Investigating the Wear Mechanism of TiAlN/TiN PVD-Coated WC Inserts in End Milling of Incoloy 925 Under Synergy of Bio-Degradable Fatty Acids and Nano-Metallic Solid Lubricant

Rapid tool wear in machining difficult-to-cut material is a significant challenge since it is related to tool cost, surface integrity of machined components, and power consumption. The reduction in tool wear may be accomplished by cutting fluids, especially in modern bio-degradable fatty acids. Because of its high lubricity, coconut oil is the best choice for lubricating fatty acids. However, this oil has poor heat transfer properties. Hence, to further improve its properties, copper (Cu) nanoparticles (NPs), which have a high thermal conductivity to cost ratio compared to other nanoparticles in addition to anti-frictional and anti-wear properties (due to self-repairing properties caused by their low shear strength and easy deposition on contacting surfaces), have been dispersed in coconut oil, thus creating a nano-lubricant (nano-fluid). It is found that synthesized nano-lubricants perform better in thermo-physics and tribology than pure coconut oil. Further, research has been carried out on the combined effects of coconut oil and 0.3 vol% Cu-NPs on Incoloy 925’s end milling performance and tool wear mechanism (viz., coating delamination, adhesion, abrasion, and oxidation). It is found that tool wear-rate is reduced, which in turn increases tool life, due to effective cooling and lubrication when nano-fluid-based minimum quantity lubrication (NMQL)-assisted machining is performed rather than dry and pure oil-based minimum quantity lubrication (MQL) conditions. Consequently, energy consumption in machining and surface quality of machined components are improved. [DOI: 10.1115/1.4065239]

Keywords: fatty acids, nano-metallic solid lubricant, NMQL, tool wear mechanism, cutting, fluid film lubrication, wear mechanisms

1 Introduction

Nickel-based superalloys are highly preferred in the aerospace, marine, nuclear power, chemical, and oil–gas industries owing to their exceptional corrosion resistance and strength properties. Incoloy 925 is a critical nickel-based alloy because of its excellent resistance to sulfide stress cracking and stress corrosion cracking in a “sour” environment, which makes it an ideal material for chemical, marine, and oil–gas industry components [1]. Nevertheless, high tool-tip temperatures and severe work hardening are caused by Ni-based superalloys’ limited thermal conductivity; additionally, hard carbide particles (NbC, TiC) increase abrasion wear [2]. The material is also susceptible to chemically reacting with most of the tool materials, thereby causing diffusion/adhesion wear, and it retains high strength even at high temperatures, thereby generating higher cutting forces [3]; consequently, it has a low machinability index.

The tool’s geometry is altered by wear, which impacts power consumption and the surface quality of the product. For industry and researchers, maintaining tool geometry during nickel-based alloy machining is challenging. It is presumed that the mechanical, thermal, and chemical reactions between the material of the tool and the workpiece cause tool wear. The material of the tool and the workpiece, the tool’s geometry, the cutting environment, the kind of cutting, and the process parameters all influence the dominant tool wear mode, which increases the complexity of tool wear during Ni-based alloy machining [4]. Habeeb et al. [5] proclaimed that thermal cracking was the primary cause of tool failure at high cutting speeds due to high-temperature variation. Substantial heat is usually produced during machining due to the increased friction between the workpiece and the cutting tool. This heat weakens the
cutting tool and affects its ability to cut the material effectively. One of the best methods to lower friction and boost the tool’s strength is to apply an appropriate coating to the tool substrate. The turning of Inconel 718 with uncoated and various coated tools was compared by Sahoo et al. [6]. Compared to uncoated tools, they found that all coated tools have improved machinability regarding cutting force, temperature, and flank wear. Sampath Kumar et al. [7] compared uncoated, mono, and bilayer-coated tools during the turning of Inconel 825 and reported that bilayer-coated tools performed better regarding machined surface quality, cutting force, and tool wear. However, coating delamination in dry machining is a common issue. Cutting fluid is used to avoid coating delamination and to improve machinability. However, traditional cutting fluid is not eco-friendly and economical due to high toxicity and disposal costs. Nowadays, governments are very concerned about global warming and the safety of society and are encouraging sustainable machining processes. In recent decades, several researchers have proved that minimum quantity lubrication (MQL) is one of the effective alternatives for cutting environments. For instance, according to a study by Sun et al. [8], the use of ceramic end mills in the MQL cutting environment leads to better cutting temperature, cutting forces, surface quality, and tool life than dry cutting environment while machining GH4099. However, MQL based on oil has a restricted ability to transfer heat owing to its lower thermal conductivity. The dispersion of nanoparticles (NPs) in a base oil, called nanofluid, is now trending to improve the heat transfer capacity. Numerous studies have shown that base oil and nanoparticles work together to improve tribological performance and heat transmission capacity. Sen et al. [9], for instance, showed that combining silica and palm oil enhanced the milling performance of Inconel 690. Yldirim et al. [10] reported that hBN-based nanofluid improved the machining performance of Inconel 625. Babu et al. [11] reported that graphene-based nanofluid during turning Hastelloy C276 improved surface finish, cutting temperature, chip thickness, and tool life due to enhanced wettability of nanofluid in comparison to base oil. Sujith and Mulik [12] reported enhanced turning performance of Al7079/7 wt% TiC with coconut oil-Al2O3-based nanofluid. It had been reported that the performance of nano-MQL proved superior to that of dry and pure MQL conditions.

It has been proved that adding nanoparticles in base oil improves the machinability of superalloys. However, selecting base oil and nanoparticles is crucial for specific applications. It has been reported that natural bio-based (plant) oils have higher lubricity, viscosity, shear ability, load-carrying capacity, and lower volatility compared to synthetic and mineral oils [13,14]. The main attraction of plant-based oils in machining applications is due to their chemical composition of triacylglycerol molecules consisting of esters and long-chain polar fatty acids. In the application of boundary lubrication, fatty acids are preferable owing to their capability to adhere to metallic surfaces due to the presence of the polar carboxylic group, which retains the closely packed structure and constructs a monolayer film, which leads to a reduction in friction and wear by keeping down metal to metal contact [14]. In the face of these favorable conditions, vegetable oils have some drawbacks, like low thermal-oxidative stability and high pour point. From the machining point of view, oxidative stability is essential since, after oxidative degradation, the oils may lose their tribological properties. Jayadas and Nair [15] compared thermogravimetric analysis of coconut oil, sesame oil, sunflower oil, and 2T (two-stroke) oil and reported that coconut oil had the highest oxidative stability owing to the high percentage of saturated fatty acids.

On the other hand, to enhance the tribological and thermal properties of base fluids, different types of nanoparticles like multi-walled carbon nanotube (MWCNT) [16,17], molybdenum disulfide (MoS2) [18], aluminum oxide (Al2O3) [19], copper oxide (CuO), zinc oxide (ZnO) [20], graphene nanoplatelets (GNPs) [21], silicon dioxide (SiO2) [22], iron oxide (Fe3O4) [23], titanium dioxide (TiO2) [24], and hexagonal boron nitride (hBN) [25] were added. Verma et al. [26] improved the tribological performance of castor oil by mixing the silica and molybdenum disulfide. Along with these nanoparticles, copper (Cu) nanoparticles are used extensively as solid lubricant material due to their favorable lubricity, low hardness, low shear strength, and repair effect properties [27,28]. Padgurskas et al. [29] investigated the tribological performance of Cu-, Fe-, and Co-based nano-lubricants. They reported that Cu-based nano-lubricants outperformed other nano-lubricants due to the high plasticity of Cu causing easy deposition on friction surfaces, which, in turn, removed the oxide layer caused by the attrition of friction surfaces. Cu nanoparticles’ thermal conductivity at 20 °C is approximately 3000 times more than motor oil’s and roughly 700 times greater than water’s, according to Wong and Castillo [30,31]. Khan et al. [32] investigated coconut oil and separately blended copper (Cu) and silver (Ag) nanoparticles at different concentrations of mass during the turning of EN31 steel and reported that the coefficient of friction, cutting force, and temperature for Cu-added coconut oil was lower than Ag-added coconut oil. However, they did not mention the reasons for the better performance of Cu-based nano-lubricant compared to Ag-based nano-lubricant, but it could be possibly due to less density of Cu than

### Table 1 Key tool wear/tool life data for various cutting materials under different cutting environments

<table>
<thead>
<tr>
<th>References</th>
<th>Mode of operation</th>
<th>Workpiece material</th>
<th>Tool/insert</th>
<th>Cutting parameters</th>
<th>Cutting environments</th>
<th>Tool wear/tool life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babu et al. [11]</td>
<td>Turning</td>
<td>Hastelloy C276</td>
<td>TiAlN-TiC</td>
<td>Speed 62 m/min, feed 0.2 mm/rev, depth of cut 1 mm, cutting time 3 min.</td>
<td>Dry, Canola oil, oil + 0.5 wt% graphene</td>
<td>0.21 mm, 0.19 mm, and 0.13 mm flank wear of tool, respectively</td>
</tr>
<tr>
<td>Sujith and Mulik [12]</td>
<td>Turning</td>
<td>Al-7079/7 wt% TiC</td>
<td>Coated carbide</td>
<td>Speed 206.33 mm/min, feed 0.15 mm/rev, depth of cut 1 mm, cutting time 160 s</td>
<td>Coconut oil + 0.4 vol% Al2O3, Coconut oil, dry</td>
<td>0.32% and 10.5% higher tool life, respectively, compared to dry</td>
</tr>
<tr>
<td>Makhesana et al. [34]</td>
<td>Turning</td>
<td>Inconel 625</td>
<td>TiAlN PVD-coated carbide</td>
<td>Speed 70 m/min, feed 0.20 mm/rev, Depth of cut 0.5 mm, cutting time 30 min.</td>
<td>Dry, Sunflower oil, Oil + 1.5 vol% MoS2, Oil + 1.5 vol% Graphite</td>
<td>0.38 mm, 0.34 mm, 0.30 mm, and 0.26 mm flank wear of tool, respectively</td>
</tr>
<tr>
<td>Li et al. [35]</td>
<td>Milling</td>
<td>Titanium alloy TC4</td>
<td>TiAlN-coated tungsten steel</td>
<td>Speed 796 rpm with 6 mm dia. of tool, feed 0.016 mm/tooth, axial depth of cut 0.1 mm, tool flank wear cutoff 0.3 mm</td>
<td>Dry, Compressed air, LB 2000 oil, Oil + 0.1 wt% graphene</td>
<td>7920 mm, 8800 mm, 11,440 mm, and 14,080 mm cutting length, respectively</td>
</tr>
<tr>
<td>Ondin et al. [36]</td>
<td>Turning</td>
<td>PH 13-8 Mo stainless steel</td>
<td>PVD TiAlN-(AlCr)2O3</td>
<td>Speed 120 m/min, feed 0.1 mm/rev, depth of cut 0.8 mm, chip volume 90,000 mm³</td>
<td>Dry, Cuttex SYN10 (cutting oil), Oil + 0.6 vol% MWCNT</td>
<td>0.55 mm, 0.33 mm, and 0.171 mm flank wear of tool, respectively</td>
</tr>
</tbody>
</table>
Ag, which in turn leads to better stability than Ag. Yuan et al. [33] investigated the compatibility of diamond, Cu, and SiC nanoparticles with vegetable oils. They reported that Cu-based nanofluid provides a better surface finish owing to the soft nature of Cu nanoparticles, which makes easy deposition on the surface, whereas diamond and SiC-based nanofluids provide a poor surface finish due to higher hardness, leading to scratching and plowing on the surface.

There are several reports on the machinability of materials under different cutting environments. Some of the machinability data on tool wear/tool life based on the wear of flank face for the various cutting tools at different machining parameters for the various cutting materials under different cutting environments (variety of oils) are given in Table 1.

According to the literature review, using copper as a nano-additive and coconut oil as a base oil are preferable options for enhancing tool performance while machining superalloys. Unfortunately, there is limited research on it, and more research is needed to explore the performance of Cu-based modified coconut oil in machining Ni-based superalloys. Moreover, no thorough investigation of the combined effects of biodegradable (coconut) oil and nano-metallic solid lubricant (Cu) on the wear behavior of TiAIN/TiN physical vapour deposition (PVD)-coated tungsten carbide inserts in the end milling of Incoloy 925 has been conducted to date.

2 Experimental Methodology

This methodology section is divided into three subsections: Formulation of Nano-Cutting Lubricant, which describes the selection of ingredients of nano-lubricant and their specification and methods used to synthesize the nano-lubricant; Workpiece and Machine Tool, which describes details of the workpiece and cutting inserts, machining process and MQL parameters, and experimental machining setup; and Measuring Equipment, which is further subdivided into two sections: measuring equipment to characterize the thermophysical and tribological properties of formulated nano-lubricants and measuring equipment for technological responses of machining and tool wear.

2.1 Formulation of Nano-Cutting Lubricant. Cu nanoparticles have the highest thermal conductivity (approx. 400 Wm⁻¹ K⁻¹ [37]) except for some very costly nanoparticles like MWCNTs, diamonds, and silver. In addition to better thermal conductivity, it also acts like a solid lubricant due to its ductile nature and ability to self-adjust shape [27,38]. It was purchased from Nanoshel, India (CAS: 7440-50-8). Specification and toxicological–ecological information of Cu nanoparticles are listed in Table 2. The morphology of particles could be seen from the FESEM (field emission scanning electron microscopy) image (Fig. 1(a)), whereas EDX (energy dispersive X-ray) of Cu nano-powder is shown in Fig. 1(b).

Table 2 Specification and toxicological–ecological information of Cu nanoparticles

<table>
<thead>
<tr>
<th>Specification</th>
<th>Toxicological and ecological information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>Powder</td>
</tr>
<tr>
<td>Color</td>
<td>Reddish</td>
</tr>
<tr>
<td>Density</td>
<td>8.96 g/cm³</td>
</tr>
<tr>
<td>Average particle size</td>
<td>80–100 nm</td>
</tr>
<tr>
<td>Purity</td>
<td>99.9%</td>
</tr>
<tr>
<td>Skin</td>
<td>No effect</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Non-toxic</td>
</tr>
<tr>
<td>Ecological impact</td>
<td>No negative impact</td>
</tr>
<tr>
<td>Eyes</td>
<td>Irritation</td>
</tr>
</tbody>
</table>

Ag, which in turn leads to better stability than Ag. Yuan et al. [33] investigated the compatibility of diamond, Cu, and SiC nanoparticles with vegetable oils. They reported that Cu-based nanofluid provides a better surface finish owing to the soft nature of Cu nanoparticles, which makes easy deposition on the surface, whereas diamond and SiC-based nanofluids provide a poor surface finish due to higher hardness, leading to scratching and plowing on the surface. Incoloy 925, 60 mm × 70 mm × 15 mm, was used as a workpiece material. The standard chemical composition of Incoloy 925 is listed in Table 3, whereas the microstructure of Incoloy 925 is shown in Fig. 3(b). The cutting tools were PVD TiAIN/TiN-coated inserts (ISO EDPT10T316PDERHD) from Kennametal and a shoulder mill tool holder (ISO 16A02R025A16ED101). Vertical milling (model: Hardinge, VMC 600 II) was used as the machine tool. The experimental setup is shown in Fig. 3(a), whereas Fig. 3(c) shows the microstructure of the cross-section of an insert. Figure 3(c1)–(c6) shows elemental mapping of the insert material and coating, whereas Fig. 3(d) shows elemental distribution of the insert material and the coating. Experiments were conducted with cutting velocity (v) of 80 m/min, feed (fz) of 0.075 mm/tooth, axial depth of cut (ap) of 0.3 mm, radial depth of cut (ar) of 10 mm, nose radius (r) of 1.6 mm, clearance angle of 15 deg, and positive rake angle of 15 deg. The cutting parameters were decided after the inspiration from the literature [40–42], recommendations from the tool manufacturer, and pretrial test, whereas the optimized MQL parameters by Yadav et al. [43] were selected for this experiment. All the experiments have been conducted at fixed process parameters (as mentioned earlier) with a repetition of three times for all the cutting environments. Thus, only cutting environments (viz., dry, pure coconut oil, and nanofluid) were allowed to be variable in order to see the comparative machining performance of synthesized nano-lubricant with other cutting environments.

2.3 Measuring Equipment

2.3.1 Equipment Used to Characterize the Physical Stability and Measure the Thermophysical, Rheological, and Tribological Properties of Nano-Lubricant. Ultraviolet-visible spectroscopy (model: UV-3600i Plus, Shimadzu) was used to determine the physical stability of the nano-lubricants. Following the ASTM E1530 standard, discovery thermal conductivity (model: DTC-300, TA Instruments) was utilized to evaluate the thermal conductivity of the nano-lubricant. The viscosity and flow characteristics are assessed using a rheometer (TA Instruments, model ARES-G2). The wettability of the nano-lubricant was evaluated on a polished workpiece with the aid of a drop-shape analyzer (model: DSA-100, Kruss). A tribological test in reciprocating mode was performed using a multifunctional tribometer (Rtec Instruments, model: MFT 5000), which ASTM G133 standardizes. The test used a mirror-polished WC (Tungsten Carbide) ball with a diameter of 6 mm, a disc (Incoloy 925), a stroke length of 2 mm, a 20 Hz frequency, and an applied load of 100 N for 60 min. These tribological parameters were selected after the inspiration from the literature information [34,42,44,45] and to accomplish the nearest condition of machining. Notably, the previous study by Yadav et al. [42] used the equipment mentioned earlier. Hence, in order to calculate the relative thermophysical and tribological properties of Cu-based nanofluid with base oil (coconut oil), previous data on coconut oil was used for this study. Wear tracks were analyzed using scanning electron microscopy (SEM) (model: EVO 18 special edition, Zeiss).

2.3.2 Equipment Used for Technological Responses of Machining and Tool Wear Mechanism. A rotary dynamometer (model: RCD 9170A, Kistler) with 5238B type of amplifier and Dyno-ware software was used to record the signals of cutting forces, whereas cutting temperatures were recorded using a thermal camera (model: TUMX, Micro-Epsilon, Germany) having maximum measuring capacity of 900 °C with T&M connect software. In this study, emissivity was set to 0.2 after inspiration from the
literature [46] and the datasheet for emissivity provided by the manufacturer. Surface roughness (Ra) is evaluated according to ISO 4287 [34] using Taylor Hobson equipment (model: Form Talysurf 50); surface topography was captured with a 3D optical profilometer (model: Zeta-20, Zeta Instruments), whereas surface topography was observed using FESEM (model: TESCAN, Magna). Topology and types of wear mechanisms were identified using FESEM (model: TESCAN, Magna) equipped with EDX. Further, to identify the types of oxides on the worn tool, Raman spectroscopy (RENISHAW in-Via Raman Microscope) with excitation laser wavelength of 514 nm and gratings 1800 lines/mm was used. Tool wear progression was measured according to ISO 3685 [47] using a stereo zoom microscope (model: Stereo discovery.V20, Carl Zeiss). Tribo-thick film was observed with the help of FESEM (model: Quanta 200, FEI).

3 Results and Discussion

This section deals with five subsections: Physical Stability of Nano-Lubricant, which describes the best level of concentration (Vol%) for the highest physical stability of nano-lubricants; Properties of Nano-Lubricant, which describes comparative improvements in thermal conductivity, viscosity, wettability, and coefficient of friction with pure coconut oil; Technological Responses of Machining, which describes cutting temperature, energy consumption, and surface quality under different cutting environments; Tool Wear and Its Mechanism, which describes different types of tool wear and its mechanisms (viz., coating delamination, abrasion, adhesion, and oxidation) under different cutting environments; and Tool Life, which describes the final tool life under different cutting environments.

3.1 Physical Stability of Nano-Lubricant. The physical stability of nanoparticles in oil specifies that nanoparticles retain uniform dispersion in oil for a longer duration. UV-visible spectroscopy is one of the techniques to measure the physical stability of nano-lubricants, in which, at a specific wavelength, the substance (sample) absorbs most of the light. According to Beer–Lambert law [48], the amount of light absorbed by a substance is directly proportional to concentration. However, higher concentration leads to easy sedimentation caused by aggregation of nanoparticles. Thus, by measuring the absorbance of a substance at a specific wavelength, we can measure the substance’s concentration (presence of particles). Higher absorbance shows the higher presence of nanoparticles. Therefore, absorbance and wavelength were selected to compare the physical stability of nano-lubricants at different volume concentrations. The physical stability of dispersed nanoparticles in oil is essential since nano-lubricants’ performance depends highly on their stability. Figure 4 shows the spectra of UV-Vis for different nano-lubricants. It is observed that the absorbance intensity of nano-lubricant at 0.3 vol% after 24 h of ultrasonication is the highest, followed by 0.1 vol% and 0.5 vol%. The increase in absorbance intensity with the rise in volume concentration from 0.1 vol% to 0.3 vol% is by Beer–Lambert law. In contrast, the intensity of absorbance at 0.5 vol% is the lowest, which may be due to a very high sedimentation rate [49]. Based on this physical stability test result, nano-lubricant at 0.3 vol% Cu is selected for further study.

3.2 Properties of Nano-Lubricant

3.2.1 Thermal Conductivity. The thermal conductivity of cutting lubricants determines their ability to dissipate heat effectively. Equation (1) is used to determine the relative thermal conductivity, a critical measure for evaluating the change in thermal conductivity of nano-lubricants relative to base oil.

\[ K_r = \frac{K_{nl}}{K_{bl}} \]  

Table 3 Chemical compositions of Incoloy 925 (wt%) [1]

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>2.7</td>
<td>14.3</td>
</tr>
<tr>
<td>Cu</td>
<td>97.3</td>
<td>6.6</td>
</tr>
</tbody>
</table>

![Fig. 1 (a) FESEM image and (b) EDX of Cu nano-powder sample](image)

![Fig. 2 Detailed procedure for formulation of nano-lubricant](image)

![Table 3 Chemical compositions of Incoloy 925 (wt%)](table)
where $K_r$, $K_{nl}$, and $K_{bl}$ are relative thermal conductivity, thermal conductivity of nano-lubricant, and thermal conductivity of base lubricant (oil), respectively.

Relative thermal conductivity is greater than one at all temperatures and rises with temperature, as seen in Fig. 5(a). It represents that the nano-lubricant’s thermal conductivity at all temperatures is higher than base oil. The improved thermal conductivity of the nano-lubricant in comparison to oil is caused by the high surface-to-volume ratio and the thermal conductivity of the distributed nanoparticles. The increase in relative thermal conductivity at higher temperatures is probably due to the more pronounced Brownian motion shown by the dispersed nanoparticles. The temperature-dependent increase in energy provided to the nano-lubricant causes the molecules to accelerate, which in turn causes the nanoparticles to move faster because of the increased energy and Brownian motion [50,51].

3.2.2 Viscosity. Reduced flowability is the result of increased lubricant viscosity. Maintaining suitable viscosity is crucial during the cutting process as it assists in creating a thick layer that separates the surfaces in contact, reducing the coefficient of friction. Relative viscosity is calculated from Eq. (2) and is popularly used to signify the fluctuation of dynamic viscosity of nano-lubricant with temperature.

$$\mu_r = \frac{\mu_{nl}}{\mu_{bl}}$$  \hspace{1cm} (2)

where $\mu_r$, $\mu_{nl}$, and $\mu_{bl}$ are relative viscosity, viscosity of nano-lubricant, and viscosity of base lubricant, respectively.

The relative viscosity of the nano-lubricant at various temperatures is displayed in Fig. 5(b). It is evident that when temperature rises, relative viscosity varies dramatically. When the temperature increases from 30 °C to 50 °C, the relative viscosity decreases, but as the temperature rises from 50 °C to 90 °C, relative viscosity again starts to increase. The reduction in relative viscosity with the increase in temperature is due to decreased attractive binding energy (cohesive forces) of molecules; in contrast, the rise in relative viscosity is due to possible agglomeration of nanoparticles aligned perpendicular to the fluid flow direction [52].

### Fig. 3
(a) Experimental setup, (b) microstructure of Incoloy 925, (c) microstructure of insert, (c1–c6) EDX elemental mapping of insert material and coating, and (d) EDX elemental distribution of insert material and coating.

### Fig. 4
Spectra of nano-lubricants after 24 h of ultra-sonication.
3.2.3 Rheology (Flow Behavior). Figure 5(c1) displays the viscosity measurements for nano-lubricant at various shear rates, which describes the flow behavior of nano-lubricant. The viscosity of nano-lubricant at all the tested shear rates is practically the same, and no significant variation is observed. It implies that the shear rate does not affect the viscosity of the nano-lubricant. The plot of shear stress with shear rate (Fig. 5(c2)) confirms this observation. The linear curve illustrates the Newtonian behavior of the nano-lubricant as the shear rate and shear stress simultaneously increase. Gupta et al. [53] observed similar behavior for the different nano-lubricants. Hence, regardless of the cutting shear rate, fluids are anticipated to maintain their initial properties while machining.

3.2.4 Wettability. Wettability is the ability to cover the solid surface, which helps improve the tribological performance and heat transfer in the cutting area. The wettability of the nano-lubricant can be evaluated by measuring the contact angle of the nano-lubricant. A low contact angle is preferred since, in this case, a constant volume of droplets spreads over a large area compared to a higher contact angle. According to Fourier’s law, a higher surface area can enhance the heat transfer rate. The typical images of the wettability for the base lubricant (coconut oil) and the nano-lubricant (coconut oil + 0.3 Vol% Cu) are shown in Figs. 6(a) and 6(b), respectively. The contact angle of the nano-lubricant is observed to be reduced by 33.54%, which signifies better wettability of the nano-lubricant than the base lubricant. The reduction in contact angle of nano-lubricants implies that when nanoparticles are dispersed in the base lubricant, it helps reduce the cohesive forces of molecules and the surface tension. Thus, increased wettability would help improve the heat transfer during the end milling of Incoloy 925. A similar reduction in the contact angle of nano-fluid was found in a previous study by Yadav et al. [42].

3.2.5 Coefficient of Friction and Morphology of Wear Tracks. From Fig. 7(a), it is observed that the coefficient of friction (COF) for both lubricants is less than dry, which signifies a reduction in the COF for both lubricants than the dry condition. Due to the absence of any lubricant in dry conditions (see Fig. 8(a)), COF is found to be high. The reduction in COF for base lubricant may be because coconut oil, owing to the presence of almost 90% saturated fatty acids, helps to formulate the dense monolayers that are adsorbed onto the mating surfaces [54], as demonstrated by Fig. 8(b). In contrast, the high reduction in friction coefficient for the nano-lubricant could be explained by the fact that the nanoparticles occupied the asperity valleys, thus lowering the contact surfaces between the tribo-pair [55,56], as demonstrated by Fig. 8(c). Further, Cu nanoparticles may tend to be reshaped owing to their soft nature and orientation parallel to tribal-pair motion. Consequently, they reduce the shear stress, resulting in the optimum lubrication phenomenon.

SEM images (Figs. 7(b1)–(b3)) were used to examine the surface morphology and degradation of the worn track surfaces under
different lubrication conditions. The worn track surface exhibits cracked ridges, deposited wear debris, large furrows, and material adhesion in the dry state as a result of high friction and higher heat generation (Fig. 7(b1)). Adhesion wear is also the main process that arises from the friction-induced transient fusing of the rubbing surface at high contact temperature [58]. When the surface is lubricated with coconut oil, less abrasion occurs during wear, and shallow furrows are replaced with microplows and micro-grooves. As a result, it has been observed that the lubricating effect of coconut oil results in a smooth surface devoid of significant surface flaws (Fig. 7(b2)). Due to the copper protective film formation on the friction surfaces [28], the dispersion of Cu-NPs in coconut oil further improves the worn track surface (Fig. 7(b3)).

3.3 Technological Responses of Machining

3.3.1 Cutting Temperature. The high heat generation during machining is a significant concern since it influences the coating and increases the tool wear, reducing the tool’s capability to cut the material. In addition, it also increases the power consumption and cutting forces and consequently reduces the surface quality of the machined components. Figure 9(a) shows captured thermal images of the cutting zone under different conditions. Figure 9(b) shows that cutting temperature is reduced by 18.82% and 37.1% for MQL and nanofluid-based minimum quantity lubrication (NMQL)-aided machining, respectively, than dry machining. Reduction in cutting temperatures for base lubricant and nano-lubricant conditions are in agreement with the observed trends in the previous discussion on thermal conductivity (Fig. 5(a)), wettability (Figs. 6(a) and 6(b)), and COF (Fig. 7(a)).

3.3.2 Energy Consumption. Energy consumed during the machining process is a critical parameter to compare the utilized electrical energy as it shares the total manufacturing cost. In addition, high consumption of energy results in higher carbon emissions that severely affect the environment quality. Ni-based superalloys consume more energy; hence, an industry needs to reduce the energy consumption during machining. For evaluating the energy consumption for the machining level process, the first resultant cutting force \( F_r \) is calculated from Eq. (3), table feed \( V_f \) is computed from Eq. (4), cutting time \( T_c \) is calculated from Eq. (5), and finally, energy consumption \( E_c \) is calculated from Eq. (6) and listed in Table 4.

\[
F_r = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{3}
\]

where the force components in the \( X, Y, \) and \( Z \) directions are \( F_x, F_y, \) and \( F_z \), respectively.

\[
V_f = f_z \times Z \times n \tag{4}
\]

where \( f_z, Z, \) and \( n \) are feed/tooth, number of teeth, and revolution/min, respectively.

\[
T_c = \frac{L}{V_f} \tag{5}
\]

where \( L \) is the cutting length (60 mm).

\[
E_c = \frac{F_r \times V \times T_c}{1000} \tag{6}
\]

where \( E_c \) is in kJ, whereas \( F_r, V, \) and \( T_c \) are in N, m/min, and min, respectively.

The highest energy consumption is found during dry machining and the lowest during NMQL conditions, as seen in Fig. 9(c) and Table 4. Compared to dry, MQL and NMQL conditions use 7.03% and 44.73% less energy, respectively. The combined action of Cu nanoparticles and base lubricant may cause the
significant energy savings observed in NMQL-aided machining. As in Sec. 3.2.5, it has been demonstrated that Cu nanoparticles are crucial to tribological performance. Makhesana et al. [59] noted a comparable kind of energy consumption decrease during the turning of Inconel 690.

3.3.3 Surface Quality. Surface roughness (Ra) is a crucial metric for assessing the surface quality of components since it affects the mechanical and dimensional accuracy of the product [34]. The surface roughness of machined components for various cutting conditions is displayed in Fig. 9(d). The lowest surface roughness is produced when machining with NMQL support. Under MQL and NMQL conditions, surface roughness is reduced by 31.91% and 54.95%, respectively, compared to dry machining. Surface roughness decreases as a result of the lubrication effect in MQL because it lowers the COF. On the other hand, NMQL-aided machining leads to a more significant decrease in the COF because of the increased lubrication effect brought on by the synergistic interaction between oil and soft solid nanoparticles (Fig. 7(a)). Şirin et al. [60] have reported a similar decrease in surface roughness during the milling of nickel alloy X-750.

A 2D topography of machined components was captured (see Figs. 10(a1)–(a3)) to analyze the macroscopic surface quality of the machined surface. In dry machining, chip material is redeposited on the machined surface, which may be due to the high COF causing high-temperature generation. In contrast, the lowest or negligible chip material is redeposited on the machined surface in NMQL condition. The lower cutting temperature and smooth surface achieved through NMQL-aided machining result from combining oil and nanoparticles. This combination creates a synergistic effect that leads to a decrease in the COF.

Further, to observe the microscopic surface quality of the machined surface, FESEM images of machined components are captured (see Figs. 10(b1)–(b3)). It is further confirmed that there is a high chip material redeposition in dry machining. The utilization of MQL in machining results in reduced material redeposition
compared to dry machining. However, this method produces wider grooves. In contrast, NMQL-aided machining results in almost zero material redeposition, and finer grooves are observed, which further supports the claim that NMQL-aided machining yields high-quality products with smooth surfaces.

3.4 Tool Wear and Its Mechanism. Figures 11(a)–11(c) display the worn inserts during dry, MQL, and NMQL conditions, respectively. Dry machining induces built-up edges (BUE), spalling, craters, abrasion/adhesion, and chipping. On the other hand, MQL and NMQL-aided machining results in spalling, abrasion/adhesion, and chipping; however, NMQL condition results in less abrasion/adhesion than dry and MQL conditions. Furthermore, Figs. 12(a)–12(c) show that in the case of NMQL-aided machining, the degree of anomaly adhesion on the tool flank face is at its lowest. This could be attributed to the appropriate lubrication provided by oil and nanoparticles, which reduces the COF and heat generation.

3.4.1 Coating Delamination. Coating delamination is a common issue for the coated tool in machining any material. Generally, the coating is delaminated due to high heat generation during machining. It is commonly known that superalloys based on nickel produce a lot of heat when they are machined. Hence, high coating delamination is expected in dry machining compared to MQL and NMQL-aided machining, which leads to high built-up-edge formation (see Fig. 11(a)). In dry machining, it is confirmed that both layers of coating TiAlN and TiN (see Figs. 13(a1), (a2), (a3(1)) and (a4)) have been delaminated. It may be noted that the presence of Al, as observed from Fig. 13(a3(2)), may be due to the second layer of the coating, which is comprised of TiAlN. In MQL-aided machining also, both layers of coating (see Figs. 13(b1), (b2), (b3(1)) and (b4)) have been delaminated. However, Fig. 13(b3(2)) shows a higher presence of Al than dry machining, which indicates that as temperature reduces, the rate of coating delamination also decreases, which is again confirmed by Figs. 13(c1), (c2), (c3(1,2)), and (c4), where delamination of both types of the coating layers is less. The second coating layer is strongly and widely present due to NMQL-aided machining, which generates less heat (see Fig. 9(b)). 1 and 2 within the figure a3, b3, and c3 represent the enclosed area.

3.4.2 Adhesion Wear. Adhesion occurs due to sticking the work material onto the tool surface under high heat and pressure. Sometimes, adhesion can occur in the form of a thin layer and other times in the form of BUE/built-up layer (BUL) [61]. During dry machining, the adhesion of material on the tool surface can be seen in Fig. 11(a), which is further confirmed by EDX (see Figs. 14(a1)–(a3))—the presence of elements viz. Ni, Fe, and Cr on the worn tool prove that the work material is adhered to the tool surface. In the MQL condition, adhesion is also observed (see Fig. 11(b)), which is also confirmed by EDX (see Figs. 14(b1)–(b3)); that may be because only the base lubricant is not effective enough to reduce the amount of heat during machining. However, in NMQL condition, adhesion is significantly less or negligible (see Fig. 11(c)), which is confirmed by EDX (see Figs. 14(c1)–(c3)), which may be because base lubricant and
Fig. 12  Topography of worn tool flank face: (a) dry, (b) MQL, and (c) NMQL

Fig. 13  EDX mapping for coating delamination under different cutting conditions
nanoparticles synergize to significantly lower cutting temperature (see Fig. 9(b)).

3.4.3 Abrasion Wear. Hard abrasive particles like carbides (NbC and TiC) present in the work material (see Fig. 3(b)) pull out material in the form of particles from the tool and cause abrasive wear. Abrasive wear can also happen due to sliding friction. Sliding friction can be reduced by using proper lubrication. Figures 11(a)–11(c) show the abrasion marks. Figure 15 indicates the presence of elements like W and Co of tool material, which is only possible if the coating layer is no longer present on the tool surface, proving that abrasion has occurred. It is observed that the absence of lubrication in dry machining results in a broader abrasion width. Compared to dry machining, the MQL condition narrows the abrasion

![Fig. 14 EDX mapping for adhesion wear in different cutting environments](image1)

![Fig. 15 EDX mapping for abrasion wear in dry machining](image2)
3.4.4 Oxidation Wear. Oxidation wear occurs generally due to the reaction of sensitive tool materials like Ti and Al with the environment where oxygen is present. Figures 16(a)–16(c) show the presence of oxygen that confirms oxidation wear. However, EDX mapping is unable to identify the types of oxidations. In this regard, Raman spectra of worn tools in dry and NMQL conditions have been obtained, and various kinds of oxides like Fe$_2$O$_3$, Fe$_3$O$_4$, Al$_2$O$_3$, WO$_3$, Cr$_2$O$_3$, CoO, and TiO$_2$ are found (see Fig. 16(d)). These oxides result from a reaction between the workpiece/tool material and the environment in the presence of generated heat during the cutting operation. Constable et al. [62] also identified several oxides on tool wear using Raman spectroscopy. In contrast, Celik et al. [63] used Raman spectroscopy to study the effects of wear on oxidized/carbonitride-coated inserts. Liang et al. [41] identified similar types of oxides by conducting micro-XRD (X-ray diffraction) tests after milling GH4169 superalloy. Further, it has been observed from Fig. 16(d) that oxides are formed in dry and NMQL conditions. However, during NMQL-aided machining, the peak intensity at Raman shift (530 cm$^{-1}$) is not visible, and the peak intensity at 680 cm$^{-1}$ is shifted to 714 cm$^{-1}$ with weak (broad) intensity. Therefore, the NMQL condition produces less tool wear oxidation, as better lubrication can somewhat hinder oxidation wear [64].
3.5 Tool Life. One of the essential criteria for deciding tool life is the extent of average flank wear. The progression of flank wear versus cutting volume for different cutting conditions is shown in Fig. 17(a). It is found that in dry machining, the rate of flank wear is high as higher frictional heat is produced in the absence of lubricant/coolant, and finally, at 10,080 mm³, it crosses the tool life criteria (VB > 0.3 mm). However, in the MQL condition, the flank wear progression is slow, whereas in the NMQL condition, its progression is prolonged. The variations in the tool wear progression are attributed to the nanoparticles’ effectiveness in the underlying lubricant, which performs remarkably and can decelerate the wear-rate. It is essential to highlight that the sliding motion of the mating surfaces is enhanced by the compressed air and lubricant droplets, leading to a decrease in the COF and ultimately reducing tool wear. Dispersing the nanoparticles in lubricant further enhances its efficiency and results in steady and low tool wear. The findings are related to the superior lubricating capacity of coconut oil and Cu nanoparticles, which causes friction reduction and improves cooling. Coconut oil makes a thin film covering the machining zone, and nanoparticles can be retained in the narrow gaps and microcavity of machined surfaces, confirmed by Figs. 17(b) and 17(c).

4 Conclusions
Nano-lubricants are trending in the research field; however, suspension of the hard nanoparticles creates another issue owing to abrasion capability on the contacting surfaces. Hence, in this study, the soft nanoparticles (Cu-NPs) with better thermal conductivity and acting as a solid lubricant were suspended in the biodegradable fatty acids (coconut oil) to synthesize a sustainable lubricant for enhancing the machining performance. The thermophysical and tribological properties of the lubricants were evaluated. Further, synergistic effects of biodegradable fatty acids and nano-metallic solid lubricant on tool wear mechanism during end milling of Incoloy 925 were investigated. The following conclusions can be drawn:

- The Cu-NPs present in the nano-lubricant result in higher thermal conductivity and viscosity at all tested temperatures. Additionally, the contact angle decreases by 33.54% compared to coconut oil due to reduced cohesive forces of molecules and surface tension when adding Cu-NPs. Further, COF for the nano-lubricant is reduced by 21% and 10.65% compared to dry and coconut oil, respectively. The coefficient of friction for base lubricant decreases due to the presence of fatty acid content, which forms the dense monolayer, while nano-lubricant’s high reduction is due to nanoparticles reducing actual contact surfaces.

- Cutting temperature is lowered by 18.82% and 37.1% for MQL and NMQL-assisted machining, respectively, than dry machining. Due to the enhanced thermal conductivity, wettability, and lower COF of nano-lubricant compared to base oil, the NMQL condition results in a more significant drop in cutting temperature than the MQL condition.

- Energy consumption in dry machining is reduced by 7.03% and 44.73% with the use of MQL and NMQL-aided methods, respectively, than dry machining. The significant reduction in energy consumption for NMQL condition may be due to the combined effects of base lubricant and Cu nanoparticles.

- For MQL and NMQL conditions, surface roughness is decreased by 31.91% and 54.95%, respectively, compared to dry machining. High material redeposition is observed in the dry condition, whereas in the NMQL condition, such redeposition phenomenon is almost absent. It is attributed to improved lubrication, which lowers the cutting temperature and decreases the COF. This may be because of the deposition of soft solid nanoparticles and the formation of a tribo-thin film of fatty acids.

- Coating delamination, abrasion, adhesion, and oxidation tool wear mechanisms have been noted for all the cutting environments. However, flank wear occurs more slowly during NMQL-aided machining, followed by MQL and dry conditions, which is attributed to the synergistic interaction between fatty acids and soft metallic nanoparticles.

- Compared to dry machining, tool life for nanofluid and pure coconut oil is enhanced by 37.5% and 12.5%, respectively. The highest enhancement in tool life for nanofluid conditions is due to the deposition of Cu-NPs on friction surfaces, possibly due to the low shear strength and flexibility of metallic nanoparticles, leading to tribo-thin film formation.

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Conflict of Interest
There are no conflicts of interest.

Data Availability Statement
The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

References


