

Exploring the Wear Characteristics of Aluminum Matrix Composites

Ch Sandeep¹, K Rajesh², B. Vamshi Krishna³, M. Srisailam Goud⁴, B. Sai Kumar⁵ and
Jatoth Heeraman^{6*}

¹Associate Professor, Department of Mechanical Engineering, Institute of Aeronautical Engineering, Hyderabad – 500043,
Telangana, India.

^{2,3,4,5}Students of Mechanical Engineering Department, Institute of Aeronautical Engineering, Hyderabad – 500043,
Telangana, India.

⁶School of Mechanical Engineering, Lovely Professional University, Phagwara-144411, Punjab, India.

^{*}Corresponding Author: Jatoth Heeraman (heeramanj@gmail.com)

HIGHLIGHTS

- Examined the wear properties of an Al-23wt.% SiC alloy reinforced with varying weight percentages of Al₂O₃ and SiC particles.
- A pin-on-disc device was utilized to conduct dry sliding wear tests under different load conditions and testing parameters.
- The experimental setup utilized a conventional L9 orthogonal array to achieve optimal wear testing. assessed the impact of testing factors on WR, SWR, and COF.
- Conducted statistical validation procedures to compare experimental results with predicted outcomes through confirmation testing.
- The mechanism of wear resistance in aluminum composites is determined through identification of mechanical mixed-layer development.

Abstract: This research assesses wear characteristics of an aluminum composite, in response to global demands for weight, cost, strength, quality, and productivity, materials have transitioned from refined forms to composite structures. The study examined stir casting of an Al-23wt.% Si alloy incorporating 2, 4, and 6 wt.% Al₂O₃, as well as 5, 10, and 15 wt.% SiC. The tribological characteristics of unreinforced alloys and composites were examined under dry sliding conditions and different loads using a pin-on-disc device, a standard L9 orthogonal array is utilized in these tests. The wear rate, SWR, and COF of aluminum composites can be analyzed by investigating influence of testing parameters. Minimizing wear on aluminum composite dry slides necessitates thorough testing under specific conditions, confirmation test compares experimental and forecast statistical results. Mechanical mixed-layer growth will be identified to determine the wear resistance of composites.

Keywords: Stir Casting, Composites, Tribological characteristics, Wear test, Pin on Disc

INTRODUCTION

The increasing demand for lightweight, high-strength materials in various industries, particularly automotive and aerospace, has driven significant research into aluminum composite materials [1-3]. Aluminum alloys, known for their lightweight nature, are often reinforced with ceramic particles like Al₂O₃ and SiC to enhance their mechanical properties, including wear resistance [4-6]. The study provides a comprehensive analysis of the wear characteristics of aluminum composite materials, focusing on the experimental methodologies, key findings, and areas requiring. Tribology is the study and technology of interacting surfaces in relative motion as well as related fields and activities. The study and application of friction, wear, and lubrication concepts are all included in tribology. Greek word "tribos," which meaning "rubbing"[19].

Selecting and Developing the Materials

The stir casting process is commonly employed to produce aluminum composites [7-9], integration of reinforcing particles (Al₂O₃ and SiC) into the molten aluminum alloy (Al-23wt.% Si). The precise weight percentages of these reinforcements are critical for determining composite's ultimate mechanical and tribological characteristics [11-12]. Al₂O₃ and SiC exhibit significant strength and wear resistance, making them suitable candidates for enhancing the performance of aluminum matrix [5, 13]. It is essential to carefully control the distribution and bonding of these particles during fabrication, as these factors significantly influence overall performance [14],

[9]. Achieving consistent wear behavior necessitates a composite characterized by high homogeneity [7]. Wear testing may identify localized stress concentrations and premature failure resulting from uneven particle dispersion [14].

Analysis of Wear Mechanisms and Microstructural Characteristics

To optimize performance of aluminum composites, it is essential to understand their wear processes [1-2], abrasive wear, adhesive wear, and fatigue wear can occur simultaneously [4]. The interaction of hard particles embedded in counter face with aluminum composite results in abrasive wear, High adhesive pressures result in material migration between sliding surfaces, a phenomenon referred to as adhesive wear. Crack initiation and development result from fatigue wear, induced by cyclic loading and tension [15], scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are two microstructural analysis methods commonly employed to investigate worn surfaces and identify primary wear mechanisms [5]. These methods allow for precise determination of MML, surface roughness, and the presence of fractures or other flaws [19].

Impact of Reinforcement and Assessment Standards

The wear properties of Al-23wt.% SiC alloy are significantly influenced by the weight percentages of Al₂O₃ and SiC additions, addition of reinforcing particles has been shown to enhance wear resistance, as evidenced by numerous studies. The ceramic particles exhibit greater toughness and strength compared to the aluminum matrix, which accounts for this phenomenon, agglomeration and porosity resulting from excessive reinforcement addition may diminish mechanical and tribological properties of the material [7]. The intended use and characteristics inform the optimal reinforcing weight percentage, as noted in several sources, including [2], [4], [1], and [15]. The applied load is a significant factor influencing the wear of aluminum composites during pin-on-disc testing, heavier weights lead to increased contact pressure and stress, resulting in higher wear rates and coefficients of friction (COR). Conversely, wear and friction tend to decrease with reduced loads, Higher wear rates are frequently linked to increased sliding speeds, considering complex interactions among these factors and the material composition is essential when designing the experiment [4, 1, 15, 2].

Methodology

2.1 Stir Casting

Stir casting is a process used to produce metal matrix composites (MMCs), particularly those combining aluminum with various reinforcement materials. This technique involves stirring the reinforcement materials into a molten metal matrix to achieve a homogeneous distribution of the reinforcements [20].

1. Preparation

- Selection of Materials: Choose an aluminum alloy as the matrix metal and select appropriate reinforcement materials (e.g., ceramics like silicon carbide or alumina, or metallic particles).
- Cleaning: Ensure that the aluminum and reinforcement materials are clean and free of contaminants. The surfaces should be free from oxidation and other impurities [21].

2. Melting

- Heating: Melt the aluminum alloy in a furnace. The temperature must be high enough to fully liquefy the aluminum but controlled to avoid oxidation and other potential issues.
- Degassing: Remove any trapped gases in the molten aluminum to prevent defects in the final composite. This can be done using degassing agents or techniques like mechanical stirring or vacuum.

3. Stirring

- Introducing Reinforcements: Once the aluminum is molten and at the desired temperature, the reinforcement materials are added.
- Mechanical Stirring: Use a stirring mechanism to mix the reinforcement particles uniformly throughout the molten aluminum. This step is crucial for achieving a uniform distribution of the reinforcements.[22]
- Stirring Parameters: Control the stirring speed, duration, and temperature to ensure good dispersion of the reinforcements and to avoid premature solidification.

4. Casting

- Mold Preparation: Prepare the casting molds, which can be sand molds, metal molds, or other types suitable for the intended product.

- Pouring: Pour the stirred melt into the prepared molds. The temperature and flow rate must be controlled to minimize defects such as cold shuts or porosity.[23]

5. Solidification

- Cooling: Allow the composite to cool and solidify. The cooling rate can affect the microstructure and properties of the final product.[24]

6. Post-processing

- Machining: Perform any necessary machining or finishing operations to achieve the desired final shape and surface finish.
- Inspection: Conduct quality checks to ensure the composite meets the required specifications in terms of mechanical properties and appearance.

Stir casting is widely used in the aerospace, automotive, and manufacturing industries due to its ability to enhance the mechanical properties of aluminum, such as strength and wear resistance, by incorporating reinforcements.[25]

2.2. Pin-On-Disk (POD) Abrasion Testing

This kind of wear testing equipment is used to measure tribological characteristics like wear and friction. The pin on disk test is the most appropriate of numerous tribometer types used to measure materials for friction and wear its presented in fig 1. The method's popularity is due to its abundance of tribological contacts, which may be simply represented by a pin on disk motion, and its relative simplicity. These contacts include lubricated biological implant contacts, rail wheels, dry bolt screw connections, and rail contact. The pin-on-disc test rig gets its name from the fact that a pin is pressed up against a revolving disc. Using a loading lever with a weighted pan which allows it to add dead weights as needed load is imparted to the specimen (pin). Abrasive wear occurs between the moving parts because of the pin being forced up against the disc when the pressure is applied. With the aid of sensors, the wear and frictional force are determined. The data is then sent to the system, which already has software installed. This allows us to acquire the graphs of the wear rate and coefficient of friction it shown in their part in fig. 2. The program itself allows for a comparison of the generated graphs [26-28].



Figure.1: Pin/Ball on Disc Tester

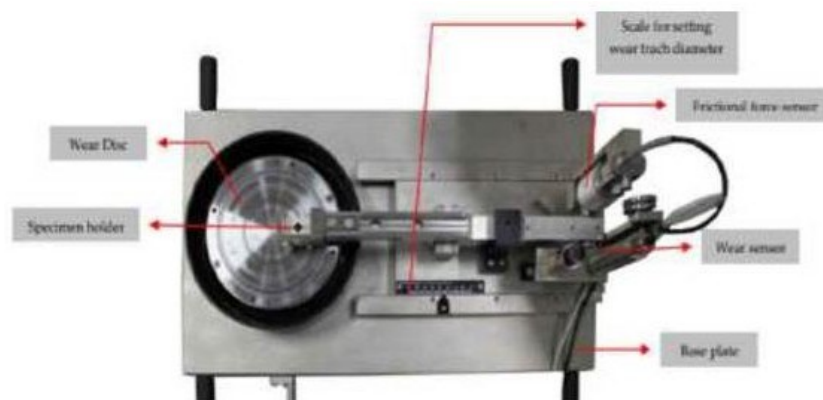


Figure.2: Pin on Disc Parts

- LVDT sensor measures the wear generated.
- Load cell measures the frictional force.
- Proximity sensor senses the speed of the disc.

Test circumstances and important parameters for the pin-on-disk wear test rig is that it works by pressing two surfaces against one another to set up a rubbing experiment. Nonetheless, it seems that a variety of factors might affect the test outcomes, thus the specific test design must closely resemble the real tribological interaction that is being studied. When creating a pin-on-disk wear test, the following elements need to be considered [29-30].

2.3. Procedure

Pin shape: The pin can be of either of the shapes that are suitable for the test, i.e., it can be a cylindrical pin with hemisphere head or a pin with ball a send.

2.3.1. Pin Alignment: This part of the experiment plays important role, because if we do not set the pin correctly, misalignment can take place and because of that non uniform loading will act on the pin, hence it directly shows effect on the test results.

2.3.2. Pin material: The material selected for the pin is very important. It needs to be considered that typically, the behavior of tribological properties of the same material is different by their use i.e. if that material is used for the pin or the material is used for the plate. It is practically true for the contact between soft and hard materials. This discrepancy results from the wear primarily occurring on softer materials. If the ball on the disc case is considered, a softer ball will wear down more quickly and generate a flat-on-flat contact with a pressure profile that differs greatly from the first one. If the disk is softer, plowing wear will happen and a groove will form on the disk.

2.3.3. Pin location: Generally, in this experiment the pin is pressed against the rotating disc. As a result of the abrasion the material on the softer material is removed and falls down because of gravity it values are presented in table 1 [31-32].

Table 1: Machine specifications

Machine Specifications	
Specimen pin size	Ø6mm, Ø8mm, Ø10mm, Ø12mm
Wear disc size	Ø160mm x 8mm thick
Wear track diameter	Ø60- Ø80mm
Disc speed	500-1000 rpm
Normal load	10N-100N
Frictional force	0N-50N
Wear	0µ-1500µ

2.4. Material selection

The selection of material that is to be studied plays a pivotal role in the entire process. The materials that are to be studied are pure aluminum (Al), Aluminum composition1, Aluminum Composition2. These materials have applications such as gears, camshafts, crankshafts and piston pins. Aluminum composition1: Aluminum Oxide 2wt% (Al_2O_3) Silicon Carbide 5wt% (SiC) Aluminum Silicon 93wt% (Al-Si). Aluminum Composition2: Aluminum Oxide 4wt% (Al_2O_3) Silicon Carbide 10wt% (SiC) Aluminum Silicon 86wt% (Al-Si) [33-35].

2.3. Sample Preparation

The specimen (pin) for the test is made with the help of the dimensions of the standard specimen that is provided with the test rig.

The dimensions are:

Total length of specimen=32mm

Radius of curvature of sample head (hemi sphere) =5.13mm Depth of sample head=4mm

Diameter of sample=10mm

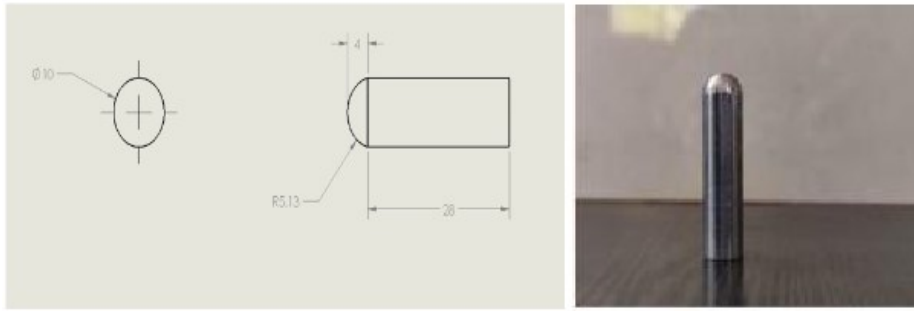


Figure.3: Sample specimen

The specimen prepared on the CNC lathe machine and three samples for each material are made. First raw material of cylindrical shape is turned down to 11mm diameter. Again, the sample is fixed in the spindle; the contour turning is done for 4mm length with 5.13mm radius of curvature and 10mm diameter test rig and experimentation are presented in fig. 4-7. The rest is turned down to 10mm diameter it presented in fig. 3 and test conditions are presented in table 2.

2.4. Working procedure on pin on disc

2.4.1. Machine setup

1. Check all the power connections and switch on the power supply.
2. Turn on the MCB on the test rig and on the controller unit.
3. Move the sliding block under the loading lever, press the start button on the controller, by revolving the rpm knob set the rpm to required value and press stop button on controller.
4. Clean the disc with the help of acetone. Fix the specimen in the hardened jaws with the help of Allen keys and adjust the height of the specimen as well.
5. Adjust the wear track diameter (WTD) by losing the studs on the lower end, and then fix it.
6. Apply the required load on weight pan with the help of dead weights.
7. Set the time duration of the test on the controller unit.

2.5 Test Parameters

Table: 2 Test conditions followed

Parameter	Pure Al	Al composition1	Al composition2
Load (N)	30	30	30
Speed (RPM)	500	500	500
WTD (mm)	80	80	80



Figure.4: Pin on disc Test Rig

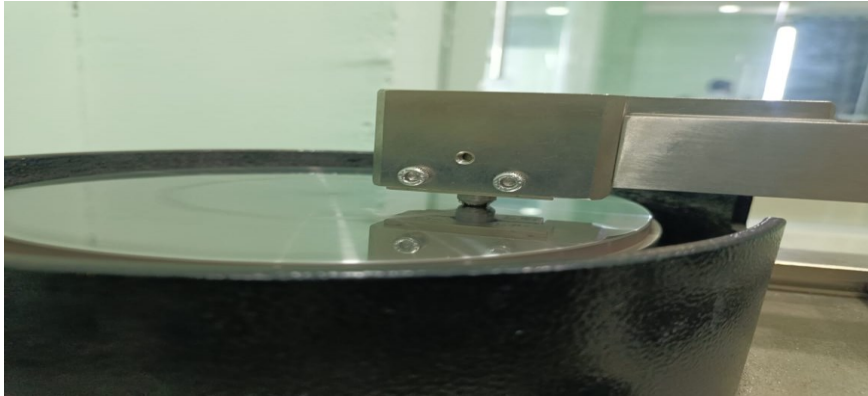


Figure.5: Experimentation
RESULTS



Figure 6: Pin/Ball on disc tester readings

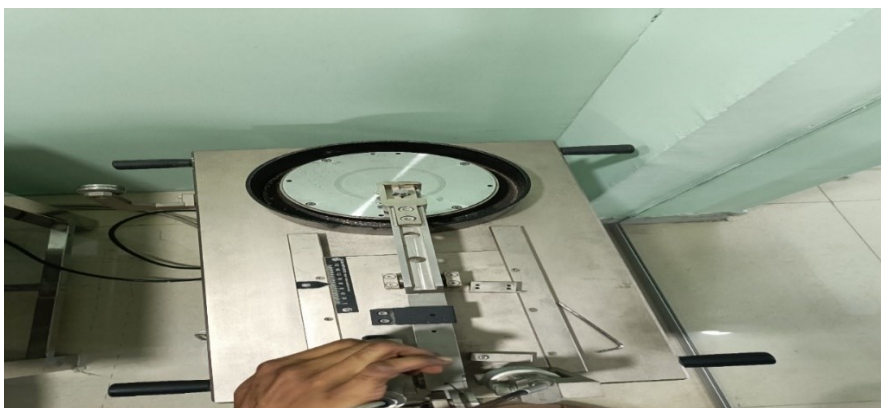


Figure 7: Testing on pin/ball on disc test rig

3.1. Pure Aluminum wear.

Referring to fig. 8, it is concluded that the wear and frictional force of Pure Aluminum material at 30N load and 500rpm ranges between $0\mu\text{m}$ and $720\mu\text{m}$, and the friction force is in between 9N and 16N. From the graph, it is observed that wear is high at the start, and it gradually becomes constant.

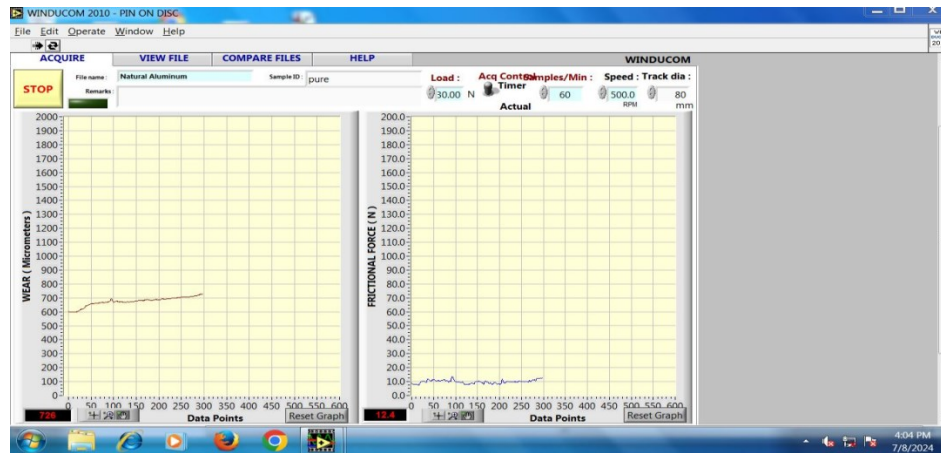


Figure 8: Graph of Pure Al at 30N, 500rpm and 80WTD

3.2. Al composition1 wear.

The wear is gradually increasing and the rate of wear ranges from 100 μ m to 850 μ m at a load of 30N and 500rpm, whereas the frictional force ranges from 18N to 8N. From the below mentioned graph it is observed that the wear rate is gradually increasing, and the friction force is constant throughout the experimentation for this specimen it shown in fig. 9.

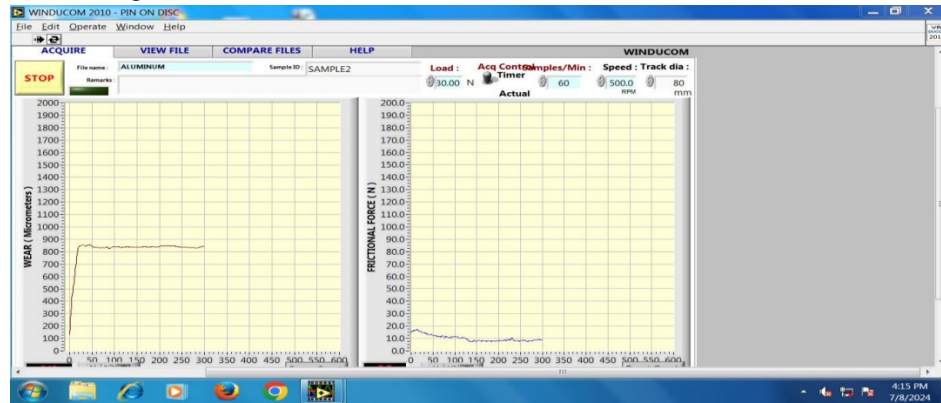


Figure 9: Graph of Al Composition1 at 30N, 500rpm and 80WTD

3.3. Al composition2 wear

At a load of 30N and 500rpm the wear rate is increased at the beginning, but as the time passes it came to constant, and as of coefficient of friction, it is mostly uniform throughout the experiment. The wear rate ranges from 0 μ m to 875 μ m, and the frictional force is at an average of 12N for this sample it shown in fig. 10.

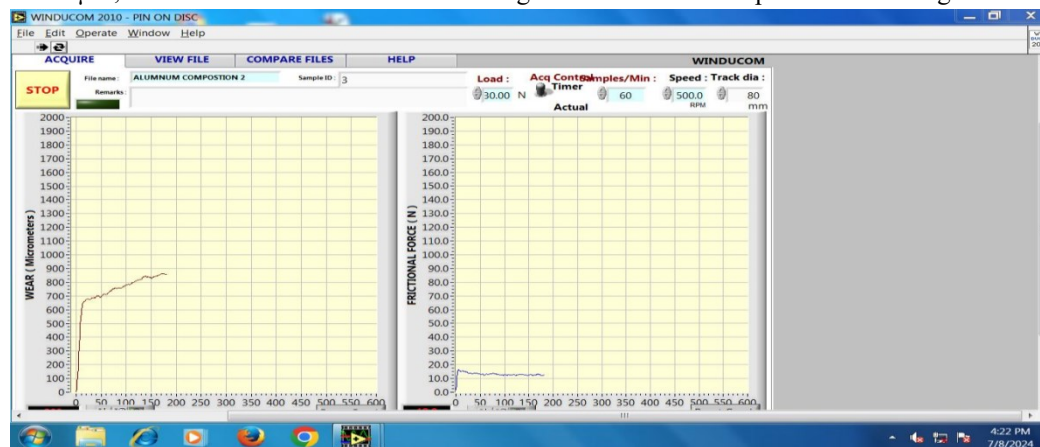


Figure 10: Graph of Al composition2 at 30N, 500rpm and 80 WTD

DISCUSSION

This study examines wear, frictional forces, and other tribological parameters under dry conditions using a disc subjected to varying loads, speeds, and wear tracks for pure aluminum (Al), aluminum composition1, and

aluminum composition². Pin diameter is measured on disc tribometer, and graphs for coefficient of friction (COF) and wear rate (WR) were constructed, leading to conclusions. The coefficient of friction (COF) exhibits a rapid increase at the onset of the test, stabilizes at a plateau, and subsequently demonstrates minimal variation. The wear rate exhibits a continuous increase throughout the test, ultimately stabilizing within a defined range. Al composition² demonstrated a consistent grip on wear rate variation compared to the other tested samples, establishing it as the superior material among the three. The highest-composition aluminum demonstrates superior stability and technical value.

Statements and Declarations

Ethics approval

The paper has been submitted with full responsibility, following the due ethical procedure, and there is no duplicate publication, fraud, or copying. There are no financial or personal interests.

Data Availability Statement

Since no new data were collected or examined for this study, data sharing does not apply to this article.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Credit Author Statement

Author have contributed significantly to the research and preparation of this manuscript.

- **Ch Sandeep:** Visualization, Resources, Funding Acquisition, Project Administration, Writing – Review & Editing.
- **K Rajesh:** Formal Analysis, Writing Review & Editing,
- **B. Vamshi Krishna:** Conceptualization, Methodology, Investigation, Writing Original Draft, Supervision,
- **M. Srisailam Goud:** Formal Analysis, Methodology, Investigation, Writing Original Draft,
- **B. Sai Kumar:** Methodology, Investigation, Writing Original Draft, Experimentation, Formal Analysis
- **Jatoth Heeraman:** Data Curation, Experimentation, Formal Analysis, Writing Review & Editing,

Funding Declaration

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing Interests Declaration

The authors declare no competing interests.

REFERENCES

- [1] Parveez, Bisma, Kittur, M.I., Badruddin, Irfan Anjum, Kamangar, Sarfaraz, Hussien, Mohamed, and Umarfarooq, M. A.. 2022. "Scientific Advancements in Composite Materials for Aircraft Applications: A Review". Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/polym14225007>
- [2] Czerwiski, Frank. 2021. "Current Trends in Automotive Lightweighting Strategies and Materials". Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/ma14216631>
- [3] Wazeer, Adil, Das, Apurba, Abeykoon, Chamil, Sinha, Arijit, and Karmakar, Amit. 2022. "Composites for electric vehicles and automotive sector: A review". Elsevier BV. <https://doi.org/10.1016/j.geits.2022.100043>
- [4] Heeraman, Jatoth, Ravinder Kumar, Prem Kumar Chaurasiya, Tikendra Nath Verma, and Davendra Kumar Chauhan. "Optimisation and comparison of performance parameters of a double pipe heat exchanger with dimpled twisted tapes using CFD and ANN." *Proceedings of the Institution of*

- Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* (2024): 09544089231223599.
- [5] Borawski, Andrzej. 2020. "Conventional and unconventional materials used in the production of brake pads review". De Gruyter. <https://doi.org/10.1515/secm-2020-0041>
- [6] Huang, Zhiping, Zhao, Wenjie, Zhao, Wenchao, Ci, Xiaojing, and Li, Wentao. 2020. "Tribological and anti-corrosion performance of epoxy resin composite coatings reinforced with differently sized cubic boron nitride (CBN) particles". Springer Nature. <https://doi.org/10.1007/s40544-019-0329-8>
- [7] Ramesh, M., Rajeshkumar, L., Srinivasan, N., Kumar, D. Vasanth, and Balaji, D.. 2022. "Influence of filler material on properties of fiber-reinforced polymer composites: A review". De Gruyter. <https://doi.org/10.1515/epoly-2022-0080>
- [8] Heeraman, Jatoth, R. Kalyani, and Banoth Amala. "Towards a sustainable future: Design and fabrication of a solar-powered electric vehicle." In *IOP Conference Series: Earth and Environmental Science*, vol. 1285, no. 1, p. 012035. IOP Publishing, 2024.
- [9] Santhosh, N., Nagegowda, Kempaiah Ujjaini, Kumar, Anand, Alamri, Sagr, Afzal, Asif, Thakur, Deepak, Kaladgi, Abdul Razak, Panchal, Satyam, and Saleel, C. Ahamed. 2021. "Influence of the Fly Ash Material Inoculants on the Tensile and Impact Characteristics of the Aluminum AA 5083/7.5SiC Composites". Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/ma14092452>
- [10] Ate, Burhan, Kytepe, Sleyman, Ulu, Ahmet, Grses, Canbolat, and Thakur, Vijay Kumar. 2020. "Chemistry, Structures, and Advanced Applications of Nanocomposites from Biorenewable Resources". American Chemical Society. <https://doi.org/10.1021/acs.chemrev.9b00553>
- [11] Heeraman, Jatoth, Ravinder Kumar, Prem Kumar Chaurasiya, Naveen Kumar Gupta, and Dan Dobrotă. "Develop a new correlation between thermal radiation and heat source in dual-tube heat exchanger with a twist ratio insert and dimple configurations: an experimental study." *Processes* 11, no. 3 (2023): 860.
- [12] Abazari, Somayeh, Shamsipur, Ali, BakhsheshiRad, Hamid Reza, Ismail, Ahmad Fauzi, Sharif, Safian, Razzaghi, Mahmood, Ramakrishna, Seeram, and Berto, Filippo. 2020. "Carbon Nanotubes (CNTs)-Reinforced Magnesium-Based Matrix Composites: A Comprehensive Review". Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/ma13194421>
- [13] Heeraman, Jatoth, Ravinder Kumar, Prem Kumar Chaurasiya, Hristo Ivanov Beloev, and Iliya Krastev Iliev. "Experimental evaluation and thermal performance analysis of a twisted tape with dimple configuration in a heat exchanger." *Case Studies in Thermal Engineering* 46 (2023): 103003.
- [14] Yang, Dexuan, Zhou, Yu, Yan, Xingheng, Wang, Honglei, and Zhou, Xingui. 2020. "Highly conductive wear resistant Cu/Ti3SiC2(TiC/SiC) co-continuous composites via vacuum infiltration process". Springer Science+Business Media. <https://doi.org/10.1007/s40145-019-0350-4>
- [15] Chaurasiya, Prem Kumar, Jatoth Heeraman, Sanjay Kumar Singh, Tikendra Nath Verma, Gaurav Dwivedi, and Anoop Kumar Shukla. "Exploring the combined influence of primary and secondary vortex flows on heat transfer enhancement and friction factor in a dimpled configuration twisted tape with double pipe heat exchanger using SiO2 nano fluid." *International Journal of Thermofluids* 22 (2024): 100684.
- [16] Meghwal, Ashok, Anupam, Ameey, Murty, B.S., Berndt, Christopher C., Kottada, Ravi Sankar, and Ang, Andrew Siao Ming. 2020. "Thermal Spray High-Entropy Alloy Coatings: A Review". Springer Science+Business Media. <https://doi.org/10.1007/s11666-020-01047-0>
- [17] Heeraman, Jatoth, Chinta Sandeep, and Prem Kumar Chaurasiya. "Heat transfer enhancement in double pipe heat exchanger: exploring twisted tape inserts with dimple configuration." *Journal of Thermal Analysis and Calorimetry* 149, no. 16 (2024): 8839-8856.
- [18] Mohit, H., Rangappa, Sanjay Mavinkere, Kushvaha, Vinod, Dhakal, Hom Nath, and Siengchin, Suchart. 2020. "A comprehensive review on mechanical, electromagnetic radiation shielding, and thermal conductivity of fibers/inorganic fillers reinforced hybrid polymer composites". Wiley. <https://doi.org/10.1002/pc.25703>
- [19] Upadhyay, Gaurav, Saxena, Kuldeep K., Sehgal, Shankar, Mohammed, Kahtan A., Prakash, Chander, Dixit, Saurav, and Buddhi, D.. 2022. "Development of Carbon Nanotube (CNT)-Reinforced Mg Alloys: Fabrication Routes and Mechanical Properties". Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/met12081392>

- [20] Heeraman, Jatoth, R. Kumar, and Prem Chausariya. "Heat transfer and friction factor augmentation using twisted tape in a double pipe heat exchanger: A critical review." In *AIP Conference Proceedings*, vol. 2800, no. 1. AIP Publishing, 2023.
- [21] Vaezi, Mohammad, Drescher, Philipp, and Seitz, Hermann. 2020. "Beamless Metal Additive Manufacturing". Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/ma13040922>
- [22] Egorov, Vladimir, Gulzar, Umair, Zhang, Yan, Breen, Siobhn, and ODwyer, Colm. 2020. "Evolution of 3D Printing Methods and Materials for Electrochemical Energy Storage". None. <https://doi.org/10.1002/adma.202000556>
- [23] Liu, Mingzheng, et al.. 2021. "Cryogenic minimum quantity lubrication machining: from mechanism to application". Higher Education Press. <https://doi.org/10.1007/s11465-021-0654-2>
- [24] Hassan, Muhammad Hafiz, Abdullah, Jamaluddin, and Franz, Grald. 2022. "Multi-Objective Optimization in Single-Shot Drilling of CFRP/Al Stacks Using Customized Twist Drill". Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/ma15051981>
- [25] Edalati, Kaveh, et al.. 2022. "Nanomaterials by severe plastic deformation: review of historical developments and recent advances". Taylor & Francis. <https://doi.org/10.1080/21663831.2022.2029779>
- [26] D.I. Adeyemi, A. Bolaji, O.A. Mosobalaje, J.O. Oluyemi, D.S. Moshood, Effect of Heat Treatment on Some Mechanical Properties of 7075 Aluminium Alloy, *Materials Research*, vol. 16
- [27] Heeraman, Jatoth, Laxmi A. Bewoor, Anand Bewoor, S. Kaliappan, Pravin P. Patil, and S. Socrates. "Applications of firefly algorithm in hydrology." In *AIP Conference Proceedings*, vol. 2800, no. 1. AIP Publishing, 2023.
- [28] Hoskins F., Folgar Portillo F., Wunderlin R. and Mehrabian R., Composites of Aluminium Alloys, Fabrication and Wear Behaviour, *Journal of Materials Science*, 17, 2, 1982, 477-498
- [29] Spencer D., Mehrabian R. and Flemings M., Rheological Behaviour of Sn-15 Pct Pb in the Crystallization range, *Metall. Trans.*, 3, 1972, 1925-1932
- [30] Chaurasiya, Prem Kumar, Jatoth Heeraman, Anoop Pratap Singh, K. Sudha Madhuri, and Vinod Kumar Sharma. "Numerical exploration of heat transfer and friction factor in corrugated dual-pipe heat exchangers using SiO₂ and CuO nanofluids." *Thermal Science and Engineering Progress* 56 (2024): 103076.
- [31] Ghosh P.K. and Ray S., Influence of Process Parameters on the Porosity Content in Al(Mg)-Al₂O₃ Cast Particulate Composite Produced by Vortex Method, *AFS Transactions*, 88, 1988, 775-782
- [32] Druždžel A., Friction and wear of Al-based MMCs under conditions of oscillatory relative motion, PhD thesis, Delft University of Technology, Faculty of Mechanical Engineering and Marine Technology, 1996
- [33] Jun D., Yao-hui L., Si-rong Yu and Wen-fang L., Dry sliding friction and wear properties of Al₂O₃ and carbon short fibres reinforced Al-12Si alloy hybrid composites, *Wear*, 257, 2004, 930–940
- [34] Heeraman, Jatoth, Sumit Kumar, S. Kaliappan, Pravin P. Patil, and Dheerendra Vikram Singh. "Paddy residue potential as energy resources-A critical review." In *AIP Conference Proceedings*, vol. 2800, no. 1. AIP Publishing, 2023.
- [35] Korkut M.H., Effect of particulate reinforcement on wear behaviour of aluminium matrix composites, *Materials Science and Technology*, 20, 1, Jan 2004, 73-81