperature and artificial ageing was done for 8 hours.

Figure 1 Preparation of sample in Muffle furnace

Figure 2 Programmable muffle furnace used for heat treatment

2.4. Spur gear Manufacturing of Forged Al alloy Reinforced with Al_2O_3 Nano Particles

The hot forged and heat treated Al-nano Al_2O_3 composite billets were cut into gear blanks of about 70 mm diameter. The spur gears were machined on the universal milling machine. The final dimensions of the machined spur gears are:

Pitch circle diameter (D) = 50 mm; Number of teeth (T) = 29; Module (m) = D/T = 1.72 mm

Figure 3. Manufactured Al-nano Al_2O_3 composite spur gears

2.5. Hardness Test

The Rockwell hardness of Al-nano composites reinforced with 0.5, to 3.0 wt.% of nano Al2O3 particles in as cast, heat treated and forged & HT conditions were measured in using Rockwell B scale on digital Rockwell hardness testing machine. The hardness test specimens of 20mm dia. and 15mm height were prepared using standard metallographic practices. The 1/16 inch diameter hardened steel ball indenter with 100 Kg load was used for the hardness tests.

2.6. Fabrication of Wear Testing Set up for Spur Gears

A set-up for wear testing of spur gears was fabricated. It consist a 0.5HP Single Phase Foot Mounted Motor 1440 rpm, pillow block bearing, coupling and shaft. The two gears mounted on separate shafts meshing together and the load was applied by hanging weights in pan through pulley mounted on shaft and then gears were rotated by the motor for different time duration like 1, 2 and 3 hours. Initial and final weights of both the gears were taken with help of precision electronic balance before and after the test. Difference in weight shows the wear loss. Wear testing set-up for Spur gears consist of:

- Induction Motor: Specifications: 0.5hp 4p Single Phase Foot Mounted Motor, 1440 rpm
- Pedestal or Pillow Block Bearing with housing
- Shafts: Two shafts for mounting of two meshing gears are provided.
- Coupling

2.7. Wear Testing of Al-nano Al_2O_3 Composite Gears

Figure 4 Wear testing setup

The wear testing of Al-nano Al_2O_3 composite gears were performed in following steps:

- First, mount all the components on the frame as shown in the figure 4.
- Take the initial weight of the gears using precision weighing machine with least count of 0.01 mg.
- Now properly mesh the gears with each other.
- Then apply 1 kg load on the drive shaft with the help of mild steel strip.
- Run the motor for one hour.
- After one hrs stop the motor and take out the gear from the setup.
- Now measure the weight of both the gears.
- Find the difference in weight which will give the wear loss of gears (in 1 hour).
- Similar measurement procedure was followed for the wear rate for 2 and 3 hrs under 1 kg load.
- Similar measurement procedure was followed for the wear loss under 2 kg load in 1, 2 and 3 hrs test durations.
- In summary, the wear rate of 0.5% nano composites gears , 1.5% nano composites gears, and 2.5% nano composites at 1 kg (1,2,& 3 hrs) and 2kg (1,2,&3 hrs) were measured.

3. RESULTS AND DISCUSSIONS

The results obtained from the hardness test and wear testing of Al-nano composite gears manufactured from hot forged and heat treated gear blanks are reported here in this section.

3.1 Hardness Test

The Hardness test were performed on the Al-nano Al2O3 composite samples using Rockwell hardness testing machine. The as cast, hot forged and heat treated samples of Al-nano composites with 0 to 3 wt. % nano alumina were tested using Rockwell hardness B scale (HRB). The cylindrical samples were prepared using different compositions of as cast, hot forged and heat treated nano composites and they were polished using metallographic practices. The variation of hardness with wt. % of nano alumina particles is shown in figure 5. The figure 5 shows that the hardness increases with increase in wt. % of nano alumina and the hardness also increases after hot forging and heat treatment. The increase in hardness of Al-nano composites with wt. % of is due the hindrance offered by hard nano alumina particle to the movement of dislocations. The forging result in increase in hardness due to grain refinement, strain hardening effect and decrease in porosity, and enhancement of bonding between aluminium and nano alumina particles.

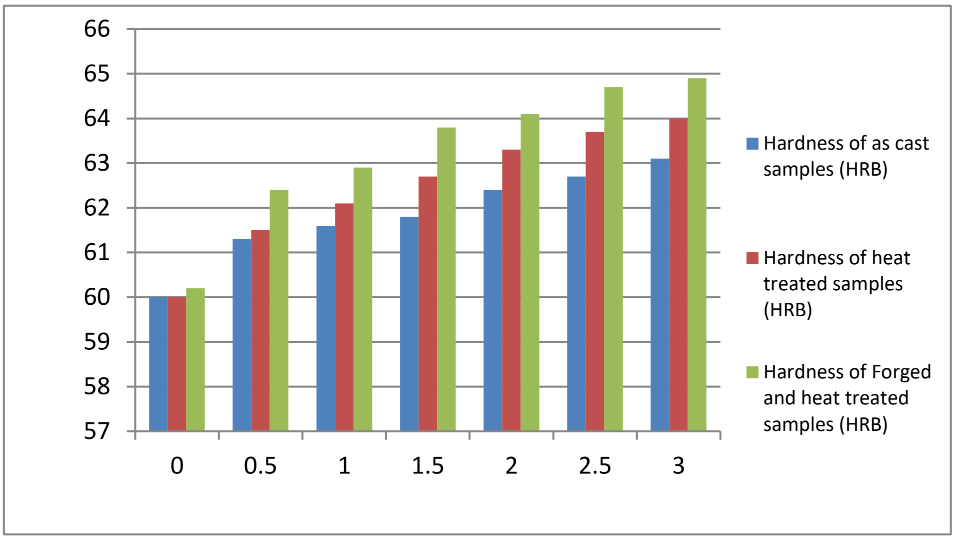

Figure 5. Variation of hardness with wt. % of nano alumina for Al-nano Al_2O_3 composites in as cast, heat treated and hot forged & HT samples

3.2. Wear Test on Automotive Gears

The wear test of hot forged and heat treated Al-nano Al_2O_3 composite gears with 0.5 to 3 wt. % nano alumina were performed on the fabricated wear testing set-up. The wear tests were performed under 1 and 2 kg load for 1, 2 and 3 hours of test durations. The results of the wear testing of Al-nano Al_2O_3 composite gears are shown in tables 1 to 12 and the variations of the wear loss with test duration and wt. % of nano Al2O3 reinforcement has been depicted in figure 6, 7, 8 & 9 respectively. The figure 6 and 7 show the variation of wear/weight loss with the test duration under 1 & 2 kg load respectively, which reveals that the wear loss increases with test duration and the wear loss is minimum for Al-3 wt. % nano Al2O3 composite gears. Presence of superior interfacial bond in the hot forged and heat treated Al-nano alumina composite gears is found to prevent the possibility of pull out of hard Al2O3 particles from the matrix there by eliminating the chances of three body wear and hence increase in wear resistance [11].

Figure 8 and 9 show that the wear loss decreases with increase in weight present of nano Al_2O_3 particles under 1 and 2 kg load respectively. This is due to increase hardness of with wt. % of nano alumina particles. Further the wear loss under 2 kg load is more than that under 1 kg load. The wear loss increases with increase in load due to the formation of higher plastic deformation zone on the sample surfaces and the delamination wear takes place at increased loads. During the wear testing of gears the high speed and load causes fracture at the interfacial zones between reinforcement and the Al alloy and hence the higher wear loss. The results are in line with that reported by other researchers [9-11]. The wear loss decreases maximum up to 41.34 % and 38.25 % for 3 hour test duration with increase in wt. % of nano alumina from 0.5 to 3 wt. % for 1 and 2 kg load respectively.

The hard alumina particles have very low ductility and they have the ability to withstand stresses without plastic deformation or fracture under low load conditions. It is well already recognized that if we prevent the plastic deformation of the material at the counter interface, the wear resistance can be improved and surface damage can be reduced. The alumina particles have the ability to withstand relatively high stresses and are effective in increasing the wear resistance**.**

Table 1 Weight losses under 1 kg load for Al-0.5 wt. % nano alumina composite gears

	Initial weight in gm	**1hr**	**2hr**	**3hr**
Gear 1	91.4746	91.4173	91.3411	91.2347
Wear (gm)		0.0573	0.1335	0.2399
Gear 2	93.9576	93.9014	93.1694	93.0613
Wear (gm)		0.0562	0.1294	0.2375

Table 2 Weight losses under 1 kg load for Al-1.0 wt. % nano alumina composite gears

	Initial weight in gm	**1hr**	**2hr**	**3hr**
Gear1	92.5768	92.5227	92.4466	92.3455
Wear (gm)		0.0541	0.1302	0.2313
Gear2	96.2936	96.2399	96.169	96.0639
Wear (gm)		0.0537	0.1246	0.2297

Table 3 Weight losses under 1 kg load for Al-1.5 wt. % nano alumina composite gears

	Initial weight n gm	**1hr**	**2hr**	**3hr**
Gear 1	91.4669	91.4150	91.3419	91.2435
Wear (gm)		0.0519	0.125	0.2234
Gear 2	95.1472	95.0966	95.0265	94.9252
Wear (gm)		0.0506	0.1207	0.222

Table 4 Weight losses under 1 kg load for Al-2.0 wt. % nano alumina composite gears

	Initial weight in gm	**1hr**	**2hr**	**3hr**
Gear 1	100.7375S	100.6998	100.6381	100.5569
Wear (gm)		0.0377	0.0994	0.1806
Gear 2	93.4113	93.3606	93.2893	93.2130
Wear		0.0507	0.1226	0.1989

Table 5 Weight losses under 1 kg load for Al-2.5 wt. % nano alumina composite gears

	Initial weight in gm	**1hr**	**2hr**	**3hr**
Gear 1	97.9225	97.8924	97.8391	97.7779
Wear (gm)		0.0301	0.0834	0.1446
Gear 2	98.3599	98.3261	98.2670	98.2017
Wear (gm)		0.0338	0.0929	0.1582

Table 6 Weight losses under 1 kg load for Al-3.0 wt. % nano alumina composite gears

	Initial weight in gm	**1hr**	**2hr**	**3hr**
Gear1	102.4719	102.440	102.3928	102.3321
Wear (gm)		0.0319	0.0791	0.1398
Gear2	98.5984	98.5680	98.5195	98.4582
Wear (gm)		0.0304	0.0789	0.1402

3.3. Weight losses in gm at 2 kg

Table 7 Weight losses under 2 kg load for Al-0.5 wt. % nano alumina composite gears

	Initial weight in gm	1hr	2hr	3hr
Gear1	91.2347	91.1713	91.0857	90.9765
Wear (gm)		0.0634	0.149	0.2582
Gear2	93.0613	93.0028	92.9146	92.7937
Wear (gm)		0.0613	0.1495	0.2704

Table 8 Weight losses under 2 kg load for Al-1.0 wt. % nano alumina composite gears

	Initial weight in gm	1hr	2hr	3hr
Gear1	92.3455	92.2836	92.1992	92.0818
Wear (gm)		0.0619	0.1463	0.2637
Gear2	96.0639	96.0035	95.9193	95.8067
Wear (gm)		0.0604	0.1446	0.2572

Table 9 Weight losses under 2 kg load for Al-1.5 wt. % nano alumina composite gears

	Initial weight in gm	1hr	2hr	3hr
Gear1	91.2435	91.1853	91.1026	91.0005
Wear (gm)		0.0582	0.1409	0.243
Gear2	94.9252	94.3492	94.2702	94.1576
Wear (gm)		0.0576	0.1366	0.2492

Table 10 Weight losses under 2 kg load for Al-2.0 wt. % nano alumina composite gears

	Initial weight in gm	1hr	2hr	3hr
Gear1	100.5569	100.4998	100.4343	100.3451
Wear (gm)		0.0571	0.1226	0.2118
Gear2	93.2130	**93.1557**	93.0875	93.0081
Wear (gm)		**0.0573**	0.1255	0.2049

Table 11 Weight losses under 2 kg load for Al-2.5 wt. % nano alumina composite gears

	Initial weight in gm	1hr	2hr	3hr
Gear1	97.7779	97.7308	97.6712	97.6068
Wear (gm)		0.0471	0.1067	0.1711
Gear2	98.2017	94.1529	94.0915	94.0263
Wear (gm)		0.0488	0.1102	0.1754

Table 12 Weight losses under 2 kg load for Al-3.0 wt. % nano alumina composite gears

	Initial weight in gm	1hr	2hr	3hr
Gear1	102.3317	102.2880	102.3930	102.3317
Wear (gm)		0.0437	0.103	0.1657
Gear2	98.4582	98.4141	98.3547	98.2975
Wear (gm)		0.0441	0.0985	0.1607

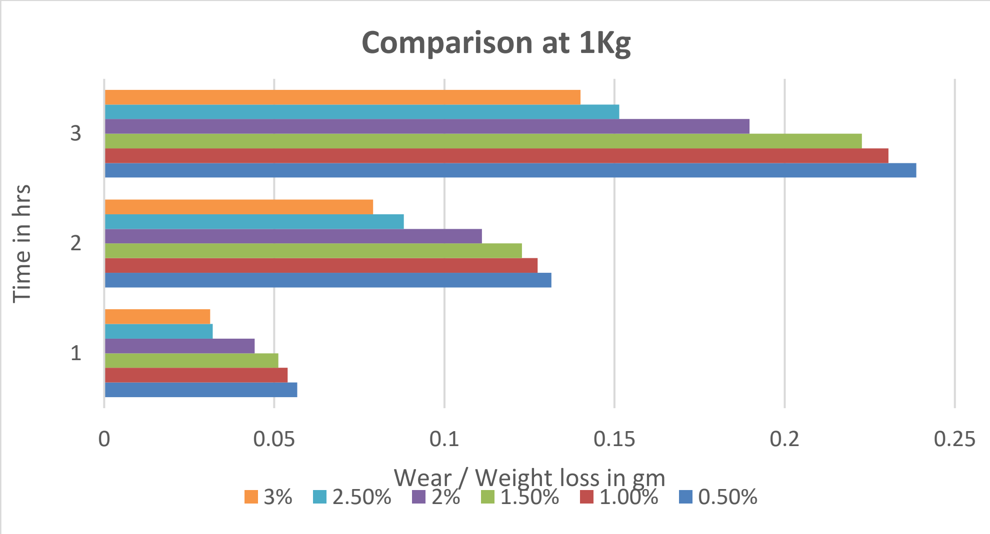

Figure 6. Variation of wear loss with test duration for Al- nano Al_2O_3 composite gearsat 1 Kg load

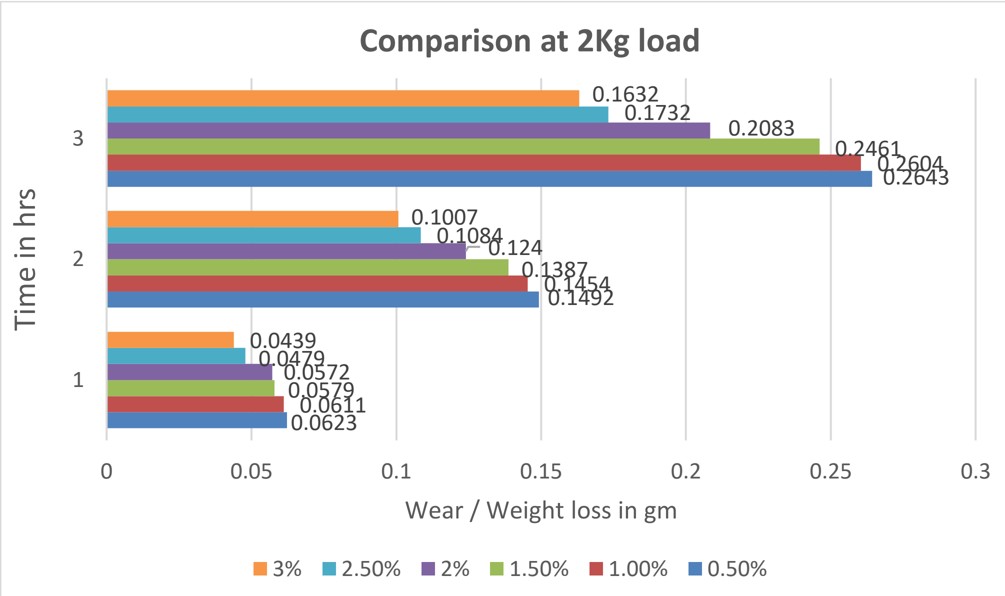

Figure 7. Variation of wear loss with test duration for Al- nano Al_2O_3 composite gears at 2 Kg load

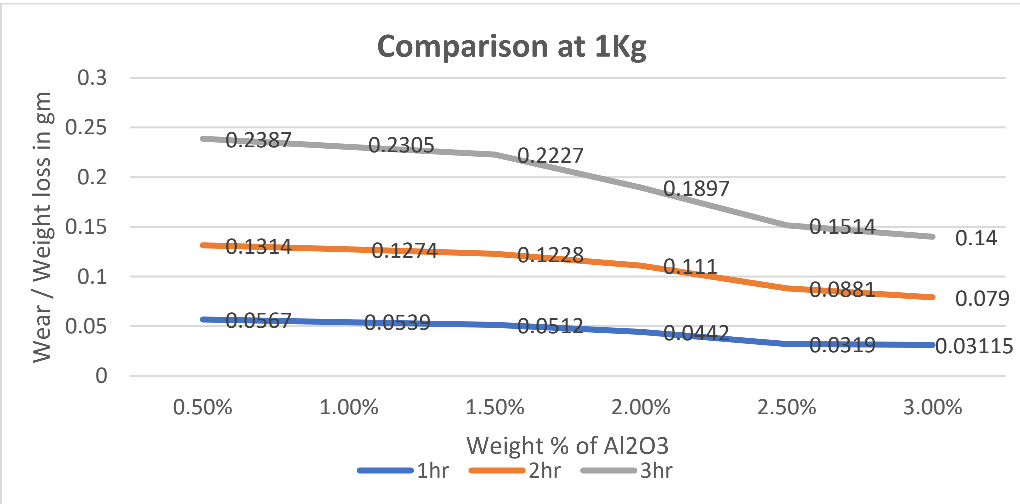

Figure 8. Variation of wear loss with wt. % of nano alumina for Al-nano Al_2O_3 composite gears under 1 Kg load

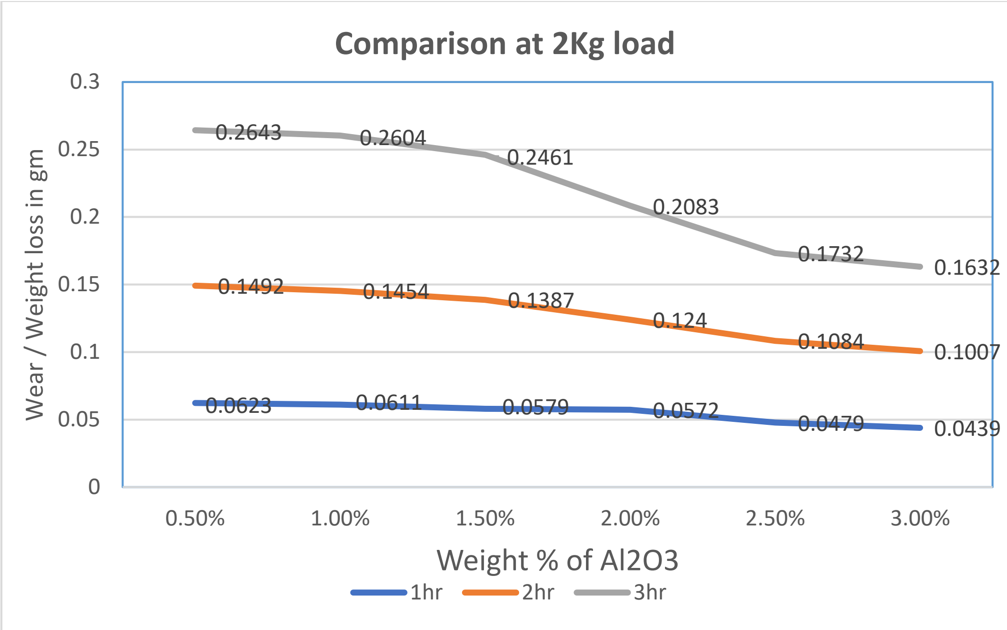

Figure 9. Variation of wear loss with wt. % of nano alumina for Al-nano Al_2O_3 composite gears under 2 Kg load

4. CONCLUSIONS

The following conclusions were established from the present study:

- Aluminum matrix nano Al_2O_3 composite gears have been effectively developed using ultrasonic assisted stir casting followed by hot forging and heat treatment. Hot forging did not caused any damage on composites.
- The Rockwell hardness of the Al-nano alumina composites were found to increase with higher wt. % of Al_2O_3 and the forging and heat treatment resulted in higher hardness compared to as cast samples.
- A setup for wear testing of gears was designed and fabricated and the wear test were performed on the Al-nano Al_2O_3 composite gears with different compositions under 1 and 2 kg load and test duration of 1, 2 and 3 hrs.
- The wear loss was found to decrease with increasing weight % of nano alumina and increase with increase in test duration and increasing load.
- The fabricated aluminum nano composite gears have almost 1/3 of the density as compared to steel and enhanced wear resistance hence they are recommended for possible replacement for the existing gears in automotive and industrial applications.

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