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(RESEARCH ARTICLE)

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Mechanical, Tribological, Economic and 3D Modeling Evaluation of Stir-Cast Al6061/Al_2O_3/Graphite Hybrid Composites as a Replacement for Grey Cast Iron Engine Valve Guides

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Abstract

The increasing demand for light weight and high performance materials in the automotive sector has driven the development of advanced aluminium based composite as potential substitute for ferrous alloys.

The research scope included the fabrication of Al6061 composites reinforced with Al_2O_3 and graphite particulates using the stir casting technique, followed by extensive characterization of their mechanical and tribological properties. To ensure practical relevance, a comparative cost evaluation was also carried out. In addition a 3D model of engine valve guide was developed in AutoCAD to validate dimensional compatibility and visualize integration of composite into real world application.

The result demonstrated that the hybrid composite offers superior hardness and wear resistance compared to grey cast iron, with graphite providing solid lubrication and Al_2O_3 enhancing load bearing capacity. The AutoCAD modeling confirmed dimensional feasibility, with economic analysis indicated the composite as cost effective alternative.

The integration of experimental evaluation with 3D design modeling highlights the hybrid composite potential as a light weight, durable and economical replacement for grey cast iron valve guides, there by contributing to fuel efficiency and sustainable automotive material.

Keywords: Tribological behaviour; Engine guide valve; hybrid composite; Life-cycle cost analysis; 3D modeling

1. Introduction

The automotive industry is continuously seeking advanced materials that can provide weight reduction, improved wear resistance and cost effective without compromising performance. Traditionally grey cast iron has been widely employed in engine components such as valve guides due to its machinability, damping capacity and reasonable wear resistance. However, its relatively high density, lower strength-weight ratio and susceptibility to wear in demanding operating conditions limit its applicability in modern light weight engine designs.

Aluminium matrix composites have emerged as promising alternative owing to their low density, high specific strength and excellent thermal properties. Reinforcement of aluminium alloys with solid lubricant particles has shown significant improvement in both mechanical and tribological performance. In particular, Al6061 alloy reinforced with Al_2O_3 provides enhanced hardness and strength, while graphite acts as a solid lubricant, improving wear resistance and reducing friction.

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Extensive studies have reported the individual benefits of reinforcing aluminium alloy with lubricating phases. However limited researches integrated both ceramic and solid lubricant reinforcement into a hybrid composite and evaluate their combined influence on mechanical, tribological and economic performance. Furthermore, few studies have considered practical validation through 3 dimensional design modeling of automotive components.

The present works aim to investigate the mechanical, tribological and economic Feasibility of stir-cast Al6061/Al_2O_3/graphite hybrid composites as a replacement for grey cast Iron Engine valve guides. In addition to experimental characterization, a 3D AutoCAD model of valve guide has been developed to confirm dimensional compatibility and assess the potential for real world application. This study provides a comprehensive approach to advancing light weight hybrid composites for automotive engineering.

2. Materials and Methodology

The methodology adopted in this study was formulated based on detailed review of experimental requirements for identifying a suitable alternative to grey cast iron in engine valve guides. The proposed hybrid composite, Al6061/Al_2O_3/Graphite was fabricated using stir casting process.

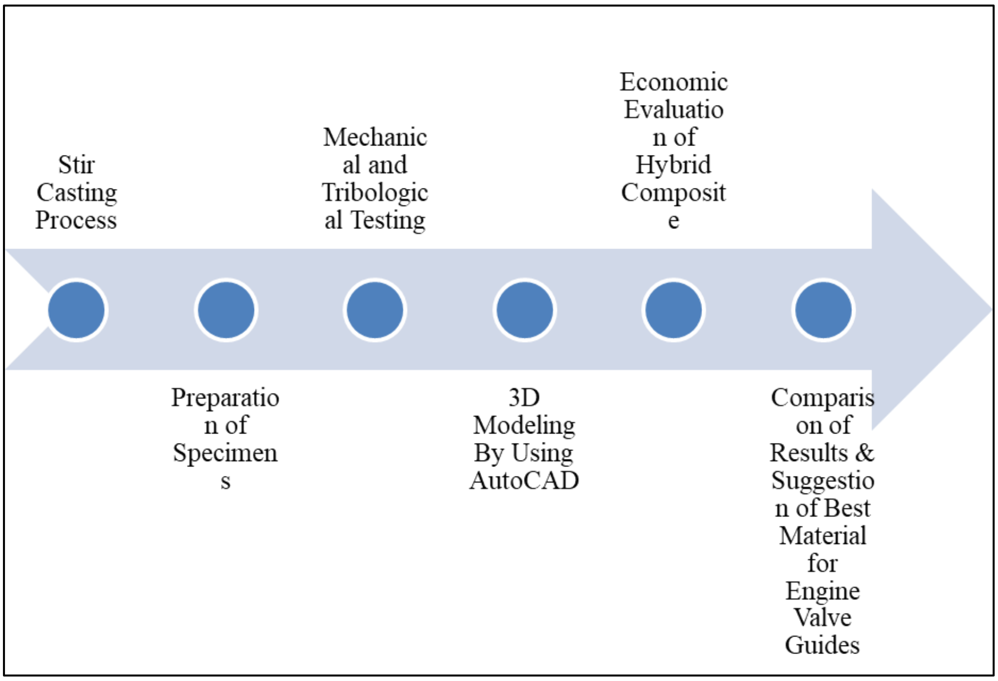

Figure 1 Methodology Chart

2.1. Stir Casting Process

Among various metal-matrix composites fabrication techniques, stir casting was selected due to its simplicity, cost-effectiveness, and capability to produce uniform distribution of reinforcements. The process involves melting the base Al6061 alloy is crucible, preheating Al_2O_3 and graphite particles to improve wettability and then introducing them into molten alloy while stirring at controlled speed. The slurry is poured into sand molds and allowed to solidify.

The system consists of a crucible furnace, mechanical stirrer, pre heating chamber, and an argon gas supply to minimize oxidation. Reinforcement particle preheated to 400 degree Celsius before addition. Stir was carried out a control speed for 10 minutes to ensure uniform distribution. The molten mixture was then cast into preheated sand molds.

The choice of stir casting enables incorporation of both ceramic and lubricating phases into aluminium matrix. This method provides balance of mechanical strength and tribological properties while keeping processing cost effective for automotive application.

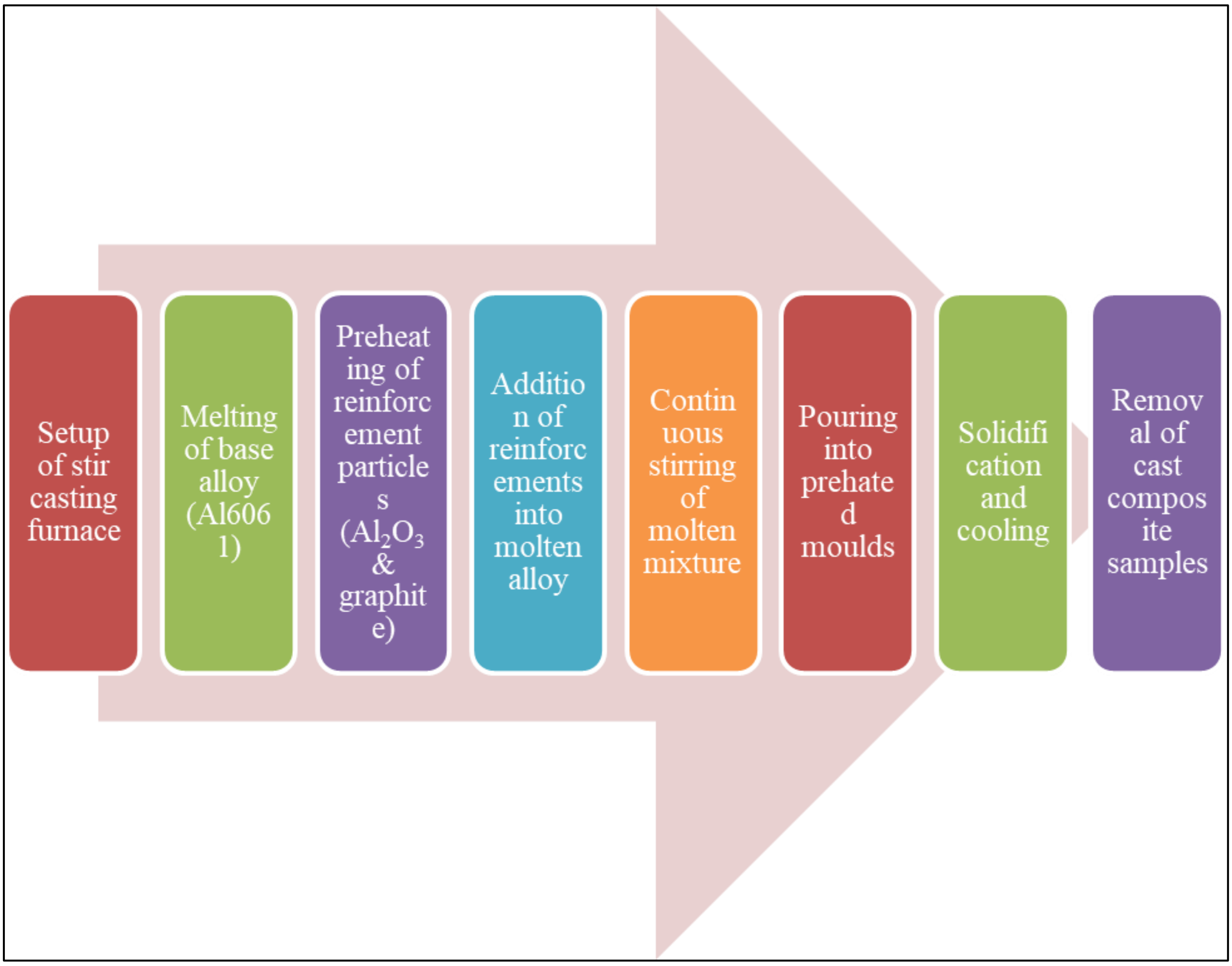

Figure 2 Casting Procedure

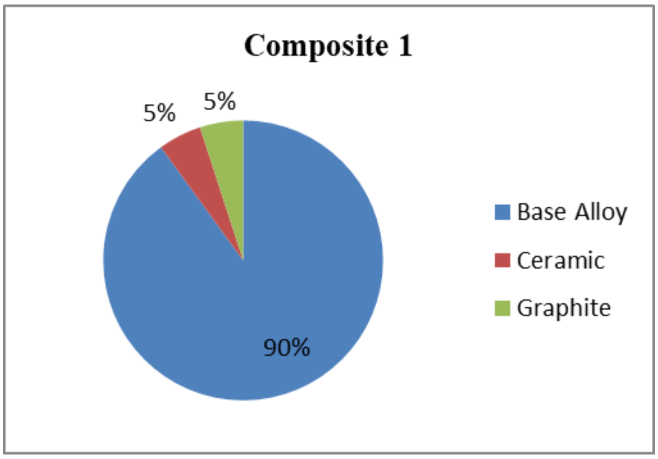

Figure 3 Compositions of Composite 1

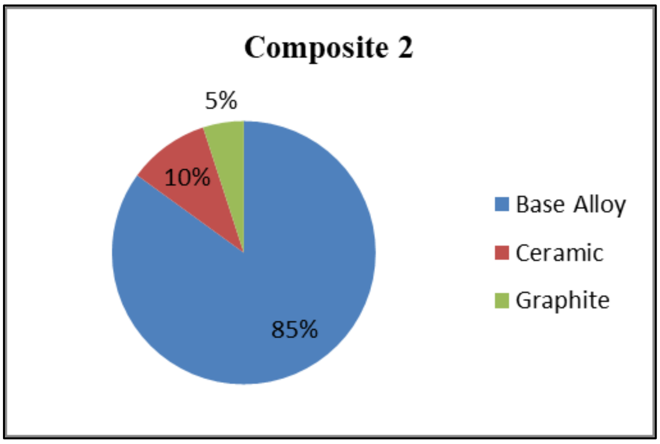

Figure 4 Compositions of Composite 2

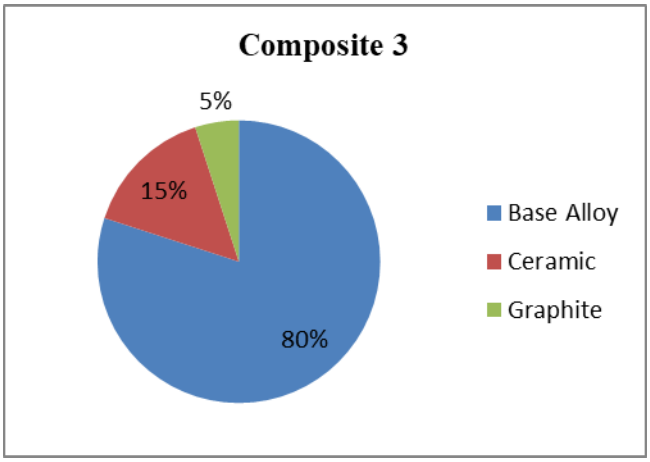

Figure 5 Compositions of Composite 3

2.2. Preparation of specimens

The specimens are prepared for various testing for finding mechanical and tribological behaviour. Milling machine and turning machines are used for this purpose. Cylindrical shaped and square shaped specimens are prepared for tensile testing and wear testing respectively. Square shaped specimens are used for the micro hardness test by using Vickers hardness testing machine.

2.3. Mechanical and Tribological Testing

2.3.1. Tensile Testing

Tensile testing is used for finding tensile strength of the specimen by using universal testing machine. The tensile strength is evaluated on cylindrical shaped specimen. As per ISO6892-1, the tensile strength is evaluated on the cylindrical rod of casted composites. This UTM has maximum loading capacity of 1000kN.

Table 1 Tensile Test Results

Specimen	Ultimate Tensile Strength
Base Alloy	178.17 N/mm^2
Composite 1	238.62 N/mm^2
Composite 2	267.11 N/mm^2
Composite 3	301.49 N/mm^2

The variation of ultimate tensile strength with varying Al_2O_3 can be reveled from the tensile test result. The graphite additions normally decrease the strength but addition of Al_2O_3 particles improves the properties by stress transfer from aluminium matrix to reinforced particles.

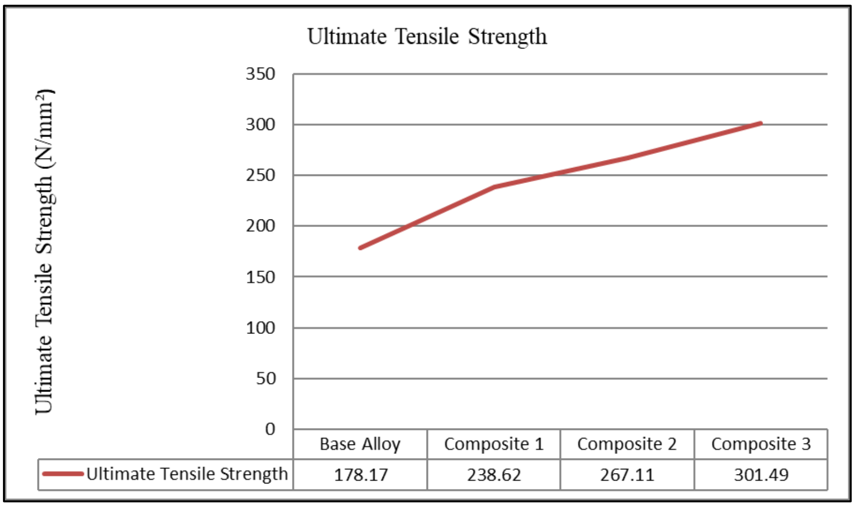

Figure 6 Variation of Tensile Strength

It can be clearly seen that the ultimate tensile strength of composite is higher than the base alloy which is the clear indication of composite being successfully casted.

2.3.2. Hardness Testing

The hardness test is used for finding hardness over very small area of the specimen by using Vickers hardness testing machine. This test was carried out according to ASTM standards using Vickers hardness testing machine with diamond indenter and 500 g load for 30 seconds.

Table 2 Hardness Test Results

Specimen	**Composite 1**	**Composite 2**	**Composite 3**
Hardness Value	98.64	118.21	134.43

The volume of ceramic particles in matrix increased the overall hardness of the composite.

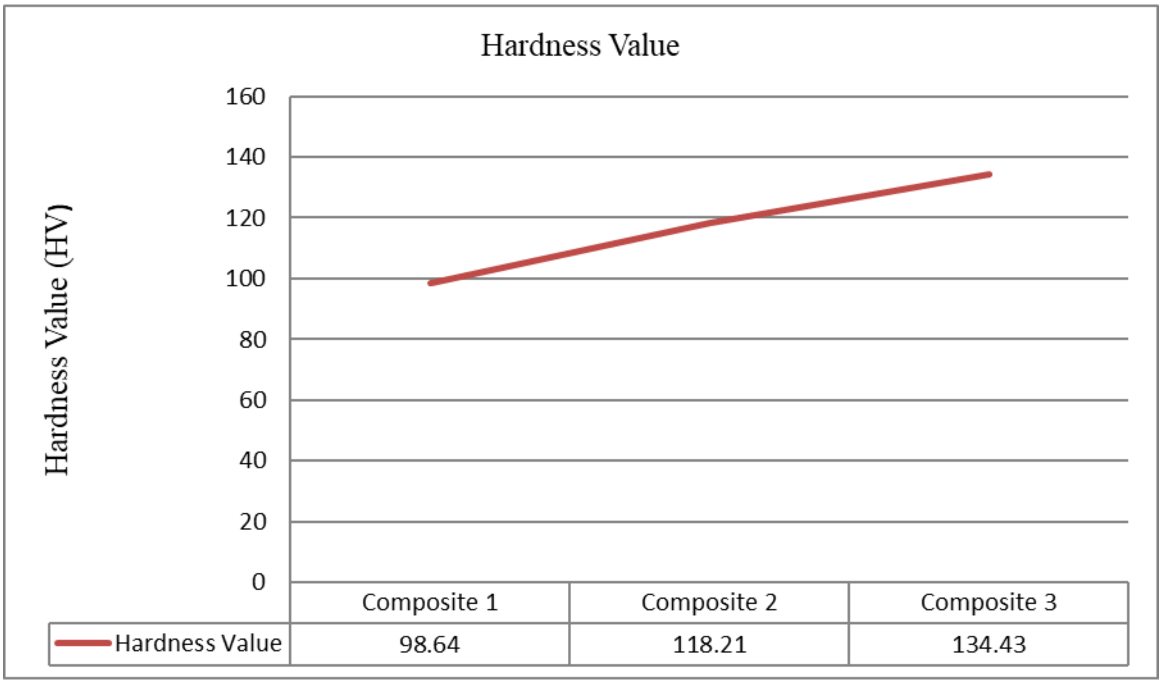

Figure 7 Variation of Hardness Value

From the graph it was observed that maximum hardness obtained from composite 3 which means Al_2O_3 contribute maximum hardness on the matrix composite. Here 15% of Al_20_3 consist on the composite 3 specimen but graphite percentage remains same in all composites.

2.3.3. Wear Testing

Pin-on-disc apparatus used for finding wear resistance of the composites. The size of the specimen 25mm height, 10 mm breadth and 10mm width was prepared. Testing parameters for the testing, sliding distance is 4000m, sliding velocity 1.58m/s and loads are 10N, 20N, and 30N. This test was carried out on a dry sliding condition and normal room temperature.

A 160mm diameter chromium disc of 63HRC was used as a counter surface. The frictional force compensated by the pin during sliding is measured by computer system.in each test after running the fixed sliding distance the specimen was removed. Here wear rate of composite determined by using height loss method.

Table 3 Wear Test Results

weight	Loss of Volume	Sliding Distance	Load	Specific Wear Rate
%	mm^3	m	N	mm^3/Nm
5	20.692	4000	10	0.000038
5	32.811	4000	20	0.000043
5	40.409	4000	30	0.000048
10	16.871	4000	10	0.000020
10	20.847	4000	20	0.000023
10	25.553	4000	30	0.000026
15	16.362	4000	10	0.000009
15	29.391	4000	20	0.000010
15	35.777	4000	30	0.000012

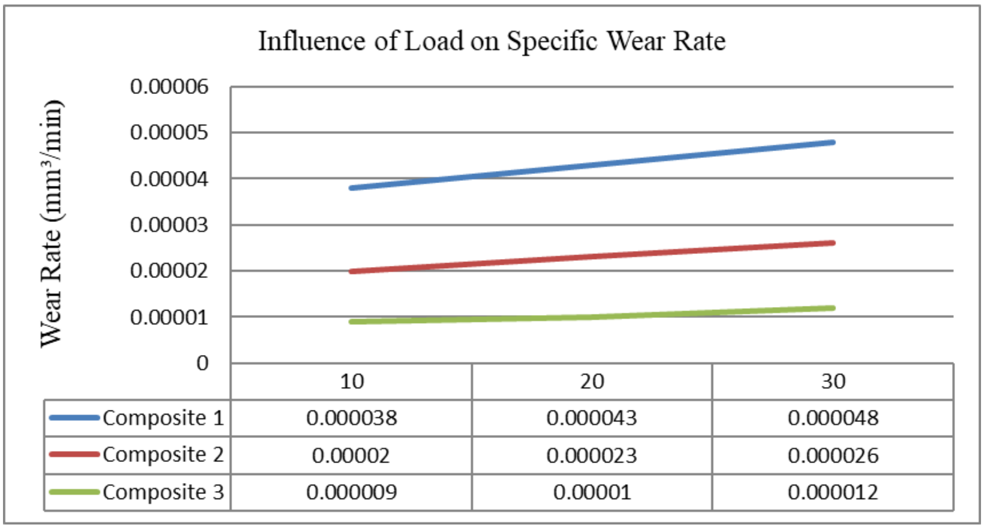

Figure 8 Influence of Load on Specific Wear Rate

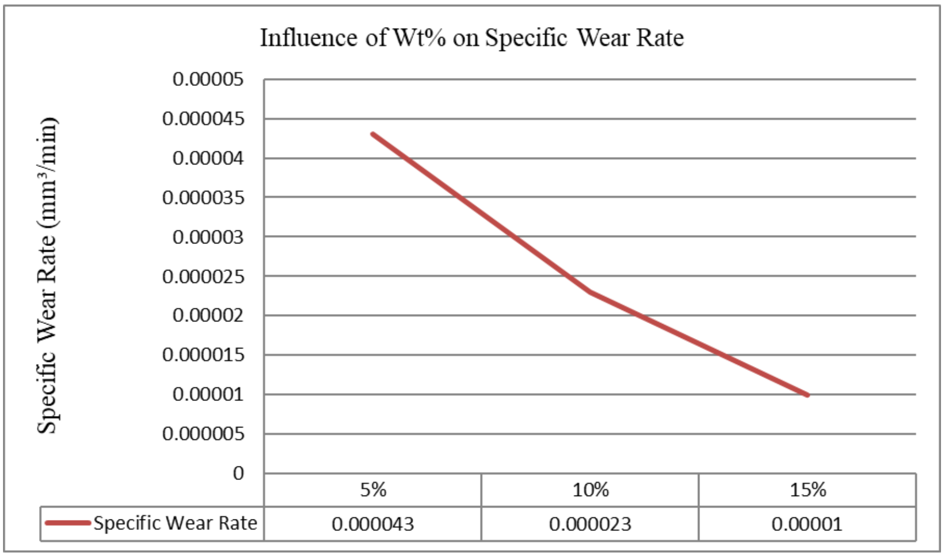

Figure 9 Influence of Wt% on Specific Wear Rate

From above graph variation shows the Al_2O_3 particles as a load bearing elements in the composite. As the result of this the formation of stable was lubricating film on the surface of composite. The graphite film minimize the degree of shear stress transferred to the underneath of the sliding contact area which result in plastic deformation in sub region which cause reduce the wear rate in composite.

2.4. Three Dimensional Modeling by Using AutoCAD

Drafting is the discipline of composing drawing that visually of how is constructed. Professional drafting is a desirable and necessary function in design and manufacture of mechanical components. It is very useful for to identify the shape and size of the machine components and also give an idea of its working features.

Assembling drawing can be used to that consist of more than one component. Models show how components fit together and exploded view showing the relationship between the components. In this modeling gives that the relationship between engine valve and engine valve guide.

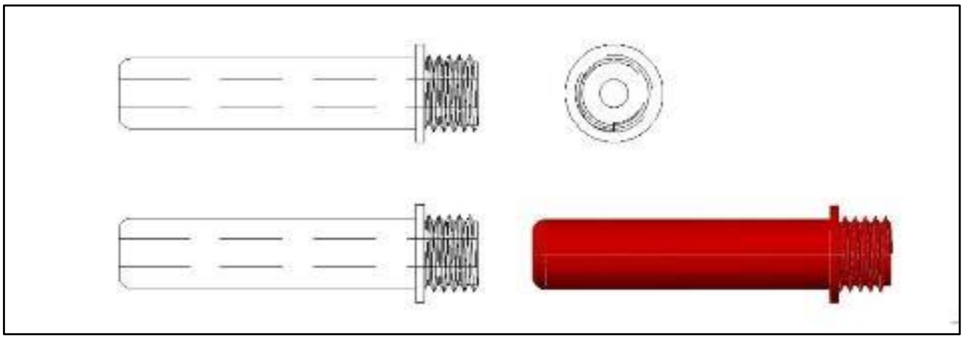

Figure 10 2D Drafting of Engine Valve Guide

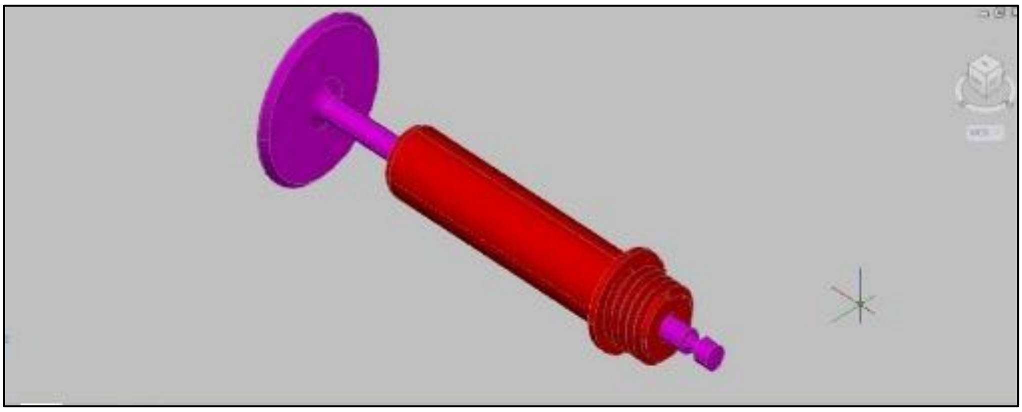

Figure 11 Assembling Models of Engine Valve and Guide

2.5. Economic Evaluation of Hybrid Composite

Target service time	= 4000 hours
Grey cast iron cost per guide	= 28
Life of grey cast iron guide	= 1000 hours
Hybrid composite cost per guide	= 95
Life of composite per guide	= 4000 hours
Downtime cost per replacement	= 50

2.5.1. Define core formula and compute number of guides required

Number of grey cast iron guides required = T/L

= 4000/1000 = 4

Number of composite guides required = 4000/4000 =1

These values give the expected counts of parts need to cover 4000 hours on an average basis.

2.5.2. Compute life cycle cost before downtime

Life cycle cost without downtime = N*C

Life cycle cost of grey cast iron valve guide = 4*28 = 112

Life cycle cost of composite valve guide = 1*95 = 95

Thus, on pure purchase or manufacture cost alone over 4000 hours, grey cast iron cost is 112 and the composite cost is 95

2.5.3. Include downtime

In each replacement causes downtime cost add to T/L

Grey cast iron engine valve guide total with downtime = 112 + (4*50)

= 312

Total cost of composite with downtime = 95+50

= 145

2.5.4. Fuel or operating savings

Composite density = 2.7 g/cm^3

Grey cast iron density = 7.2 g/cm^3

Fuel savings = Weight difference * Fuel cost per kg of load per hour * Total operating hours

Mass of grey cast iron valve guide = 0.15 kg

Mass of composite guide = 0.055 kg

Weight difference = 0.15-0.055= 0.095 kg

For four cylinder engine total difference = 0.38 kg

On average 10kg reduction of vehicle weight can improve fuel economy about 0.1 to 0.3%. Scaling this, a 0.38kg reduction might save 0.01% of fuel.

If fuel cost is 100 per liter and the engine consume 5litre/hour then the 4000 hour fuel cost

= 4000*5*100

=200,000

0.01% of 200,000 = 20

The efficiency benefits plus reduced friction from graphite additionally 0.01 to 0.02%. so the overall total saving cost reach up to 40 over 4000 hours.

Total composite net = 145 - 40

=105

In case of grey cast iron guides has no comparable fuel saving, so its remains 312.

2.5.5. Final remarks

The steps demonstrate why the composite is economically attractive over 4000 hours. The greater service life reduce replacement frequency, downtime and net operating savings.

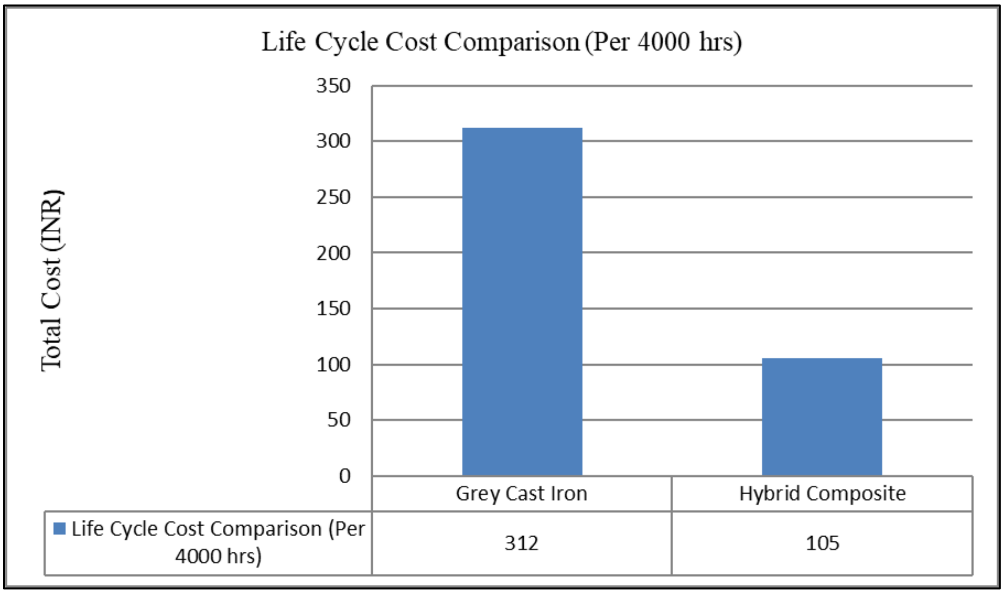

Figure 12 Life Cycle Cost Comparison

2.6. Comparison of Results and Suggestion of Best Material for Engine Valve Guides

The comparative study between grey cast iron and the developed hybrid composite shows clear difference in mechanical, tribological and economic performance. Grey cast iron exhibits an ultimate tensile strength of around 150 to 200N/mm^2, Vickers hardness range between 180 and 220 HV and relatively high specific wear rate under increasing loads. While it is widely used due to its low cost and easy machinability, its shorter service life and high wear rate make it less reliable for extend operation.

On the other than the hybrid composite reinforced with 15% of Al_2O_3 and 5% of graphite displayed significantly improved results. The tensile strength reached around 200N/mm^2 to 300 N/mm^2 and the hardness increased to 90 – 130 HV and specific wear rate remained much lower across all tested loads. It demonstrates the excellent resistance to wear. Furthermore, the presence of graphite contributes to self-lubricating behaviour, reducing friction and improving durability. In addition, life cycle cost analysis revealed that although the composite has higher initial cost but its gives longer service life and lower replacement frequency reduce the overall cost per hour of operation compare to grey cast iron.

2.6.1. Suggestion of best material

Based on the combined results of mechanical properties, wear resistance and cost analysis, the Al6061/Al_2O_3/Graphite hybrid composite is suggested as the most suitable material for engine valve guide applications. It not only offers higher strength and hardness but also ensures superior wear resistance and reduces maintenance requirements. The improvement in life cycle cost efficiency further support its adoption as a replacement for grey cast iron, especially in modern engines where performance, durability and fuel efficiency are critical.

3. Conclusion

The comparative evaluation between grey cast iron and hybrid composite has shown that while grey cast iron remain cost effective and widely available but it suffers from high wear rate and shorter service life under loading condition. In contrast the hybrid aluminium composite demonstrated superior tensile strength, hardness and much lower specific wear rate along favorable life cycle cost benefits due to its reduced replacement frequency. These finding suggest that hybrid composites are promising alternative for engine valve guide applications, offering improved durability, reliability and overall economic efficiency.

Future research is recommended to validate these composite in real world engine environments. Future scope include investigating fatigue and thermal resistance under cyclic loading, conducting large scale manufacturing trial to assess casting quality and machining behaviour and performing long duration engine test to confirm tribological performance under practical lubrication condition. Exploration of other reinforcement combinations, such as SiC or B_4C with graphite may also provide additional pathways for optimizing composite performance in high stress automotive components.

Compliance with ethical standards

Disclosure of conflict of interest

Declare that there is no conflict of interest regarding the publication of this research. This work was conducted independently and no financial, commercial or personal relationships influenced the research, analysis or conclusion in this study.

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