Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 2, No. 4, February : 2024

# ENHANCING Ti-6Al-4V DRILLING EFFICIENCY: OPTIMIZATION THROUGH HYBRID NANOFLUID LUBRICATION AND MICROSTRUCTURAL ANALYSIS

**Piyush A. Dalke,** Research Scholar, Dept. of Mechanical Engineering, Chhatrapati Shivaji Maharaj University, Panvel, Navi Mumbai, Maharashtra, India -410206.
**Dr. Atul V. Karanjkar,** Professor, Dept. of Mechanical Engineering, Chhatrapati Shivaji Maharaj University, Panvel, Navi Mumbai, Maharashtra, India -410206.
**Dr .Girish P.Deshmukh,** Professor, Dept. of Mechanical Engineering, A C Patil college of Engineering, Navi Mumbai, India- 410210. Email: piyush180114@csmu.ac.in

**Abstract:**
This study focuses on improving Ti-6Al-4V alloy drilling using a tungsten carbide tool and a hybrid nanofluid ($Al_2O_3$ and $SiO_2$) under minimum quantity lubrication (MQL). Through a systematic Taguchi mixed orthogonal array L16 design, the research explores feed rate, point angle as well as spindle speed to optimize drilling performance. The hybrid nanofluid, designed for efficient heat dissipation and lubrication, outperforms conventional MQL and dry drilling methods, showcasing reduced tool wear, superior surface quality, and environmental sustainability. The study identifies optimal conditions resulting in minimized thrust force 296 N, torque 2.04 N-m, and surface roughness 0.48 µm. Microstructural analysis validates these findings, highlighting the potential of hybrid nanofluids in refining grain structure. This research provides insights into tailoring cutting parameters and nanofluid formulations for optimal Ti-6Al-4V drilling, presenting an innovative approach to enhance metal machining processes.
**Keywords:** Hybrid nanofluids, Drilling performance, Minimal quantity lubrication (MQL), Tool wear, Surface roughness, Lubrication effectiveness

## I. Introduction
A small quantity of lubricant is used during machining processes as part of a lubrication technique called minimal quantity lubrication (MQL). In contrast to conventional flood lubrication techniques that involve inundating the cutting zone with a substantial volume of coolant, MQL employs a meticulously regulated amount of lubricant that is directly administered to the interface of the cutting tool. The implementation of this focused strategy presents numerous benefits: The implementation of MQL in machining operations has been found to have a notable positive effect on reducing the environmental impact. This is primarily due to the significant reduction in the quantity of lubricant and coolant utilized, resulting in an important reduction in waste generation and the potential for environmental contamination. Cost Savings: The implementation of MQL results in a reduction of operational expenses related to the procurement, management, and disposal of significant volumes of lubricants.
Enhanced Tool Longevity: The precise implementation of lubricant in MQL facilitates the mitigation of friction and heat production, resulting in an extended lifespan for tools and a reduction in tool degradation. The utilisation of minimum quantity lubrication (MQL) offers effective cooling as well as lubrication specifically at the cutting area, leading to enhanced surface quality and diminished work piece distortion. Productivity is raised because MQL reduces the amount of downtime needed for maintenance, clean-up, and coolant replenishment, which increases machine uptime and output. Nanofluids are colloidal suspensions consisting of nanoparticles dispersed in a base fluid, offering unique properties and potential applications as lubricants. By incorporating nanoparticles, nanofluids can enhance the lubrication characteristics of the base fluid, leading to improved performance in various industrial processes.
The combination of nanofluids with Minimal Quantity Lubrication (MQL) in drilling processes presents an intriguing opportunity. Nanoparticles dispersed in the lubricant can further enhance the

lubrication effectiveness of MQL by reducing friction, heat generation, and tool wear. This combination has the potential to improve drilling performance and overcome the limitations of traditional lubrication methods. The research aims to study the characteristics as well as performance hybrid nanofluids used in conjunction with MQL for drilling operations. The specific objectives include evaluating cutting forces, tool wear, torque, as well as surface roughness. With conducting experimental analysis, this study aim to assess the efficiency of hybrid nanofluid and provide insights into its potential as a lubricant for improved drilling performance. The research scope encompasses a comprehensive examination of the hybrid nanofluid's effects on drilling parameters and lubrication conditions to understand its practical applicability and benefits.

## II. Literature

The present study introduces a mechanics model that focuses on the deep hole gun drilling process of Ti-6A-l4V alloy. The model incorporates the Johnson as well as Cook flow stress model to accurately describe the material behaviour during drilling. The objective of this study is to carry out an analysis of the drilling process in order to anticipate the cutting forces, temperature distribution, and hole quality that occur during gun drilling[1].The aim of this study is to examine methods for improving the efficiency of cutting during high speed drilling Ti6Al4V. This is achieved by incorporating internal cooling mechanisms and micro-groove textures into carbide twist drills. The experiments aim to evaluate and compare the performance of textured drills in relation to conventional drills. This evaluation involves the assessment of various factors, including tool wear, surface roughness, as well as cutting forces [2].The main aim of this experimental study is to analyse the utilisation of micro electrical discharge machining (EDM) drilling method on Ti6Al4V material employing a helical electrode. This study aim to examine the influence of different process parameters, including discharge current, pulse duration, and rotational speed, on the drilling act and quality of holes [3]. The objective of this study is to examine the machinability of Carbon Fibre Reinforced Polymer (CFRP)/Ti6Al4V stacks during drilling operations, as well as the resulting quality of the drilled holes. The investigation focuses on the influence of different cooling conditions on these aspects. The experiments assess the cutting forces, delamination, and hole quality by employing various cooling techniques, including flood cooling, Minimum Quantity Lubrication, as well as cryogenic cooling [4].

The current study aims to examine process of micro-hole drilling in Ti6Al4V through the utilisation of a sequential electro micro machining (SEMM) system. The SEMM (Single Edged Micro Milling) development is presented since a technique for the fabrication of micro holes in Ti6Al4V material. Examining the effects of various process parameters on drilling performance, material removal rate, and hole quality is the aim of this study [5]. The primary aim of this study is to acquire a thorough comprehension of the chip formation process and the subsequent quality of holes in the specific context of dry drilling of additive manufactured Ti6Al4V. The purpose of this study is to investigate how chip morphology, cutting forces, with hole quality are affected by cutting parameters, specifically cutting speed, feed rate, as well as drill diameter. [6].

The present study presents an analytical model that aims to forecast the occurrence of exit burrs during the drilling process of Ti6Al4V alloy. The proposed model integrates multiple factors, including cutting parameters, tool geometry, and material properties, in order to forecast the dimensions and morphology of exit burrs that arise during the drilling process [7]. In the particular context of drilling CFRP- Ti6Al4V stacks, this research paper compares and contrasts vibration-assisted and conventional drilling techniques. This study examines the effects of cutting forces, delamination, and hole quality in laminated structures made of titanium alloy (Ti6Al4V) and carbon fiber reinforced polymer (CFRP) on vibration frequency, amplitude, and tool geometry. [8]. This study's main goal is to look into cutting responses and assess the effects of different drilling sequences in stacks made of titanium (Ti) and carbon fibre reinforced polymer (CFRP). The purpose

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 2, No. 4, February : 2024
of the experiments is to assess the way various drilling sequences affect the cutting forces, delamination, and hole quality in stacks made of titanium (Ti) and carbon fiber reinforced polymer (CFRP)[9].
In order to assess the thermal effects of the Ti6Al4V alloy encountered during the drilling process, a numerical model was developed. The model examines the thermal effects on the material during drilling, accounting for heat generation, heat transfer, and workpiece temperature distribution.[10]. This work looks into how Minimum Quantity Lubrication (MQL) affects the rate at which tool wear develops during low-frequency vibration-assisted CFRP/Ti6Al4V stack drilling. With the use of vibration assistance, this study examines the impact of Minimum Quantity Lubrication (MQL) parameters on cutting forces, tool wear, and hole quality in carbon fiber-reinforced polymers (CFRP)/Ti6Al4V stacks during drilling operations [11].
The present study aims to evaluate the thermal effects that occur during the dry drilling process of Ti6Al4V. This study employs analytical and numerical techniques to examine the process of dry drilling, with the aim of predicting temperature elevation, reduction in forces, and the resulting quality of the drilled hole. These predictions are made by considering the thermal properties of the material being drilled and the specific cutting conditions employed [12].This study examines the microstructural properties of Ti6Al4V during the process of laser drilling, with a specific focus on the influence of magnetic field strength and ultrasonic vibration amplitude. This study investigates the effects of ultrasonic vibration and magnetic field on the quality of holes, thickness of recast layer, and micro structural alterations in Ti6Al4V [13].
Electrodes with a rotating shape are used in the study of self-flushing in Ti6Al4V EDM drilling [14]. The aim of this research is to examine how the self-flushing mechanism affects hole quality, tool wear, and debris removal in Ti6Al4V EDM drilling.This experimental study's primary goal is to investigate the use of abrasive waterjet cutting during drilling operations on stacks made of titanium alloy (Ti6Al4V) and carbon fiber reinforced polymer (CFRP). The purpose of this study is to find out the way various abrasive waterjet cutting parameters affect delamination, cutting forces, and hole quality in CFRP/Ti6Al4V stacks. Three parameters are being considered: abrasive flow rate, standoff distance, and pressure [15].
Nanofluids' effects on drilling performance metrics like cutting forces, tool wear, roughness of the surface, along with hole quality are studied. The goal of the study is to comprehend how the composition of SiO2 and Al2O3 nanoparticles in nanofluids affects the effectiveness of drilling. Finding the ideal nanoparticle composition to improve drilling performance is the aim. Nanofluids' potential benefits and drawbacks across industries are examined by analysing their impact on drilling parameters.

## III. Experimental Methodology

Experiments with drilling were carried out with the assistance of a vertical machining centre (VMC) that featured a spindle RPM range that could reach up to 8000 revolutions per minute. The VMC can handle 400 kg of weight and 7.5 kW of power at its maximum capacity. This investigation made use of an external spray system, which includes a compressor, a mixing chamber, a reservoir for lubricating fluid, and a nozzle. The angle of the nozzle, measured in degrees, was set to be 45 degrees. Throughout the entirety of the research, the rate of fluid flow was fixed at 120 millilitres per hour, and the pressure of the air supply was held constant at 6 bars. As can be seen in Figure 1, the apparatus used in the experiment consisted of a dynamometer called a Kistler, which was used to measure the amount of torque (TQ) and thrust force (TF).

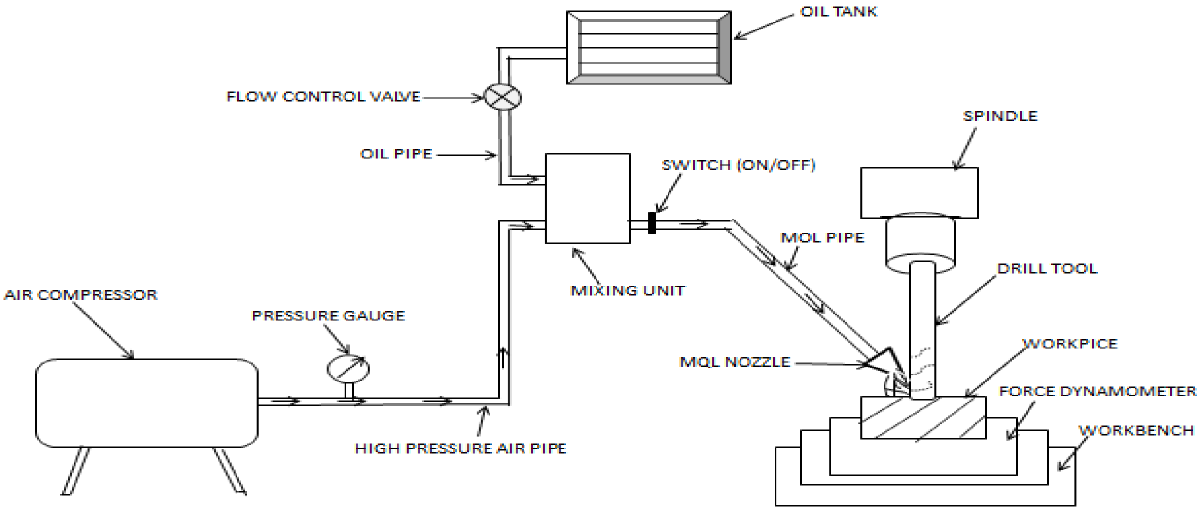


Figure 1: Drilling setup

Preparation of the hybrid nanofluids, selection of nanoparticles, and mixing techniques.The present investigation involved the synthesis of a hybrid nano-fluid through the combination of Al2O3 and SiO2 nano-powders in a proportion of 90:10, utilising distilled water as the solvent. This hybrid nano-fluid's role in the machining process was to act as a cutting fluid to reduce heat generation and friction. Beakers were filled with distilled water to a volume of 150-ml to make the nano-fluid. Al2O3 as well as SiO2 nanopowders were dissolved in water at a 1.0% weight-to-volume ratio. The mixture was subsequently subjected to sonication for three hours at a frequency of 50 Hz. The utilisation of sonication facilitated the uniform dispersion of nanoparticles within the fluid, thereby ensuring the creation of a hybrid nano-fluid that is both well-mixed and stable.

The experimental arrangement employed for the sonication procedure, showcasing the presence of a beaker containing distilled water and nano-powders. A 50 Hz frequency is used by the sonication apparatus in the illustration. To keep the conditions constant, the procedure was done at room temperature.This hybrid nano-fluid was created to reduce friction and heat and improve cutting performance and machining efficiency. This experiment involved the utilisation of four process parameters, each accompanied by their respective units and corresponding levels, as part of a study or experiment. These parameters affect cutting performance and surface quality during machining.

The first parameter is the spindle's speed, which is expressed in revolutions per minute (rev/min), which is the rate at which the spindle rotates. In the study, 900, 1200, 1500, and 1800 revolutions per minute were considered for the spindle speed. The Feed Rate, or how quickly the cutting tool moves along the workpiece, is the second parameter. A millimetre per minute (mm/min) unit is used to measure it. Four feed rate levels 20, 30, 40, and 50 mm/min are examined in the study.

The third parameter, called Point Angle, describes the angle formed by the drill bit's or cutting tool's cutting edges. The unit of measurement is denoted in degrees (°). The study incorporates two distinct levels of point angle, specifically 118° and 135°. It is worth noting that two cells within the dataset are left vacant, indicating either the omission of other point angle levels or the unavailability of their corresponding values. This study aim to understand the influence of these procedure parameter on the machining process and optimise the settings for achieving desired results, such as enhanced cutting performance and surface quality.

## IV. Results and Discussion

This work uses a Taguchi mixed orthogonal array L16 design to examine a hybrid nanofluid (90:10 Al2O3 with SiO2) under minimum amount lubrication while evaluating Ti6Al4V drilling by a tungsten carbide (WC) tools. The hybrid nanofluid, composed of Al2O3 nanoparticles and 0.1% wt. SiO2, outperforms dry conditions and alternative lubricants like graphene nanoparticles, nano-

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 2, No. 4, February : 2024

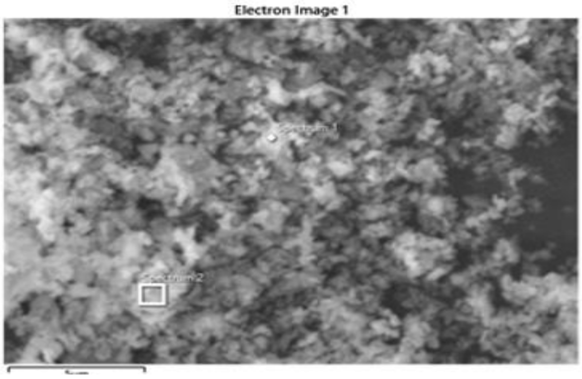
diamond particles (ND), molybdenum disulfide ($MoS_2$), and multi-walled carbon nanotubes. Surface roughness improves with increasing spindle speed, attributed to reduced built-up edge (BUE) formation, enhancing overall surface finish.As the spindle speed increases, thermal softening reduces the thrust force and torque during drilling, resulting in a decrease in these forces. However, when feed rate is noticeably increased, larger chip sizes result in increased thrust force, torque, and surface roughness. Point angles ranging from $118^0$ to $135^0$ degrees increase surface roughness but decrease thrust force and torque.

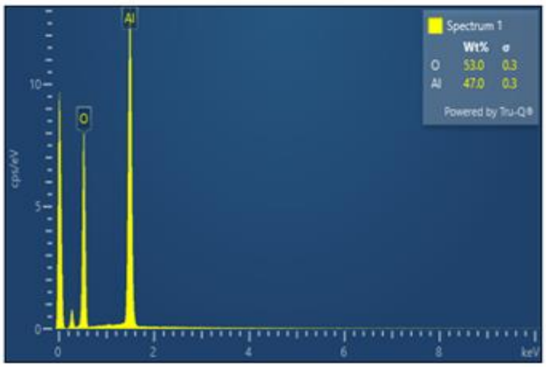
Through Taguchi method optimization, two ideal conditions are found: when the spindle speed is 1800 rpm, the feed rate is 20 mm/min, as well as the point angle is $135^0$ degrees, (N4F1D2) yields the lowest thrust force (296 N) along with torque (2.04 N-m). At a point angle of $118^0$, a distinct set (N4F1D1) produces the lowest surface roughness (0.48 µm) while maintaining the same spindle speed and feed rate. Under ideal circumstances, microstructural analysis reveals dynamic transformations that result in fine grain refinement; alternative parameters, particularly a point angle of $135^0$, cause grain distortion.

The study explores the intricate dynamics among cutting parameters, lubrication conditions, and drilling performance, with a focus on optimizing the machining process for Ti-6Al-4V using a hybrid nanofluid. SEM analysis reveals that $Al_2O_3$ nanoparticles exhibit a white non-spherical, as well as agglomerated structure with an average size of 30 to 50 nm, while $SiO_2$ nanoparticles appear spherical with an standard size ranging from 40 to 70 nm. EDS analysis demonstrates varying compositions of oxygen, aluminum, with silicon for both materials. XRD analysis confirms the crystalline nature of α-$Al_2O_3$ and the amorphous nature of $SiO_2$.

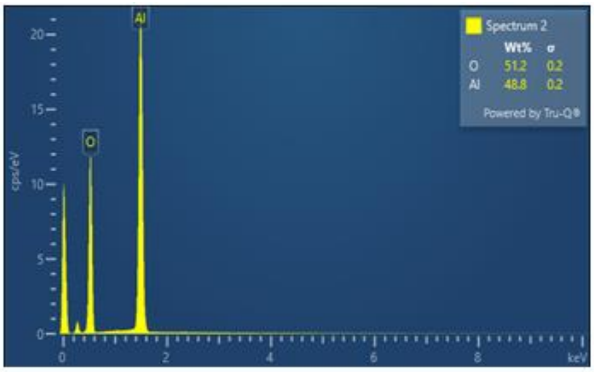
The hybrid nanofluid presents a mixed morphology, combining non-spherical, agglomerated $Al_2O_3$ nanoparticles with spherical $SiO_2$ nanoparticles. EDS examination of the hybrid nanofluids indicates a blend of oxygen, aluminum, and silicon, with varying weight percentages across different spectra. XRD analysis reveals a predominance of $Al_2O_3$ peaks over $SiO_2$, with $Al_2O_3$ peaks exhibiting higher intensities, suggesting a significant contribution of $Al_2O_3$ to the hybrid nanofluid's characteristics. Overall, the study underscores the potential of the hybrid nanofluid in enhancing Ti-6Al-4V machining processes, with further research warranted to optimize its composition and elucidate its mechanisms for industrial applications.

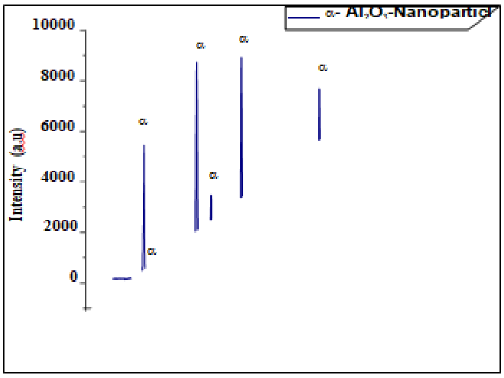
Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 2, No. 4, February : 2024



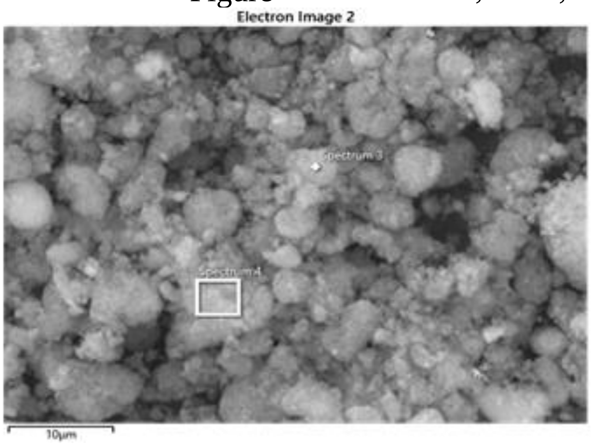

(a) Al2O3 SEM analysis (b)EDS Analysis at Al2O3 Spectrum 1

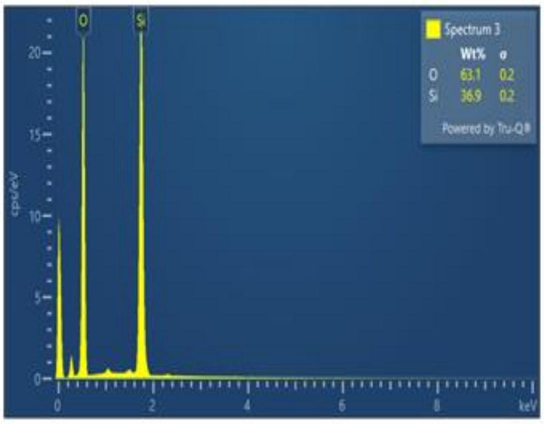


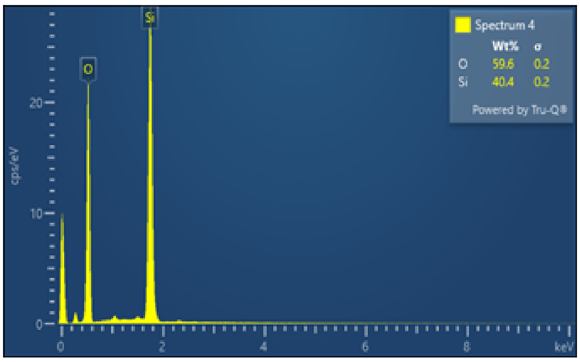

(c) EDS Examination at Al2O3 Spectrum 2 (d) XRD Examination Al2O3

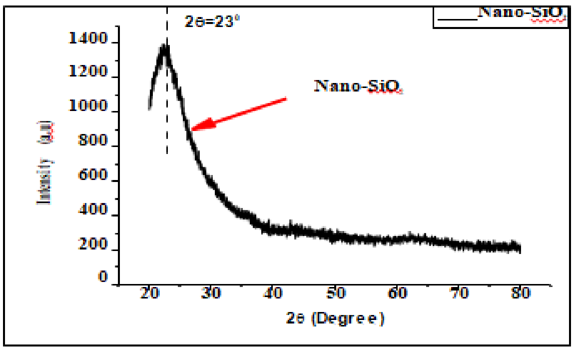
Figure 2: Al2O3 SEM, XRD, as well as EDS examination




(a)SiO2 SEM examination (b) EDS examination at SiO2 Spectrum 3




(c)SiO2 Spectrum 4 EDS examination (d)SiO2 XRD examination

Figure 3: SiO2 SEM, XRD, and EDS examination

Drilling processes generate significant heat and friction, impacting tool wear, surface finish, and overall efficiency. Traditional approaches like dry drilling and conventional MQL (min quantity lubrication) have limitations, but hybrid nanofluids offer promising advancements. This section compares these methods for a research paper, highlighting the advantages of hybrid nanofluids.

| Parameter | Dry Drilling | Conventional MQL | Hybrid Nanofluid ($Al_2O_3 + SiO_2$) |
|---|---|---|---|
| Cooling & Lubrication | Minimal, relies on heat dissipation through tool &workpiece | Limited, mainly reduces friction in contact zone | Enhanced: Nanoparticles form a thin film on the tools work-piece interface, improving heat transfer and lubrication. |
| Tool Wear | High due to high friction and temperature | Moderate, reduced friction but limited film stability | Low: Nanoparticles act as rolling bearings, minimizing wear. |
| Surface Roughness | High due to friction and tool degradation | Moderate, improved lubrication smoothens surface finish | Excellent: Stable Nano film provides exceptional surface quality. |
| Cutting Forces | High due to friction and temperature | Moderately reduced, improved lubrication lowers overall force | Significantly reduced: Nano film minimizes friction and chip adhesion. |
| Torque | High due to friction and temperature | Moderately reduced, improved lubrication lowers overall torque | Significantly reduced: Nano film minimizes friction and chip adhesion. |
| Environmental Impact | No coolant usage, but dust generation | Reduced coolant consumption, but potential environmental concerns | Eco-friendly: Minimal lubricant usage, no harmful chemicals, reduced waste. |

Overall, hybrid nanofluids like $Al_2O_3 + SiO_2$ offer significant advantages over dry drilling and conventional MQL in terms of improved drilling performance, surface quality, tool life, and environmental friendliness. However, cost and technical considerations require careful evaluation for each specific application.Under optimal conditions in Ti6Al4V drilling with a tungsten carbide (WC) tools as well as hybrid nanofluid, thrust force minimizes at 296 N, torque reduces to 2.04 N-m, and surface roughness decreases to 0.48 µm. These precise outcomes result from a delicate balance spindle speed 1800 rpm, feed rate 20 mm per min, as well as point angle. The hybrid nanofluid, featuring Al2O3-SiO2 nanoparticles, contributes to wear reduction, effective friction control, and thermal softening. Microstructural analysis validates these optimal conditions, showcasing dynamic transformations leading to fine grain refinement, underscoring the precision achievable when cutting parameters harmonize with the hybrid nanofluid's attributes.

## V. Conclusion

In conclusion, the comprehensive investigation into Ti-6Al-4V drilling processes using a vertical machining centre has provided valuable insights into optimizing performance and efficiency. The experimental setup, featuring a high-capacity VMC with an 8000 RPM spindle, an external spray system, and a Kistler dynamometer, facilitated a meticulous exploration of key parameters. The hybrid nano-fluid, synthesized by combining Al2O3 and SiO2 nano-powders in a 90:10 ratio, emerged as a promising cutting fluid, aiming to reduce heat and friction during machining.

A stable and well-mixed solution was guaranteed by the meticulous preparation of the hybrid nano-fluid, which included sonicating the mixture for three hours at 50 Hz after combining 1.0% weight-to-volume ratio of Al2O3 and SiO2 in distilled water. The analysis that follows will focus on the process parameters of spindle speed, point angle, and feed rate as well as how these affect cutting performance and surface quality. The superiority of the hybrid nanofluid (90:10 Al2O3 with SiO2) over dry conditions and alternative lubricants such as graphene nanoparticles, nano-diamond particles, molybdenum disulfide, and multi-walled carbon nanotubes was revealed by the Taguchi mixed orthogonal array L16 design.

Optimization through Taguchi method pinpointed specific conditions, such as spindle speed of 1800 rpm, feed rate of 20 mm/min, as well as point angle of $135^0$, resulting in minimal thrust force (296 N) and torque (2.04 N-m). Another set with a point angle of $118^0$ achieved minimal surface roughness (0.48 µm). Microstructural analysis confirmed the dynamic transformations leading to fine grain refinement under these optimal conditions.

Comparisons with traditional methods highlighted the remarkable advantages of the hybrid nanofluid, creating a stable nanofilm on the tool-work piece interface. This not only reduced tool wear significantly but also improved surface roughness while minimizing cutting forces and torque. The environmental friendliness of the hybrid nanofluid, marked by minimal lubricant usage and reduced waste, positions it as a sustainable and efficient solution for future metalworking applications. In summary, this research contributes nuanced understandings of cutting parameters, lubrication conditions, and their intricate interplay, emphasizing the transformative potential of hybrid nanofluids in enhancing metal machining processes.

## Acknowledgment

The authors express their gratitude to the Mechanical Engineering Department of Chhatrapati Shivaji Maharaj University, Panvel, Navi Mumbai, Maharashtra, India, for their assistance.

## References

[1] Li, L., He, N., Hao, X. Q., & Yang, Y. F. (2019). Deep-hole gun drilling mechanics model of Ti6Al4V alloy based on Johnson and Cook flow stress model. International Journal of Advanced Manufacturing Technology, 104(9–12). https://doi.org/10.1007/s00170-019-04244-6

[2] Guo, D., Guo, X., Zhang, K., Chen, Y., Zhou, C., &Gai, L. (2019). Improving cutting performance of carbide twist drill combined internal cooling and micro-groove textures in high-speed drilling Ti6Al4V. International Journal of Advanced Manufacturing Technology, 100(1–4). https://doi.org/10.1007/s00170-018-2733-z

[3] Plaza, S., Sanchez, J. A., Perez, E., Gil, R., Izquierdo, B., Ortega, N., & Pombo, I. (2014). Experimental study on micro EDM-drilling of Ti6Al4V using helical electrode. Precision Engineering, 38(4). https://doi.org/10.1016/j.precisioneng.2014.04.010

[4] Xu, J., Ji, M., Chen, M., & El Mansori, M. (2020). Experimental investigation on drilling machinability and hole quality of CFRP/Ti6Al4V stacks under different cooling conditions. International Journal of Advanced Manufacturing Technology, 109(5–6). https://doi.org/10.1007/s00170-020-05742-8

[5] Tayade, R. M., Doloi, B., Sarkar, B. R., & Bhattacharyya, B. (2020). Micro-Hole Drilling on Ti6Al4V by Sequential Electro-Micro-Machining (SEMM) Approach. Journal of Advanced Manufacturing Systems, 19(3). https://doi.org/10.1142/S0219686720500249
[6] Ming, W., Dang, J., An, Q., & Chen, M. (2020). Chip formation and hole quality in dry drilling additive manufactured Ti6Al4V. Materials and Manufacturing Processes, 35(1). https://doi.org/10.1080/10426914.2019.1692353
[7] Rana, A., Dongre, G., & Joshi, S. S. (2019). Analytical modeling of exit Burr in drilling of Ti6Al4V alloy. Sadhana - Academy Proceedings in Engineering Sciences, 44(6). https://doi.org/10.1007/s12046-019-1114-0
[8] Xu, J., Li, C., Chen, M., & Ren, F. (2019). A comparison between vibration assisted and conventional drilling of CFRP/Ti6Al4V stacks. Materials and Manufacturing Processes, 34(10). https://doi.org/10.1080/10426914.2019.1615085
[9] An, Q., Dang, J., Li, J., Wang, C., & Chen, M. (2020). Investigation on the cutting responses of CFRP/Ti stacks: With special emphasis on the effects of drilling sequences. Composite Structures, 253. https://doi.org/10.1016/j.compstruct.2020.112794
[10] Díaz-Álvarez, J., De-La-Cruz-Hernández, J. A., Díaz-Álvarez, A., &Cantero-Guisández, J. L. (2015). Numerical Modelling of the Thermal Effects on Material in Drilling Processes Ti6Al4V Alloy. Procedia Engineering, 132. https://doi.org/10.1016/j.proeng.2015.12.515
[11] Hussein, R., Sadek, A., Elbestawi, M. A., &HelmiAttia, M. (2021). The effect of mql on tool wear progression in low-frequency vibration-assisted drilling of cfrp/ti6al4v stack material. Journal of Manufacturing and Materials Processing, 5(2). https://doi.org/10.3390/jmmp5020050
[12] Díaz-Álvarez, A., De-La-Cruz-Hernández, J. A., Díaz-Álvarez, J., &Cantero-Guisández, J. L. (2015). Estimation of Thermal Effects in Dry Drilling of Ti6Al4V. Procedia Engineering, 132. https://doi.org/10.1016/j.proeng.2015.12.516
[13] Raftar, O. R., Amiri, S., Khajehzadeh, M., &Razfar, M. R. (2022). The influence of ultrasonic vibration amplitude and magnetic field intensity on microstructural characteristics in laser drilling of Ti6Al4V. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 236(5). https://doi.org/10.1177/09544062211027606
[14] Goiogana, M., &Elkaseer, A. (2019). Self-flushing in EDM drilling of Ti6Al4V using rotating shaped electrodes. Materials, 12(6). https://doi.org/10.3390/ma12060989
[15] Alberdi, A., Artaza, T., Suárez, A., Rivero, A., &Girot, F. (2016). An experimental study on abrasive waterjet cutting of CFRP/Ti6Al4V stacks for drilling operations. International Journal of Advanced Manufacturing Technology, 86(1–4). https://doi.org/10.1007/s00170-015-8192-x
[16] Kalita, P., Malshe, A.P., Kumar, S.A., Yoganath, V.G., Gurumurthy, T., Study of specific energy and friction coefficient in minimum quantity lubrication grinding using oil-based nanolubricants, J. Manuf. Process. 14 (2012) 160–166.
[17] Prabhu, S., Vinayagam, B.K., AFM investigation in grinding process with nanofluids using Taguchi analysis, Int. J. Adv. Manuf. Technol. 60 (2012) 149–160.
[18] Mao, C., Tang, X., Zou, H., Huang, X., Zhou, Z., Investigation of grinding characteristic using nanofluid minimum quantity lubrication, Int. J. Precis. Eng. Manuf. 13 (2012) 1745–1752.
[19] Mao, C., Zhang, J., Huang, Y., Zou, H., Huang, X., Zhou, Z., Investigation on the effect of nanofluid parameters on MQL grinding, Manuf. Process. 28 (2013) 436–442.
[20] Mao, C., Zou, H., Huang, X., Zhang, J., Zhou, Z., The influence of spraying parameters on grinding performance for nanofluid minimum quantity lubrication, Int. J. Adv. Manuf. Technol. 64 (2013) 1791–1799.