Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Original Article

Influence of MoS_2 based nanofluid-MQL on tribological and machining characteristics in turning of AA 2024 T3 aluminum alloy

Ayşegül Yücel [a], Çağrı Vakkas Yıldırım [b], Murat Sarıkaya [c], Şenol Şirin [d], Turgay Kıvak [e], Munish Kumar Gupta [f], Ítalo V. Tomaz [g,h,*]

[a] Institute of Science, Erciyes University, Kayseri, Turkey
[b] Department of Airframes and Powerplants, Erciyes University, Kayseri, Turkey
[c] Department of Mechanical Engineering, Sinop University, Sinop, Turkey
[d] Department of Machine and Metal Technologies, Gumusova Vocational School, Duzce University, Duzce, Turkey
[e] Department of Mechanical Engineering, Faculty of Engineering, Duzce University, Duzce, Turkey
[f] Faculty of Mechanical Engineering, Opole University of Technology, Opole, Poland
[g] SEAM Research Centre, Department of Engineering Technology, Waterford Institute of Technology, Waterford, X91TX03, Ireland
[h] Laboratory of Materials Testing (LEMat), Fluminense Federal Institute, Cabo Frio–Buzios, S/n, Cabo Frio RJ, 28909-971, Brazil

ARTICLE INFO

Article history:
Received 26 May 2021
Accepted 2 September 2021
Available online 9 September 2021

Keywords:
AA 2024 T3 aluminum alloy
MoS_2 nanoparticles
Nanofluid-MQL
Surface quality
BUE/BUL formation

ABSTRACT

Aluminum (Al) alloys are of particular importance to the aerospace industry owing to the combination of characteristics including strength, ductility, toughness, fatigue life and oxidation resistance as a light metal. This is the case of AA 2024 T3 Al alloy. In particular, machining of these alloys has similar importance for productivity and part quality. Recently, the use of nanofluids, which have various advantages in terms of both cooling ability and tribological aspects, has become popular for the efficient machining of such alloys. In this context, guiding data are needed that enable industry and researchers to machine these types of alloys with high efficiency. Taking these into account, in this study, AA 2024 T3 Al alloy was machined and various machinability indicators such as surface roughness, surface topography, maximum temperature and dominant tool wear mechanism under different cooling/lubrication strategies i.e., dry cutting, base fluid minimum quantity lubrication (MQL) and mineral oil based MoS_2 nanofluid MQL (NFMQL) were investigated. As a results, significant improvements have been achieved in surface roughness, surface topography, and maximum temperature with help of NFMQL application. The intensive built-up edge (BUE) and built-up layer (BUL) formations are produced on the cutting tool when machining AA 2024 T3 Al alloy under dry cutting. On the other hand, BUE formation has been significantly eliminated thanks to NFMQL. Moreover, a less damaged cutting edge was obtained when machining Al alloy under NFMQL compared to both dry cutting and MQL environments.

* Corresponding author.
E-mail address: italo.tomaz@wit.ie (Í.V. Tomaz).
https://doi.org/10.1016/j.jmrt.2021.09.007
2238-7854/© 2021 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

© 2021 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

In the aircraft and aerospace industry, reducing costs without jeopardizing flight safety is one of the most researched topics. To achieve this, increasing the strength/weight ratio in materials used in aircraft structures is among the most fundamental issues. In this context, aluminum (Al) alloys are more preferred than steels in applications where lower weight and lower maintenance costs are required. In other words, Al alloys come to the forefront in the aviation industry in order to meet the mentioned requirements [1]. Particularly, the wing section and fuselage skin of the aircraft are the places where Al alloys are used extensively [2]. In applications, one of the most preferred Al alloys is 2024 Al alloy, whose main alloying element is copper, which also contains magnesium, manganese and various secondary alloying elements. Not only elevated strength/weight ratio but also high fatigue resistance is an important factor in choosing the material [3]. In addition, features such as high damage tolerance, fracture toughness, fatigue performance and high formability & super plasticity make 2024 Al alloys stand out [4]. Despite these positive properties, various difficulties are encountered during the machining of Al alloys. For example, the high thermal conductivity combined with the high thermal expansion coefficient significantly reduces the machinability properties, especially in the dry environment [5]. In addition, the high chemical closeness of Al alloys to most of the cutting tool components leads to these alloys to adhere/weld to the cutting tools, thus causing a high amount of built-up edge (BUE)/built-up layer (BUL) [6]. This situation is especially prominent in studies conducted under dry machining. For example; Bejar et al. [7] turned the UNS A97075-T6 (Al–Zn) under dry machining and stated that the tool life decreased due to BUE and BUL occurred on the cutting tool. Sanchez et al. [8] machined AA 2024 and AA 7050 materials under dry machining and observed wear on the cutting tool due to BUE/BUL formations. Similar results were found in various studies conducted by [9–13]. As seen in previous studies, adhesion is a very serious problem especially when machining Al alloys under dry environment. To avoid this situation, the first option that comes to mind is the utilization of cutting fluid. The cutting fluids during chip removal process provide significant improvements in critical issues i.e., cooling, lubrication, and removal of chips from the cutting region. However, water and mineral oil-based cutting fluids used as conventional coolant have low thermal conductivity. Thus, problems arise regarding the ejection of the high heat produced in machining region. Consequently, major improvements in outcomes including cutting temperature, tool wear and surface quality cannot be achieved as desired [14,15]. Apart from these, conventional cutting fluids also pose a risk to employee health and the environment. Moreover, they lift manufacturing costs for a number of purposes, including acquisition, transportation, and disposal [16,17]. Therefore, reducing the amount of conventional cutting fluids is essential for both efficiency and sustainable production. Dry machining can be preferred to eliminate limitations of cutting fluid [18]. However, when machining materials having high adhesion tendencies such as Al alloys, the absence of any lubricant may significantly reduce machining efficiency [19]. It would be more beneficial to maintain and/or increase production efficiency while reducing the volume of cutting fluids [20,21]. In this case, the first process that comes to mind is the system of minimum quantity lubrication (MQL) that operates with the idea of using compressed air to send a very limited volume of cutting oil (10-100 mL/h) to the cutting field [22,23]. Thanks to the MQL technique, better results can be obtained by using very little cutting oil (1/10000 compared to conventional coolant use) [24–26]. Also, another method used in recent years is (nanofluid MQL) NFMQL, that is helpful in improving performance of base fluid used in MQL. This method aims to improve the oil properties through inserting nano-sized additives into the cutting oil used in the MQL system [27].

Nanofluids are a new generation cooling/lubrication method obtained by adding nano-sized (i.e. <100 nm) additives into base cutting oil/liquid [28]. Nanoparticles applied to the cutting fluid/oil boost the base fluid's properties such as thermal conductivity, viscosity, wettability, pH value and tribological features [29]. In this way, important changes in the metrics are provided, such as encouraging the dissipation of heat from the cutting field, minimizing friction, improving the surface quality and tool lifespan [30]. Although the use of nanofluids in the cutting of Al alloys is limited, there is a consensus in the literature that the properties of cutting fluids improve with the addition of nano-additives. Rahmati et al. [31] explored the influences of some MQL inputs (air pressure and nozzle orientation) and nanofluid concentration ratio (0, 0.2, 0.5 and 1 wt%) while machining Al6061-T6 material. Researchers which used MoS_2 as an additive, stated that all concentration ratios gave better results than pure MQL. Sayuti et al. [32] compared pure MQL with SiO_2 doped nanofluid at different concentration ratios when machining Al 6061-T6 alloy. These researchers emphasized that the nanofluid offers significant improvements in surface finish, cutting force and cutting temperature. Najiha et al. [33] investigated the effect of SiO_2 concentration ratio into base fluid on performance indicators while machining Al 6061-T6 material. As a result, they highlighted that nanofluid with 2.5% concentration gave better results. Duan et al. [34] machined 7050 Al alloy under Al_2O_3 doped nanofluid and studied the impact of nozzle position on machining metrics. Kulkarni at al [35]. investigated the influence of effect of nanofluid based MQL application on quality characteristics during milling of Al7075-T6 alloy. They emphasized that the addition of nanoparticles to the base fluid had a positive effect on lowering the temperature at the

tool–workpiece interface without affecting the machining quality characteristics. Zhu et al. [36] studied cutting tool temperature distribution under MQL environment in drilling of Al 2024-T351 alloy. It was reported that with the application of MQL, it can reduce the temperature difference between various parts of the tool compared to dry and air cooling conditions. In addition, adhesion and BUE formation were observed along nearly the entire cutting edge under dry drilling due to the lack of lubrication and coolant.

As seen in the literature analysis, it is common for the work material to adhere to the cutting tool when machining Al alloys under dry cutting condition. Owing to adhesion, the cutting tool loses its ideal geometry and cannot perform its cutting function adequately and therefore, surface quality decreases. For these reasons, the use of cutting fluids has become important when machining Al alloys. On the other hand, in terms of the environmental limitations, employee wellbeing and manufacturing costs, the adverse properties of traditional cutting fluids have led researchers to explore alternative approaches.

Recently, nanofluids have become very popular as cutting fluids in machining operations due to their ability in terms of both cooling ability and tribological aspects. However, no study has been found on the machining of Al 2024-T3 alloy under MoS2-based nanofluid. Based on these observations, in this study, sustainable cutting environments such as base fluid MQL and MoS_2 based NFMQL cooling/lubrication were used while turning the Al 2024-T3 alloy and the results were compared with dry machining. The following sections include the experimental information, observations and discussion, and conclusions of the study.

2. Materials and methods

2.1. Workpiece, machine and cutting tool

During the chip removal tests, AA 2024 T3 Al alloy (supplied from Seykoc Aluminum company, Turkey) of 65 mm diameter and 270 mm length was utilized as workpiece material. While the chemical content of the test sample is illustrated in Table 1, its mechanical features are provided in Table 2.

Turning of the alloy was performed by ACCUWAY brand and JT-150 model CNC lathe. During the turning experiments, uncoated cemented carbide inserts (VCGT 160404 FL) with tip angles of 35°, tip radius of 0.4 mm, and a positive rake angle, manufactured by TaeguTec company, were used. While these inserts used were connected to the lathe, SVJCR 2525 M16 coded tool holder was used, also produced by TaeguTec company (Korea). However, since the tool holder mounting slot of the lathe is maximum 20 mm, the thickness of the tool holder has been reduced from 25 to 20 mm by milling. Technical characterizations of the cutting insert are provided in Table 3.

Table 2 – The mechanical features of AA 2024 T3 alloy.

Yield strength (MPa)	Tensile strength (MPa)	Elongation (50%)	Hardness (HB)
340	475	18	220

2.2. MQL system, cutting fluid and nanoparticles

MQL system manufactured by SKF company (model LubriLean-Vario) was used in the metal removal experiments. The critical MQL parameters such as nozzle diameter (2 mm), application type (outside), spraying distance (30 mm) and spray angle (30°) were fixed during all experiments. Cutting oil, which is put into the MQL system for pure-MQL experiments and used in the preparation of nanofluids as a base fluid, is a mineral-based cutting oil that provided by SKF company. Cutting oil has a density of 0.93 g/mL and a kinematic viscosity of 14 cSt at 20 °C. In the preparation of nanofluids, molybdenum disulfide (MoS_2) nanoparticles supplied from Nanografi Nanotechnology AS (Turkey) were dispersed into base fluid. MoS_2 is an additive that is used extensively in applications requiring high temperature and pressure, thanks to its high wear resistance and superior friction properties [37]. Technical characteristics of MoS_2 particles can be listed as size of 80 nm, purity 99%, density of 4.8 g/cm^3, layered structure, and black appearance. The results of scanning electron microscopy (SEM) and energy dispersive x-ray analysis (EDAX) analysis performed on MoS_2 nanoparticles utilized in preparation of nanofluid are presented in Fig. 1.

2.3. The process of preparing the nanofluids

For nanofluids preparation, a two-step mixing process was implemented. Accordingly, MoS_2 particles was added to mineral cutting oil in proportion (0.6% volume concentration) which is previously determined through preliminary experiments and literature knowledge [38] and they subjected to a series of mixing processes. In the steps followed in the mixing process, mineral cutting oil and nanoparticles were initially mixed at 1000 rpm for 60 min using a DAIHAN brand and HS-100D model mechanical mixer. After that, it was mixed for 60 min at 1500 rpm with magnetic stirrer using TERMAL brand and model N11150M. In this way, nano-additives are distributed homogeneously in mineral based cutting oil. The mixing process is shown in Fig. 2. The fresh nanofluids obtained were used without waiting against any precipitation conditions.

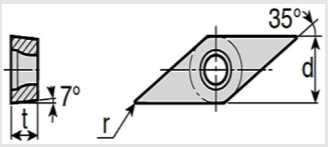
2.4. Experimental design

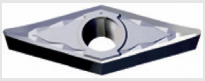
When turning AA2024 T3 Al alloy, the cooling conditions and cutting parameters such as cutting speed and feed rate were varied as presented in Table 4. Three levels of each factor were

Table 1 – The chemical content of AA 2024 T3 alloy (% weight).

Si	Cu	Mg	Mn	Fe	Ti	Zn	Ni	Al
0.294	4.43	1.47	0.452	0.344	0.062	0.166	0.018	Balance

Table 3 – Technical details of the cutting insert.





d (mm)	t (mm)	r (mm)
9.52	4.76	0.40

determined and Taguchi's L27 orthogonal array was marked as an appropriate experimental design for factors and their levels. In each experiment, the depth of cut was held at 1 mm. The outputs of the experimental design are surface roughness and maximum temperature. An overall view of the parameters used in the experiments is tabulated in Table 4. Furthermore, the experimental setup is given in Fig. 3.

2.5. *Measuring equipment and procedure*

In the investigation, after machining, average surface roughness (Ra) was handled as main measurement parameter to determine the surface condition. Portable surface roughness measuring instrument (Brand: MAHR; Model: MarSurf PS 10) was benefited in the measurements of surface roughness. The sampling length and evaluation length values of the device were set to 0.8 and 4 mm, respectively. During the measurements, the workpiece was rotated clockwise and the mean value was considered by taking measurement values from four different regions. A previously unused insert was used for each experiment. The roughness tester is calibrated with calibration blocks before measurements. Also, in order to avoid oxidizing the surfaces and affecting the results, the measurements were made immediately after the chip removal tests. During this study, OPTRIS PI 450 model thermal camera was benefited to measure the maximum temperatures at machining region. The thermal camera is positioned in such a way that it can see the cutting area exactly from a distance of 250 mm and is not affected by chip splashes. In addition, SEM pictures were obtained by using Zeiss LEO 440 made by Zeiss–Leica, Germany device to observe the conditions of worn tools. Lastly, detailed EDAX analyzes were employed for marking elemental composition to detect possible material adhesion on cutting tools.

3. Lubrication mechanism of MQL and nanofluids

MQL is an application that transfers a very small volume of cutting oil to the cutting zone in a form that can be called an oil mist by mixing it with compressed air. Basically, it performs differently in the cutting zone compared to flood cooling. While it is a completely appropriate definition to call flood cooling as a coolant because it discharges the heat from a region via convection, in the application of MQL, the concept

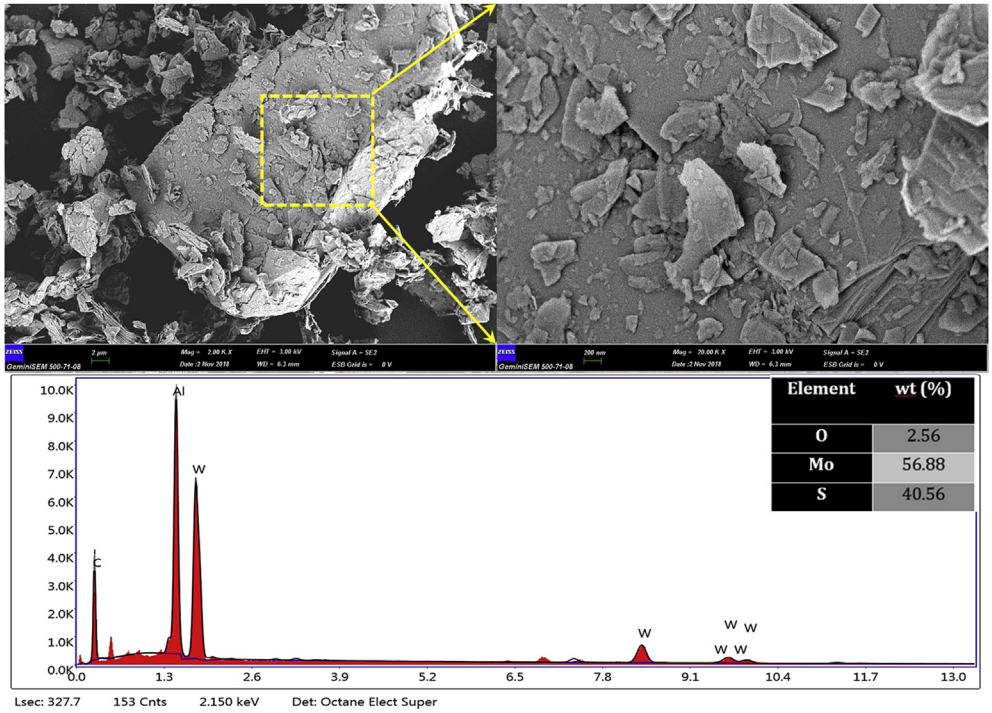


Fig. 1 – SEM and EDAX analysis of MoS_2 used in this work.

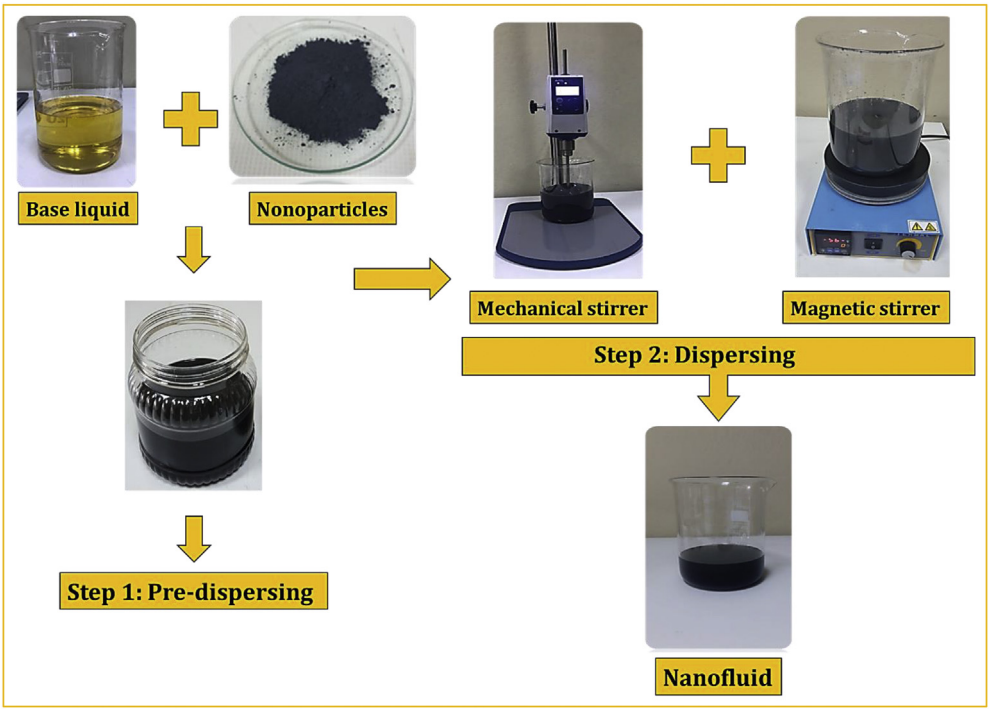


Fig. 2 – Nanofluid preparation procedure.

is more in favor of lubrication rather than coolant. A study done by Yildirim et al. [39] supports this argument and they emphasized that the lubricating ability of the MQL is superior to its cooling ability. The MQL covers the interface with a thin layer of lubricant and reduces friction and prevents friction-induced heat generation. The excellent lubricating property of a good MQL lubricant makes a great contribution to minimizing the heat transferred to the cutting tool by removing most of the heat caused by friction. In addition, depending on the thermal and physical properties of the cutting oil used, MQL also provides the discharge of heat with compressed air inherent in the system through forced convection mechanism [40]. However, deficiencies in eliminating friction and excessive heat generation with base fluid MQL, especially during high speed machining of various alloys with low thermal conductivity coefficient, posed a threat to cutting tool life, workpiece surface integrity and resulting in reduced machining efficiency [41]. In order to increase the heat transfer efficiency of MQL and to operate various tribological mechanisms, nanofluids are utilized in MQL implementation to improve the lubricating effects in the process. A certain amount of solid nanoparticles with a size of <100 nm (in one type or as multiple types of hybrid) is added to the base cutting oil to form a nanofluid and is subjected to some mixing processes to achieve a homogeneous distribution in the liquid [28]. With the compressed air in the nozzle, the nanofluid is atomized and sprayed to the area where the cutting takes place. Compressed air mainly plays a role in cooling, debris evacuation and nanofluid delivering, while the oil in MQL mainly lubricates the machining region. Nanoparticles, which

Table 4 – Test parameters.

Inputs	Details
Machine tool	ACCUWAY JT-150 CNC lathe
Work material	AA 2024 T3 Al alloy
Cutting insert	Uncoated cemented carbide inserts, ISO code: VCGT 160404 FL
Cutting speed (m/min)	300, 400 and 500
Feed rate (mm/rev)	0.1, 0.2 and 0.3
Depth of cut (mm)	1 mm
Cooling/lubrication strategy	Dry, base fluid MQL and NFMQL
Base fluid	Mineral-based cutting lubricant, density: 0.93 g/mL at 20 °C, kinematic viscosity: 14 cSt at 20 °C.
Nanoparticle and its concentration	MoS_2, 0.6% volume concentration
Nanofluid process	Two step method
MQL system	LubriLean-Vario model produced by SKF company
MQL parameters	Nozzle diameter: 2 mm, application type: outside, spraying distance: 30 mm, spray angle: 30°, flow rate: 100 mL/h, air pressure: 8 bar.
Design of experiment	Taguchi's L27 orthogonal array

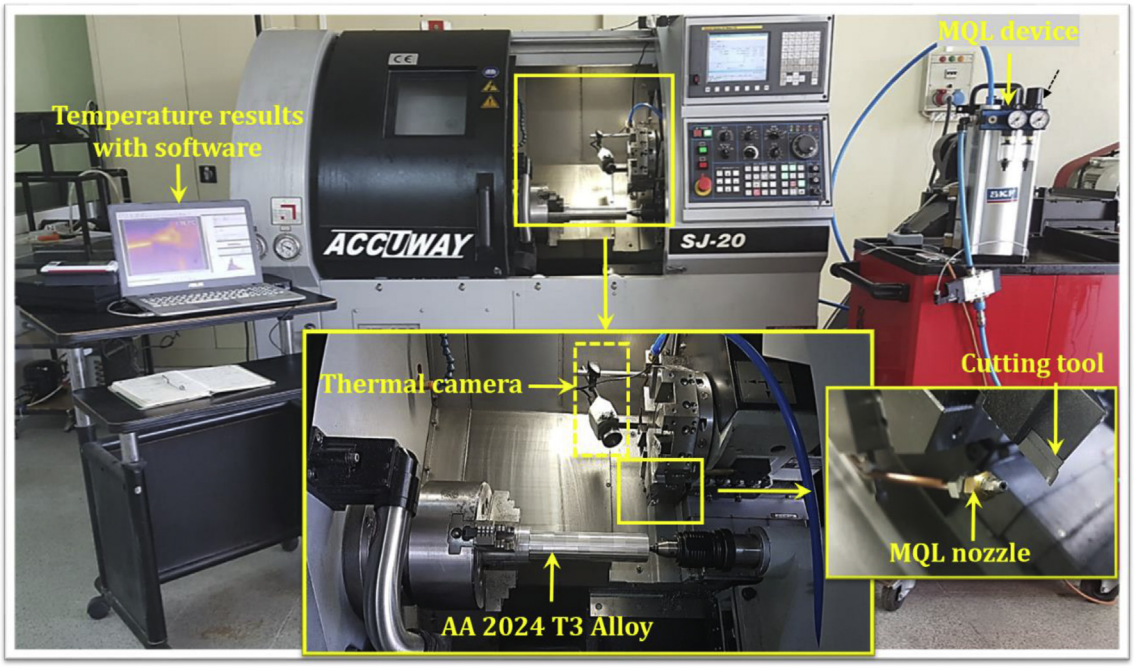


Fig. 3 – Experimental setup.

have higher thermal conductivity compared to the base cutting fluid, provide great convenience in increasing the heat transfer of the cutting zone and improving the cooling performance by further improving the heat dissipation. Also, the presence of nanoparticles enables various tribological mechanisms to work at the tool-chip-workpiece interface [42]. There is generally a consensus with the use of nanofluids in the existence of four lubrication mechanisms: (i) rolling; (ii) protective film; (iii) mending; and (iv) polishing effects, as illustrated in Fig. 4. Moreover, nanoparticles can be effective in lubrication due to sintering or melting on the tribo-film [43].

In the rolling mechanism (refer to Fig. 4 (a)), two aspects come to the fore in the contribution of nanofluids to tribological aspects. Firstly, nanoparticles are generally spherical and they act as load carriers by rolling between surfaces like a bearing during friction. Secondly, they form a sliding system that acts like a flat plate between two mating surfaces, reducing friction and wear. In the friction process, it helps to collect nanoparticles on the friction surfaces due to the effect of high temperature due to friction and the presence of the electric field generated during friction [43]. As shown in Fig. 4 (b), a protective film layer formed by the deposition of nanoparticles on friction surfaces is one of the most common mechanisms explaining tribological developments such as the reduction of friction and wear provided by these particles. The higher surface energy of rough surfaces increases the possibility of nanoparticles deposition on these surfaces. This allows the presence of a new synergistic lubrication consisting of a liquid film and non-heterogeneous dispersions of nanoparticles on the surface [44].

In mending mechanism (Fig. 4 (c)), nanoparticles tend to repair microdamages by filling micro cracks and depositing them on the rubbing surface, eventually helping to create flatter and smoother surfaces. However, beyond eliminating cracks by deposition into nanoparticles, it also has a different repair mechanism. As the size of the nanoparticles decreases, the amount of heat required for melting decreases. In the elevated temperature of the friction surfaces, these nanoparticles are smoothly melted/sintered within the microcracks within the contact area, thus acting as a filling material, penetrating the cracks and bonding tightly to the friction surface [43].

There is a consensus that rubbed surfaces lubricated with nanoparticles are much smoother owing to polishing mechanism. Abrasive nanoparticles in nanofluids act as a perfect polishing means and play an important role in achieving mechanical polishing by removing micro-deposits on friction surfaces during the friction process as illustrated in Fig. 4 (d). Because of the smoother surface polished with abrasive nanoparticles, the actual contact area of the mating surfaces is raised, lowering the friction coefficient and increasing load carrying ability [45]. In many conditions, nanofluids work not only to provide heat transfer and lubrication, but also to allow various tribological aspects by the action of multiple mechanisms. Furthermore, there may also be transitions between mechanisms depending on operating and friction conditions.

4. Results and discussion

4.1. *Surface roughness*

Fig. 5 represents main effect plots for surface roughness against cooling/lubrication strategy, cutting speed and feed rate. When the influence of cooling conditions given in the first part of Fig. 5 on the Ra is examined, it was discovered that dry machining provides the maximum Ra value. However, it

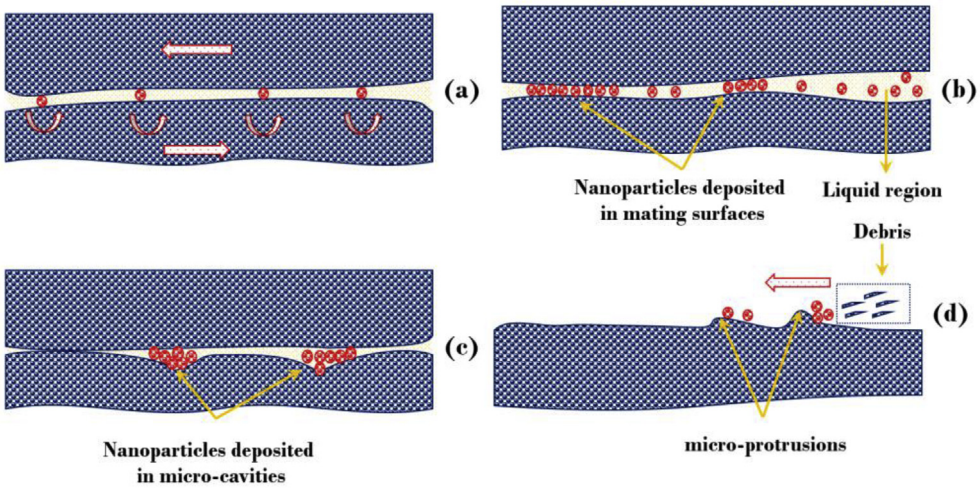


Fig. 4 – Tribological mechanisms with nanofluid a) rolling b) protective film c) mending e) polishing (Adopted and modified) [46].

decreases as the MQL device is enabled. Also, the NFMQL approach yielded the lowest Ra. The average Ra values obtained under dry, MQL and NFMQL machining environments were 4.183, 3.831 and 3.532 μm, respectively. In other words, the Ra values compared to dry machining provides 8.41% improvement in the MQL system, while this rate was obtained as 15.56% in the NFMQL system. Al-based materials have characteristics such as elevated thermal conductivity and low melting point. Moreover, they exhibit a higher thermal expansion coefficient than other metals, along with relative softness and flexibility [13]. Therefore, a dry environment is not suitable for machining such materials and the use of lubricant is mandatory to prevent adhesion. Indeed, Kannan et al. [47] stated that it is very difficult to machine Al without lubricant. Although conventional cutting fluids are offered as a solution, Al alloys contain significant amounts of silicon and therefore have high stickiness. This promotes rapid heat generation, leading to chip welding and BUE. Therefore, the high pressure of the cooling system to be used effectively removes the chips from the cutting area as well as cooling and lubrication and minimizes adhesion [13]. As a result, MQL-based cooling conditions provide significant improvements, especially when cutting Al-based materials. In addition, the MQL system can help improve surface quality by reducing thermal distortion [48]. In summary, MQL implementation can improve surface quality by forming a tribo-film layer at the tool–chip interface, reducing BUE and BUL formations, removing chips quickly from the cutting region, and breaking metallurgical problems experienced in dry cutting [49]. Under NFMQL, the pattern of surface roughness reduction persisted

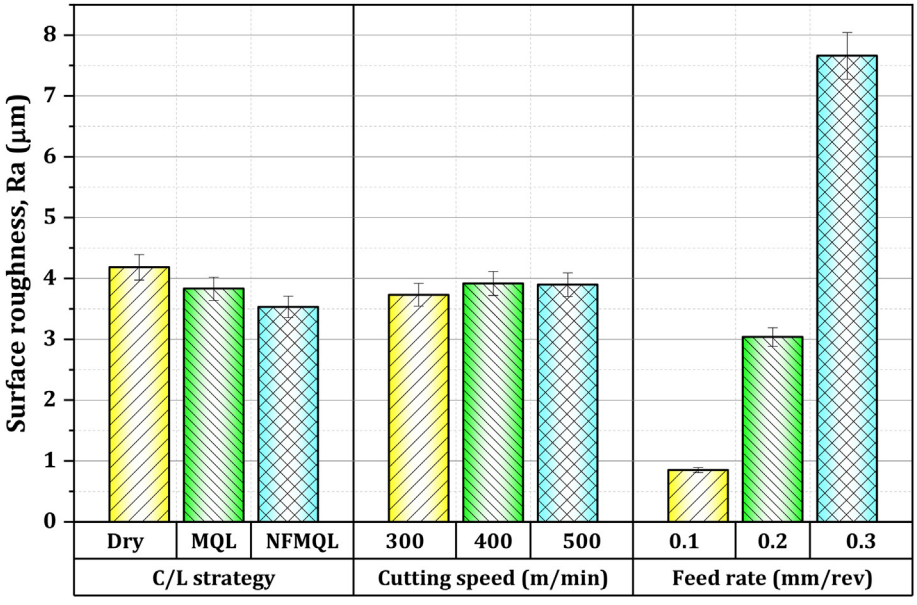


Fig. 5 – Main effect plot for Ra.

with the addition of nanoparticles to the base fluid. This has been related to the enhanced characteristics of the base fluid in which the particles are suspended. By demonstrating a ball effect at the tool-chip-workpiece interface, nano-sized solid lubricants improve the cutting fluid's tribological properties. In other words, they improve their lubrication performance due to their different molecular structures [50,51]. Nanoparticles have differing chemical activities, resulting in a range of film forming mechanisms and anti-friction properties in the machining region [52]. In addition, the thermal conductivity features of the coolant in which nanoparticles are embedded are also improved, thus dissipating the heat generated in the cutting zone more easily [53]. Rapeti et al. [54] claimed that the use of nanofluid improves the tribological and thermal properties and thus increases the surface quality. In another study, Sharma et al. [55] emphasized that compared to other cutting oils, nanofluids produce better surface finish. They proved that nanolubricants improve heat dissipation, cooling, and lubrication properties, as well as protecting the cutting insert. In the second part of Fig. 5, it is seen how cutting speed and average surface roughness are related. According to the outcomes of the tests, the lowest Ra value was obtained at a cutting speed of 300 m/min, and its value increased as the cutting speed increased to 400 m/min. At 500 m/min cutting speed, Ra decreased slightly. That is, in comparison with 300 m/min cutting speed, the average Ra value increased by 5.03% at the 400 m/min cutting speed, while this ratio was obtained as 4.44% at the 500 m/min cutting speed. When turning AA 2024 T3 Al alloy, BUE and BUL formations have been connected to this condition. The resulting heat at low cutting speeds cannot expose the material to atomic-scale plastic deformation, and thus adhesion cannot occur. On the other hand, diffusion and chemical wear processes, rather than BUE and BUL formations, can occur at extremely high temperatures. Therefore, BUE and BUL appears to be higher at medium cutting speeds [56]. In the last part of Fig. 5, the relation between the feed and the average surface roughness is given. Surface roughness is a property of feed, because as the feed rate increases, the surface roughness also increases [24]. Low feed rates can minimize cutting force and friction at the tool-chip-material interfaces. This has a positive effect by minimizing BUE and form defect. Also, with increasing feed rate, elastic deformation increases, resulting in a deterioration of surface quality [57]. It can be said that all these are responsible for the surface roughness that increases with feed.

4.2. *Surface topography*

A series of experiments were performed in this part of the study to investigate the impact of cooling/lubrication techniques on surface topography, which is an essential component of surface integrity. In this way, by keeping cutting parameters like cutting speed (500 m/min), feed (0.3 mm/rev), and depth of cut (1 mm) constant, the influences of cutting parameters on topography results were purified. 3D topography map and 2D surface photographs of turned surfaces are presented in Fig. 6.

When looking at Fig. 6, it is clear that the peak and valley differences are much higher in the dry turning phase, and these differences decrease when MQL methods are implemented (refer to 3D surface topography images). It can be easily said that the cooling condition with the least peak and valley difference is the NFMQL strategy. In other words, while the highest surface irregularities were achieved by dry machining, surface irregularities have decreased with the use of base fluid-MQL and NFMQL conditions. This correlates to the surface roughness findings from Section 4.1. Also, another situation clearly seen in Fig. 6 is that during dry machining, chip particles adhere to the surface and adversely affect the surface quality (refer to 2D machined surface images). The inability to quickly evacuate chips from the cutting region, particularly when machining light alloys like Al, causes scraping of the surfaces, chip adhesion, and, as a result, degradation of the surface quality [58]. With the inclusion of cooling systems in the cutting process, adhesion on the surfaces is eliminated. It is remarkable to improve surface quality by limiting adhesion, which is one of the major problems encountered when machining light alloys like Al. In addition, compressed air provided in the base fluid MQL and NFMQL systems also played an important role in evacuating the chips from the machining region immediately. With the use of an improved cooling-lubricating agent such as nanofluids, friction is reduced, chips are removed from the cutting zone, resulting in a smoother surface [59]. In summary, machined surface under NFMQL is smoother and has less deformation when compared to dry and base fluid MQL. This implies that when using a MoS_2 nanoparticles doped base fluid in MQL, the surface integrity can be enhanced. This result provides an important opportunity to improve the surface integrity when machining light alloys that are highly prone to sticking to machined surfaces.

4.3. *Maximum temperature*

Cutting temperatures have a substantial effect on main machining indicators including tool wear, tool lifespan, surface integrity, and chip forming process, all of which are directly related to machining performance [60]. Therefore, it is very important to measure, control and keep it at certain intervals. The influence of cutting environment strategies, cutting speed, and feed on maximum temperature detected by thermal camera in the cutting zone was studied in this part of the analysis, and the findings are demonstrated in Fig. 7. Dry machining provides the highest cutting temperature, as seen in Fig. 7. There tends to be a major drop in cutting temperatures when cutting fluid is used in the machining process. The cutting temperature is affected by the material's ductility, thermal conductivity, and thermal dissipation capacity, as well as the specific energy requirement. However, cutting temperatures in the cutting zone that are too high do serious harm to the cutting tool and the material of the workpiece. Consequently, the use of coolant is the most common method to dissipate cutting temperatures from the cutting zone [61]. The findings of this analysis are also consistent with the condition stated above, with a substantial reduction in cutting temperatures found when the MQL system was used. In the MQL system, a tiny volume of cutting fluid like oil mist penetrates the tool-chip-workpiece interface more efficiently, creating a thin film layer and helping to lower the cutting

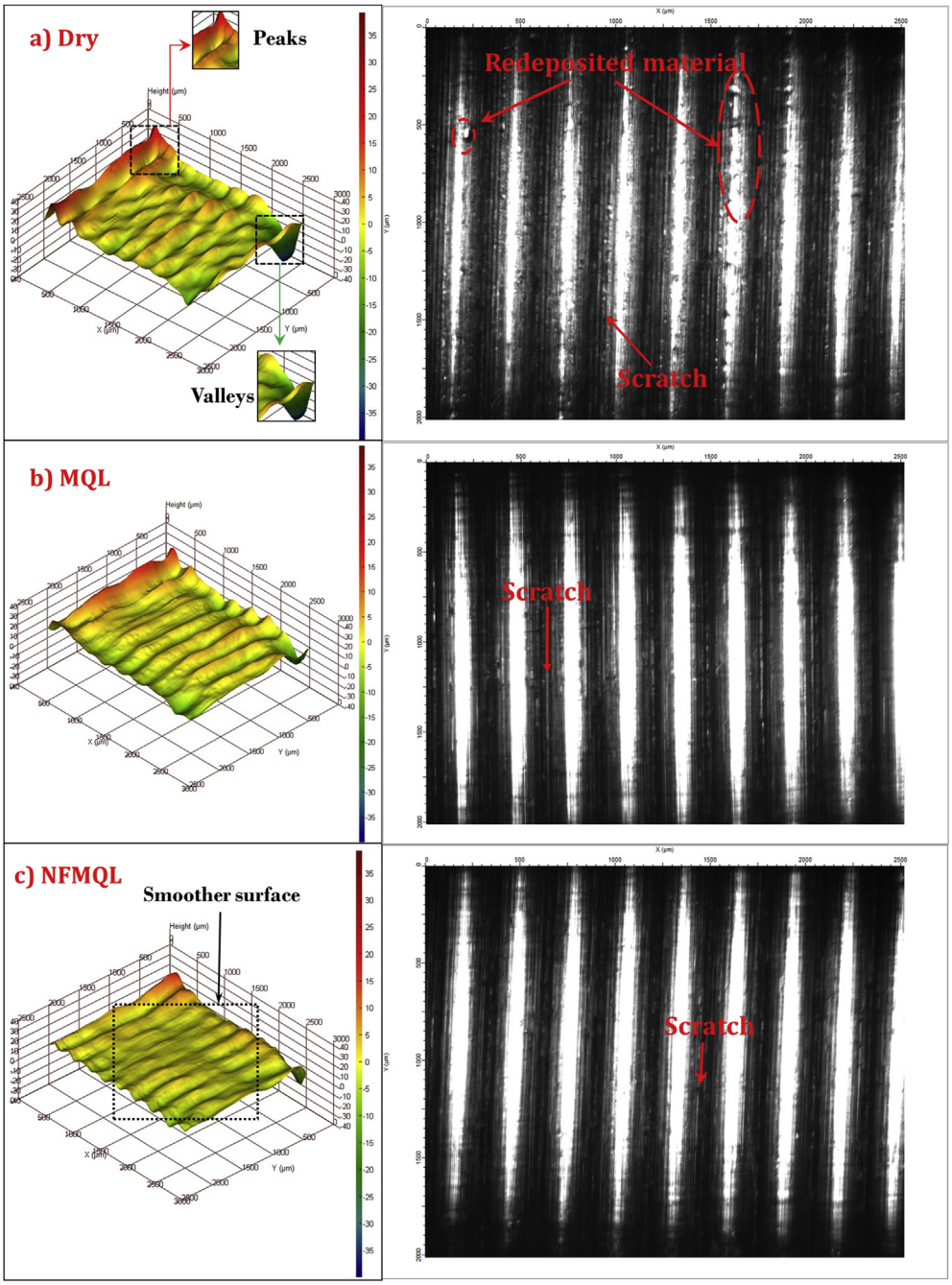


Fig. 6 – Surface topography of machined surfaces in 3D and 2D illustrations under a) dry mode, b) MQL, and c) NFMQL.

temperature by reducing friction [62]. Furthermore, it is seen that through the employment of the NFMQL method, the trend in cutting temperature also continues to decline. Compared to dry machining, the MQL implementation decreased the cutting temperature by 10.21%, while the MoS_2 nanoparticles doped NFMQL declined it by 22.44% on average. With the NFMQL system, the decrease in cutting temperature has been associated with the additives improving the thermal properties of the coolant [63]. Nanoparticles have high thermal conductivity values, for this reason, they can release the heat in machining area more rapidly through convection and conduction [64]. In addition, significant improvements can be achieved in the reduction of friction (and therefore also in temperature) thanks to the possible mechanisms that occur between the friction surfaces, namely, mending, protective film, third body, sliding and polishing effects [45]. In previous studies, thermal and tribological properties of nanoparticles were emphasized. For example; Donk et al. [65] concluded that nanofluids offer significant improvements in cutting temperature reduction through their tribological and thermal properties. Akhtar et al. [66], in their study comparing nanofluid with different cooling conditions, emphasized that nano-

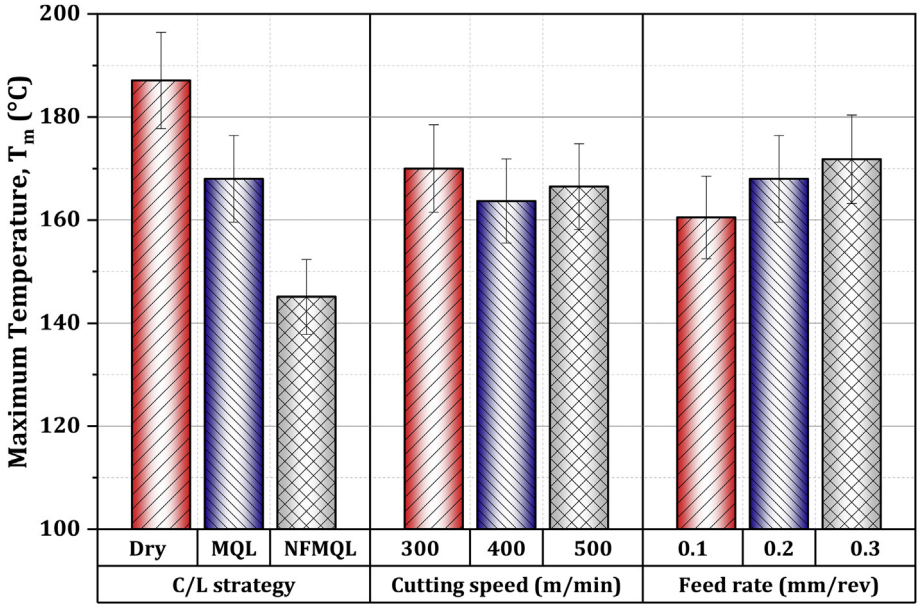


Fig. 7 – Main effect plot for maximum temperature.

additives improve the cutting fluid properties and thus reduce the cutting temperature. Moura et al. [67] claimed that nanofluids develop cutting efficiency compared to dry and wet environments. Rahmati et al. [68] stated that when cutting AA6061-T6 material, MoS_2-doped NFMQL is more effective than pure MQL and increases cutting performance. Considering the effect of the cutting speed during the turning of the Al alloy as shown in Fig. 7, although there was a slight decrease with increasing cutting speed, the further increase enhanced the temperature again. Moreover, Fig. 7 also illustrates the impact of feed rate on maximum temperature. A linear increase in temperature was observed with increasing feed rate. Compared with 0.1 mm/rev feed, the cutting temperature increased by 4.67% at 0.2 mm/rev feed, while this rate was 7.03% at 0.3 mm/rev feed. The cause of this issue is believed to be that as the feed rate increases, the cutting temperature rises as the friction and chip volume extracted rise.

4.4. *Investigation of BUE and BUL formations on cutting tool*

Tool wear is the most important parameter for evaluating tool life because of its effect on quality loss of manufactured parts and cost concerns. For this reason, a satisfying production performance by increasing tool life is only possible by minimizing tool wear. One mechanism or the combination of more than one mechanism can cause tool wear in any machining process [69]. Although, there are various wear mechanisms that damage the tool in different directions, one of the dominant wear mechanisms is undoubtedly adhesive wear [70]. The main factors that determine the adhesive wear and its degree are workpiece material, tool material, temperature and type of process [71]. When suitable conditions such as temperature range are provided, adhesion wear can reveal in two different ways. One of these is the bonding of tool material particles to the workpiece material. The other is that the workpiece material is welded to the tool material by thermomechanical effects. This is also referred to as the secondary adhesion mechanism [72]. The adhesive wear mechanism can basically damage the cutting tool in two ways. These are (i) the changing ideal tool geometry with adhered material (ii) the separation of the adhered material along with the tool material particles from the tool after a certain cycle [41]. However, interestingly, in some studies, it has been reported that the material adhering on the tool acts as a coating on the tool, protecting the tool from abrasive type wear [73]. Adhesion wear is a phenomenon particularly experienced in the machining of light alloys such as Al. Low and medium temperature ranges are conditions where this wear type is the favorite [56]. While rising temperatures can limit adhesion wear by facilitating material flow across the tool, extreme temperatures can trigger cutting tool-induced damage mechanisms. The efficiency of the indirect (or secondary) adhesive wear mechanism manifests itself in the form of BUE formation at the cutting edge and BUL formation on the tool flank and rake face [74]. In the present experimental research, the intensive BUE and BUL formations produced on the cutting tool during the machining of AA 2024 T3 Al alloy under dry cutting are shown in Fig. 8. Accordingly, it has been proven once again that BUE and BUL are one of the substantial challenges encountered when machining Al alloys. The occurrences of BUL and BUE are closely related. Although it has been thought that BUL was formed by extrusion of accumulated work material on rake face after BUE, detailed studies have revealed that BUL was initially formed before BUE and played an active role in the formation of BUE [8,72]. BUL is formed rapidly at the start of the turning process by a thermomechanical process, and the resulting composition of BUL is very close to pure Al [72]. In this process, high local

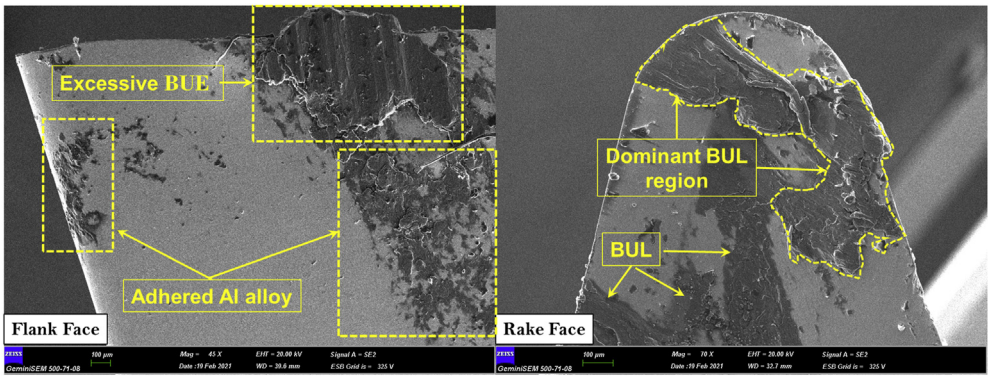


Fig. 8 – SEM image of cutting tool after dry cutting of AA 2024 T3 alloy at cutting speed of 500 m/min and feed rate of 0.3 mm/rev.

temperatures first cause the Al matrix to soften. Then, the Al is squeezed and welded on the rake face by the effect of pressure. Since the intermetallic particles in the material have a higher melting point than Al, they remain solid and are ejected with the chips [9,74]. After the BUL is created, the initial machining conditions change and provide the mechanical adhesion and BUE formation [8]. In Fig. 8, the plastered workpiece layers outside the cutting edge area and the observed BUE on the cutting edge confirmed this hypothesis. In addition, detailed EDAX analysis (refer to Fig. 9) clearly shows the elements placed on the tool. As can be seen in Fig. 8, BUE has distorted the ideal geometry of the tool, and it is obvious that this will degrade the surface quality. Moreover, it is highly likely that BUE will remove from adhered surface together with tool material at a specific moment of the cutting process, causing wear [75]. As a result, turning of Al alloy under dry conditions is not recommended due to the damage caused by excessive BUL and BUE formations to the tool geometry and therefore to the workpiece surface quality as mentioned Section 4.1. Fig. 10 represents the final condition of the cutting tool working under MQL after machining AA 2024 T3 Al alloy. Also, Fig. 11 demonstrates the distribution of the different elements on cutting insert. Accordingly, although BUL and adhered material particles were observed, the inclusion of the MQL system in the cutting process has been an opportunity to reduce the BUE generation compared to dry

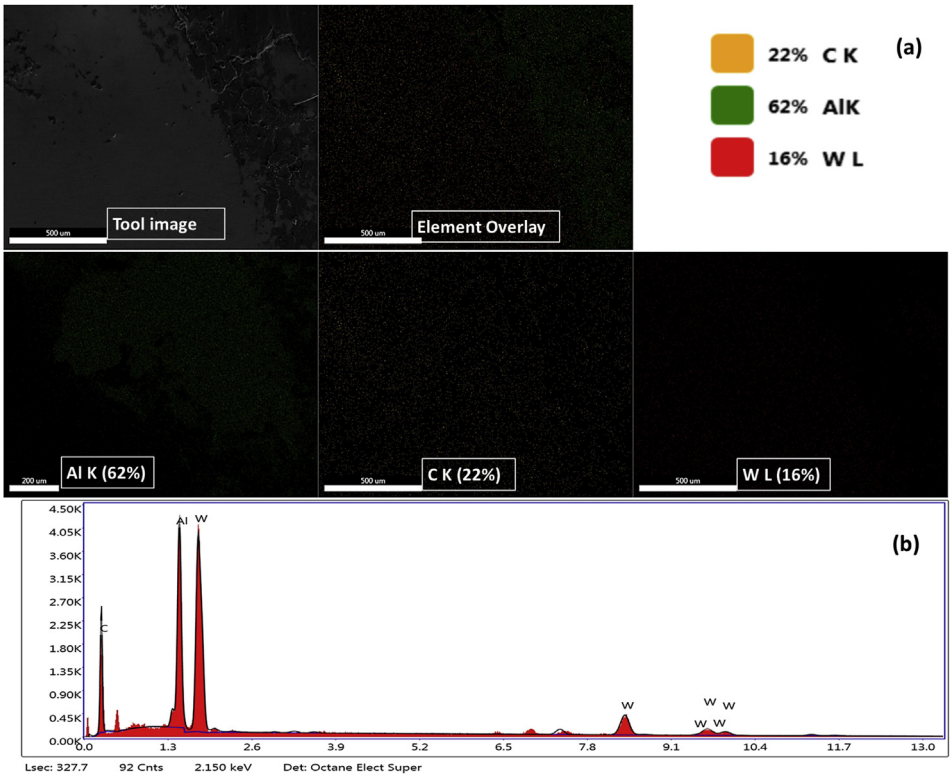


Fig. 9 – EDAX analyzes a) EDAX elemental mapping b) EDAX spectrum for tool worn under dry environment.

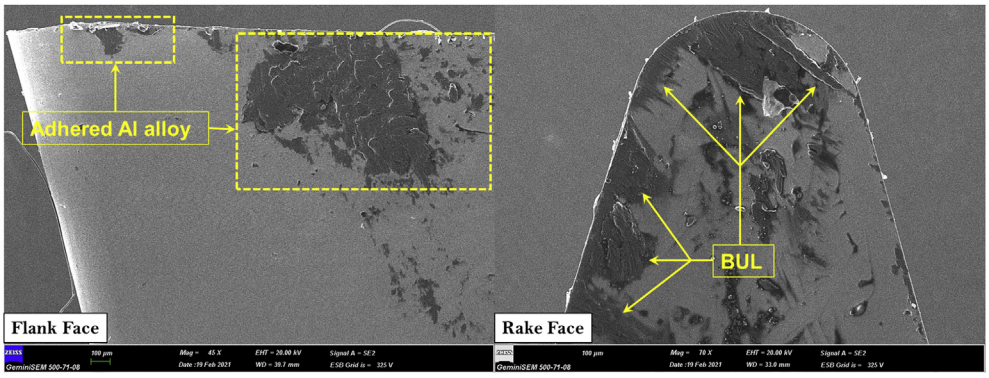


Fig. 10 – SEM image of cutting tool after MQL assisted cutting of AA 2024 T3 alloy at cutting speed of 500 m/min and feed rate of 0.3 mm/rev.

cutting. Through MQL, the development of a tribo-film layer that prevents excessive adhesion at the tool–chip interface may be related to reduced or removed BUE. Fig. 12 indicates the final state of the cutting tool working under NFMQL after machining AA 2024 T3 Al alloy. Moreover, Fig. 13 proves the distribution of the different elements placed on the tool. It is also possible to see BUL and adhered workpiece material on this tool. However, similar to the process performed in the MQL environment, the BUE formation has been significantly eliminated thanks to NFMQL. Moreover, a less damaged cutting edge was obtained when machining Al alloy under NFMQL compared to both dry cutting and MQL environments. The event has been associated with improving the features of the base fluid in which the particles are suspended. By

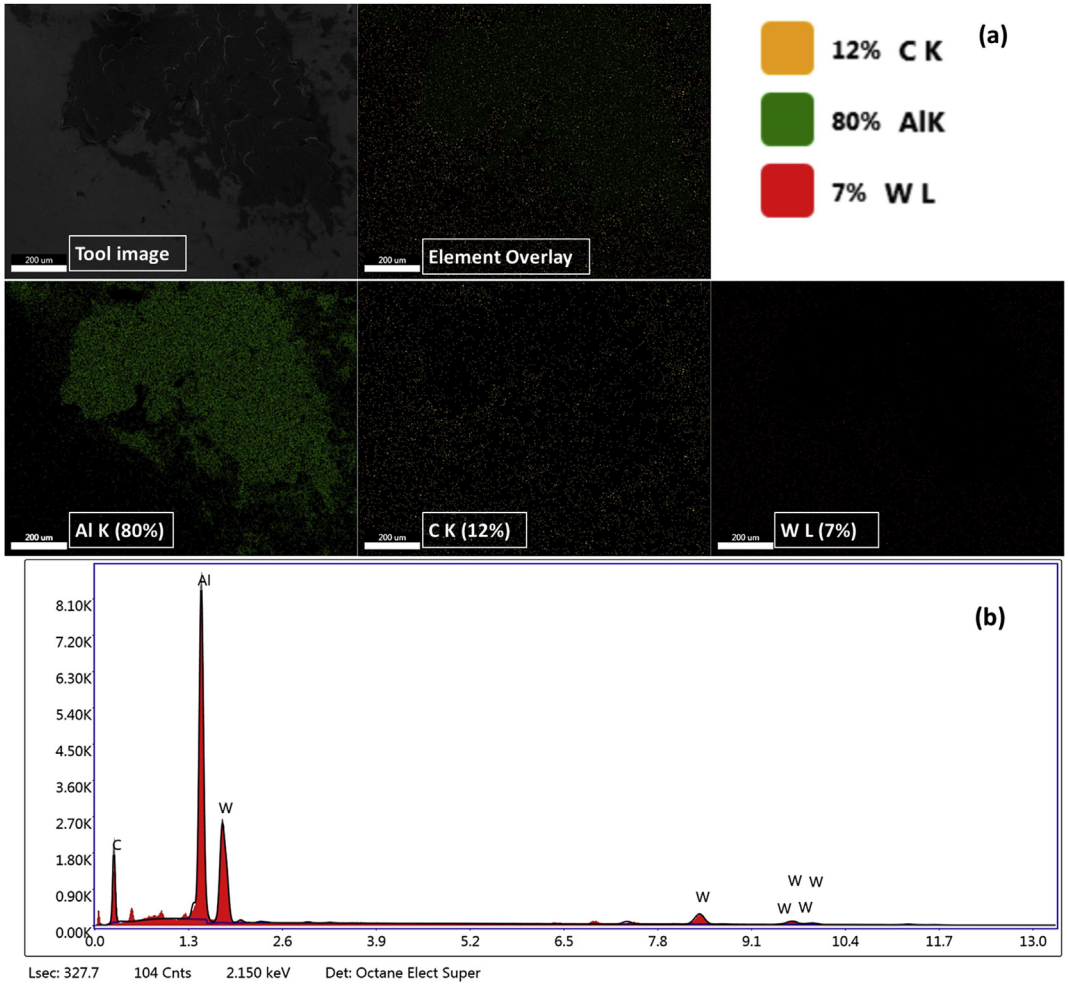


Fig. 11 – EDAX analyzes a) EDAX elemental mapping b) EDAX spectrum for tool worn under base fluid MQL.

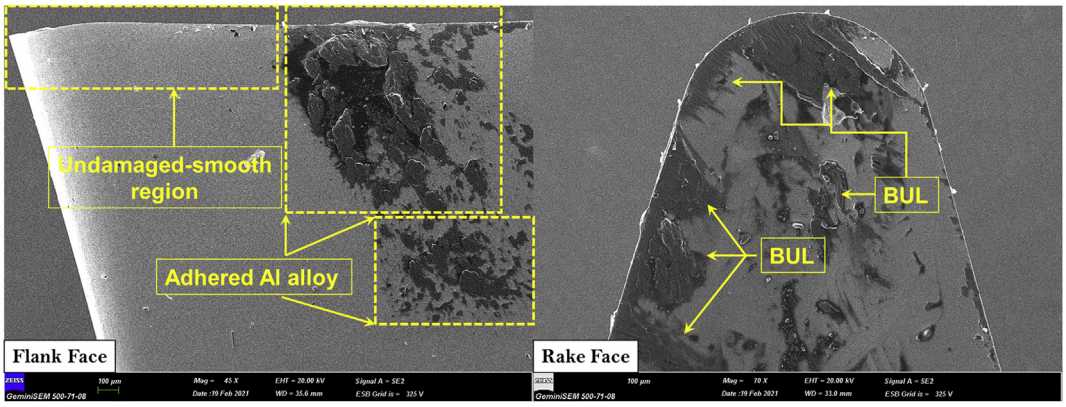


Fig. 12 – SEM image of cutting tool after NFMQL cutting of AA 2024 T3 alloy at cutting speed of 500 m/min and feed rate of 0.3 mm/rev.

demonstrating a ball effect at the tool-chip-workpiece interfaces, nano-sized solid particles boost the tribological characteristics of the base fluid. That is, particles improve lubrication performance due to their different molecular structures. Nanoparticles have differing chemical activities, resulting in a range of film forming mechanisms and anti-friction properties in the machining region [52]. These are thought to be factors that provide less adhesion to occur. In addition to the tribological properties developed with nano-fluids, the compressed air provided in the MQL and NFMQL systems enabled rapid discharge of chips from machining area and thus contributed to the reduction of adhesion.

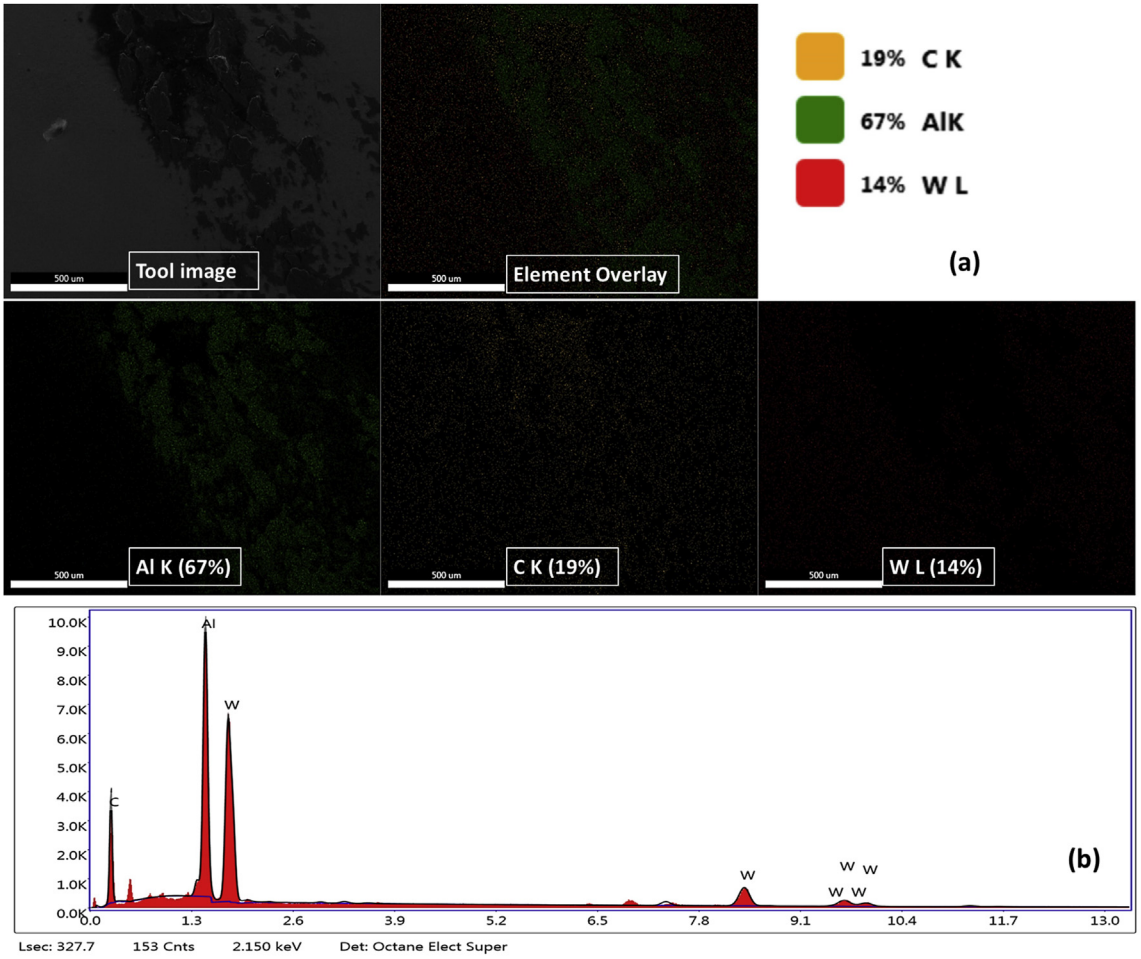


Fig. 13 – EDAX analyzes a) EDAX elemental mapping b) EDAX spectrum for tool worn under NFMQL.

5. Conclusion

The current research paper focused on critical machinability indicators such as surface roughness, surface topography, maximum temperature and dominant tool wear mechanism during turning of AA 2024 T3 Al alloy under various cooling/lubrication strategies i.e., dry cutting, base fluid MQL and MoS_2 nanoparticles dispersed NFMQL. The conclusions reached from this research can be drawn as follows:

- When compared to dry machining, the Ra values exhibit 8.41% improvement in the base fluid MQL strategy, while this rate was obtained as 15.56% in the NFMQL. The increased surface quality may be attributed improvements with MQL due to the formation of a tribo-film layer at the tool–chip interface, reducing BUE and BUL formations, rapid removal of chips from the cutting zone and breaking metallurgical problems encountered in dry cutting. Moreover, the further improvement in surface quality with the NFMQL has been associated an advance in the tribological aspects of the base fluid through MoS_2 nanaoparticles.
- According to surface topography results, there is a high difference between peaks and valleys, scratches and chip adhesion observed on the machined surface during dry cutting. They have decreased with the use of base fluid-MQL and NFMQL conditions. Also, machined surface under NFMQL is smoother and has less deformation when compared to dry and base fluid MQL.
- Compared to dry machining, the base fluid MQL implementation helps to decline cutting temperature by 10.21%, while the MoS_2 nanoparticles doped MQL decreased the cutting temperature by 22.44% on average. With the NFMQL system, the decrease in cutting temperature has been associated with the additives improving the thermal properties of the coolant.
- Because of the effectiveness of the adhesive wear mechanism, the intensive BUE and BUL formations formed on the cutting insert when machining AA 2024 T3 Al alloy under dry cutting. Accordingly, it has been proven once again that BUE and BUL are one of the main problems encountered in the machining of Al alloys.
- BUE formation has been significantly eliminated thanks to NFMQL. Moreover, a less damaged cutting edge was obtained under NFMQL compared to both dry cutting and MQL environments. The event has been associated with improving the features of the base fluid. In addition to the tribological properties developed with nanofluids, the compressed air provided in the MQL and NFMQL systems also enabled rapid removal of chips from the cutting area and thus contributed to the reduction of adhesion.

Author contributions

Ayşegül Yücel: Writing-original draft, Investigation, Resources, Data Curation, Funding acquisition.

Çağrı Vakkas Yıldırım: Writing-original draft, Investigation, Data Curation, Supervision, Project administration, Funding acquisition.

Murat Sarıkaya: Visualization, Writing - Review & Editing, Methodology, Formal analysis.

Şenol Şirin: Investigation, Resources, Methodology, Data Curation.

Turgay Kıvak: Writing - Review & Editing, Formal analysis, Methodology, Validation.

Munish Kumar Gupta: Conceptualization, Writing - Review & Editing, Methodology, Visualization.

Ítalo V. Tomaz: Writing - Review & Editing, Visualization, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to thank the Erciyes University Research Fund for their financial support of present work (FYL-2020-10160).

REFERENCES

[1] Bansal A, Singla AK, Dwivedi V, Goyal DK, Singla J, Gupta MK, et al. Influence of cryogenic treatment on mechanical performance of friction stir Al-Zn-Cu alloy weldments. J Manuf Process 2020;56:43–53. https://doi.org/10.1016/j.jmapro.2020.04.067.

[2] Carter Ralph W, Steven Johnson W, Toivonen P, Makeev A, Newman JC. Effect of various aircraft production drilling procedures on hole quality. Int J Fatigue 2006;28:943–50. https://doi.org/10.1016/j.ijfatigue.2005.09.009.

[3] Reis DA, Couto AA, Domingues Jr NI, Hirschmann AC, Zepka S, de Moura Neto C. Effect of artificial aging on the mechanical properties of an aerospace aluminum alloy 2024. Defect Diffus Forum 2012;326:193–8.

[4] Nakai M, Eto T. New aspect of development of high strength aluminum alloys for aerospace applications. Mater Sci Eng A 2000;285:62–8.

[5] Kustas FM, Fehrehnbacher LL, Komanduri R. Nanocoatings on cutting tools for dry machining. CIRP Ann-Manuf Technol 1997;46:39–42. https://doi.org/10.1016/s0007-8506(07)60771-9.

[6] Sarikaya M, Gupta MK, Tomaz I, Danish M, Mia M, Rubaiee S, et al. Cooling techniques to improve the machinability and sustainability of light-weight alloys: a state-of-the-art review. J Manuf Process 2021;62:179–201. https://doi.org/10.1016/j.jmapro.2020.12.013.

[7] Martín-Béjar S, Trujillo FJ, Sevilla L, Marcos M. Indirect adhesion wear parametric analysis in the dry turning of UNS A97075 Alloys. Procedia Manuf 2017;13:418–25. https://doi.org/10.1016/j.promfg.2017.09.036.

[8] Sánchez JM, Rubio E, Álvarez M, Sebastián MA, Marcos M. Microstructural characterisation of material adhered over cutting tool in the dry machining of aerospace aluminium alloys. J Mater Process Technol 2005;164–165:911–8. https://doi.org/10.1016/j.jmatprotec.2005.02.058.

[9] Carrilero MS, Bienvenido R, Sánchez JM, Álvarez M, González A, Marcos M. A SEM and EDS insight into the BUL

and BUE differences in the turning processes of AA2024 Al-Cu alloy. Int J Mach Tools Manuf 2002;42:215–20. https://doi.org/10.1016/S0890-6955(01)00112-2.
[10] List G, Nouari M, Géhin D, Gomez S, Manaud JP, Le Petitcorps Y, et al. Wear behaviour of cemented carbide tools in dry machining of aluminium alloy. Wear 2005;259:1177–89. https://doi.org/10.1016/j.wear.2005.02.056.
[11] Nouari M, List G, Girot F, Coupard D. Experimental analysis and optimisation of tool wear in dry machining of aluminium alloys. Wear 2003;255:1359–68. https://doi.org/10.1016/S0043-1648(03)00105-4.
[12] Girot F, Géhin D. Dry drilling of aluminium alloys for aeronautics. Mécanique Ind 2002;3:301–13.
[13] Kelly J, Cotterell M. Minimal lubrication machining of aluminium alloys. J Mater Process Technol 2002;120:327–34. https://doi.org/10.1016/S0924-0136(01)01126-8.
[14] Rifat M, Rahman MH, Das D. A review on application of nanofluid MQL in machining. AIP Conf Proc 2017;1919. https://doi.org/10.1063/1.5018533.
[15] Nsr K, M G, Anwar S, Rahman MA, Erdi Korkmaz M, Gupta MK, et al. Investigation of surface modification and tool wear on milling Nimonic 80A under hybrid lubrication. Tribol Int 2020:106762. https://doi.org/10.1016/j.triboint.2020.106762.
[16] Günan F, Kıvak T, Yıldırım ÇV, Sarıkaya M. Performance evaluation of MQL with AL2O3 mixed nanofluids prepared at different concentrations in milling of Hastelloy C276 alloy. J Mater Res Technol 2020;9:10386–400. https://doi.org/10.1016/j.jmrt.2020.07.018.
[17] Danish M, Gupta MK, Rubaiee S, Ahmed A, Korkmaz ME. Influence of hybrid Cryo-MQL lubri-cooling strategy on the machining and tribological characteristics of Inconel 718. Tribol Int 2021:107178.
[18] Krolczyk GM, Nieslony P, Maruda RW, Wojciechowski S. Dry cutting effect in turning of a duplex stainless steel as a key factor in clean production. J Clean Prod 2017;142:3343–54. https://doi.org/10.1016/j.jclepro.2016.10.136.
[19] Chavoshi SZ. Tool flank wear prediction in CNC turning of 7075 AL alloy SiC composite. Prod Eng 2011;5:37–47. https://doi.org/10.1007/s11740-010-0282-x.
[20] Krolczyk GM, Maruda RW, Krolczyk JB, Nieslony P, Wojciechowski S, Legutko S. Parametric and nonparametric description of the surface topography in the dry and MQCL cutting conditions. Measurement 2018;121:225–39. https://doi.org/10.1016/j.measurement.2018.02.052.
[21] Maruda RW, Wojciechowski S, Szczotkarz N, Legutko S, Mia M, Gupta MK, et al. Metrological analysis of surface quality aspects in minimum quantity cooling lubrication. Measurement 2021;171:108847. https://doi.org/10.1016/j.measurement.2020.108847.
[22] Yıldırım ÇV, Kıvak T, Sarıkaya M, Erzincanlı F. Determination of MQL parameters contributing to sustainable machining in the milling of nickel-base superalloy waspaloy. Arab J Sci Eng 2017;42:4667–81. https://doi.org/10.1007/s13369-017-2594-z.
[23] Krolczyk GM, Maruda RW, Krolczyk JB, Wojciechowski S, Mia M, Nieslony P, et al. Ecological trends in machining as a key factor in sustainable production – a review. J Clean Prod 2019;218:601–15. https://doi.org/10.1016/j.jclepro.2019.02.017.
[24] Yıldırım ÇV, Kıvak T, Erzincanlı F. Influence of different cooling methods on tool life, wear mechanisms and surface roughness in the milling of nickel-based waspaloy with WC tools. Arab J Sci Eng 2019;44:7979–95. https://doi.org/10.1007/s13369-019-03963-y.
[25] Singh G, Gupta MK, Hegab H, Khan AM, Song Q, Liu Z, et al. Progress for sustainability in the mist assisted cooling techniques: a critical review. Int J Adv Manuf Technol 2020;109:345–76. https://doi.org/10.1007/s00170-020-05529-x.
[26] Korkmaz ME, Gupta MK, Boy M, Yaşar N, Krolczyk GM, Günay M. Influence of duplex jets MQL and nano-MQL cooling system on machining performance of Nimonic 80A. J Manuf Process 2021;69:112–24. https://doi.org/10.1016/j.jmapro.2021.07.039.
[27] Wang X, Li C, Zhang Y, Ding W, Yang M, Gao T, et al. Vegetable oil-based nanofluid minimum quantity lubrication turning: academic review and perspectives. J Manuf Process 2020;59:76–97. https://doi.org/10.1016/j.jmapro.2020.09.044.
[28] Pimenov DY, Mia M, Gupta MK, Machado AR, Tomaz Í V, Sarikaya M, et al. Improvement of machinability of Ti and its alloys using cooling-lubrication techniques: a review and future prospect. J Mater Res Technol 2021;11:719–53. https://doi.org/10.1016/j.jmrt.2021.01.031.
[29] Gupta MK, Khan AM, Song Q, Liu Z, Khalid QS, Jamil M, et al. A review on conventional and advanced minimum quantity lubrication approaches on performance measures of grinding process. Int J Adv Manuf Technol 2021. https://doi.org/10.1007/s00170-021-07785-x.
[30] Şirin E, Kıvak T, Yıldırım ÇV. Effects of mono/hybrid nanofluid strategies and surfactants on machining performance in the drilling of Hastelloy X. Tribol Int 2021;157:106894. https://doi.org/10.1016/j.triboint.2021.106894.
[31] Rahmati B, Sarhan AaD, Sayuti M. Investigating the optimum molybdenum disulfide (MoS2) nanolubrication parameters in CNC milling of AL6061-T6 alloy. Int J Adv Manuf Technol 2014;70:1143–55. https://doi.org/10.1007/s00170-013-5334-x.
[32] Sayuti M, Erh OM, Sarhan AAD, Hamdi M. Investigation on the morphology of the machined surface in end milling of aerospace AL6061-T6 for novel uses of SiO2 nanolubrication system. J Clean Prod 2014;66:655–63. https://doi.org/10.1016/j.jclepro.2013.11.058.
[33] Najiha MS, Rahman MM, Kadirgama K. Performance of water-based TiO_2 nanofluid during the minimum quantity lubrication machining of aluminium alloy, AA6061-T6. Elsevier; 2015. https://doi.org/10.1016/j.jclepro.2015.12.015.
[34] Duan Z, Li C, Zhang Y, Dong L, Bai X, Yang M, et al. Milling surface roughness for 7050 aluminum alloy cavity influenced by nozzle position of nanofluid minimum quantity lubrication. Chinese J Aeronaut 2020. https://doi.org/10.1016/j.cja.2020.04.029.
[35] Kulkarni HB, Nadakatti MM, Kulkarni SC, Kulkarni RM. Investigations on effect of nanofluid based minimum quantity lubrication technique for surface milling of Al7075-T6 aerospace alloy. Mater Today Proc 2020;27:251–6. https://doi.org/10.1016/j.matpr.2019.10.127.
[36] Zhu Z, He B, Chen J. Evaluation of tool temperature distribution in MQL drilling of aluminum 2024-T351. J Manuf Process 2020;56:757–65. https://doi.org/10.1016/j.jmapro.2020.05.029.
[37] Shen B, Malshe AP, Kalita P, Shih AJ. Performance of novel MoS2 nanoparticles based grinding fluids in minimum quantity lubrication grinding. Trans NAMRI/SME 2008;36:357–64.
[38] Yücel A, Yıldırım ÇV. AA2024 alaşımının tornalanmasında nanoakışkan konsantrasyon oranı ve MMY parametrelerinin yüzey pürüzlülüğü ve kesme sıcaklığı üzerindeki etkisi. İmalat Teknol ve Uygulamaları 2020;1:18–32.
[39] Yıldırım ÇV, Kıvak T, Sarıkaya M, Şirin Ş. Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL. J Mater Res Technol 2020.
[40] Gupta MK, Song Q, Liu Z, Sarikaya M, Jamil M, Mia M, et al. Experimental characterisation of the performance of hybrid cryo-lubrication assisted turning of Ti–6Al–4V alloy. Tribol Int 2021;153:106582. https://doi.org/10.1016/j.triboint.2020.106582.

[41] Yıldırım ÇV, Sarıkaya M, Kıvak T, Şirin. The effect of addition of hBN nanoparticles to nanofluid-MQL on tool wear patterns, tool life, roughness and temperature in turning of Ni-based Inconel 625. Tribol Int 2019;134. https://doi.org/10.1016/j.triboint.2019.02.027.
[42] Jia D, Li C, Zhang D, Zhang Y, Zhang X. Experimental verification of nanoparticle jet minimum quantity lubrication effectiveness in grinding. J Nanoparticle Res 2014;16:2758. https://doi.org/10.1007/s11051-014-2758-7.
[43] Kong L, Sun J, Bao Y. Preparation, characterization and tribological mechanism of nanofluids. RSC Adv 2017;7:12599–609. https://doi.org/10.1039/C6RA28243A.
[44] Kong L, Sun J, Bao Y, Meng Y. Effect of TiO2 nanoparticles on wettability and tribological performance of aqueous suspension. Wear 2017;376–377:786–91. https://doi.org/10.1016/j.wear.2017.01.064.
[45] Öndin O, Kıvak T, Sarıkaya M, Yıldırım ÇV. Investigation of the influence of MWCNTs mixed nanofluid on the machinability characteristics of PH 13-8 Mo stainless steel. Tribol Int 2020;148:106323. https://doi.org/10.1016/j.triboint.2020.106323.
[46] Cortes V, Ortega JA. Evaluating the rheological and tribological behaviors of coconut oil modified with nanoparticles as lubricant additives. Lubricants 2019;7. https://doi.org/10.3390/lubricants7090076.
[47] Kannan C, Varun Chaitanya CH, Padala D, Reddy L, Ramanujam R, Balan ASS. Machinability studies on aluminium matrix nanocomposite under the influence of MQL. Mater Today Proc 2020;22:1507–16. https://doi.org/10.1016/j.matpr.2020.02.068.
[48] Yang M, Li C, Zhang Y, Jia D, Li R, Hou Y, et al. Effect of friction coefficient on chip thickness models in ductile-regime grinding of zirconia ceramics. Int J Adv Manuf Technol 2019;102:2617–32. https://doi.org/10.1007/s00170-019-03367-0.
[49] Guo S, Li C, Zhang Y, Wang Y, Li B, Yang M, et al. Experimental evaluation of the lubrication performance of mixtures of castor oil with other vegetable oils in MQL grinding of nickel-based alloy. J Clean Prod 2017;140:1060–76.
[50] Gao T, Li C, Yang M, Zhang Y, Jia D, Ding W, et al. Mechanics analysis and predictive force models for the single-diamond grain grinding of carbon fiber reinforced polymers using CNT nano-lubricant. J Mater Process Technol 2021;290:116976. https://doi.org/10.1016/j.jmatprotec.2020.116976.
[51] Yang M, Li C, Zhang Y, Jia D, Li R, Hou Y, et al. Predictive model for minimum chip thickness and size effect in single diamond grain grinding of zirconia ceramics under different lubricating conditions. Ceram Int 2019;45:14908–20. https://doi.org/10.1016/j.ceramint.2019.04.226.
[52] Cui X, Li C, Zhang Y, Jia D, Zhao Y, Li R, et al. Tribological properties under the grinding wheel and workpiece interface by using graphene nanofluid lubricant. Int J Adv Manuf Technol 2019;104:3943–58. https://doi.org/10.1007/s00170-019-04129-8.
[53] Şirin Ş, Sarıkaya M, Yıldırım ÇV, Kıvak T. Machinability performance of nickel alloy X-750 with SiAlON ceramic cutting tool under dry, MQL and hBN mixed nanofluid-MQL. Tribol Int 2021;153:106673. https://doi.org/10.1016/j.triboint.2020.106673.
[54] Rapeti P, Pasam VK, Gurram KMR, Revuru RS. Performance evaluation of vegetable oil based nano cutting fluids in machining using grey relational analysis-A step towards sustainable manufacturing. J Clean Prod 2018;172:2862–75. https://doi.org/10.1016/j.jclepro.2017.11.127.
[55] Sharma AK, Singh RK, Dixit AR, Tiwari AK. Characterization and experimental investigation of Al_2O_3 nanoparticle based cutting fluid in turning of AISI 1040 steel under minimum quantity lubrication (MQL). Mater Today Proc 2016;3:1899–906. https://doi.org/10.1016/j.matpr.2016.04.090.
[56] Akhtar W, Sun J, Sun P, Chen W, Saleem Z. Tool wear mechanisms in the machining of Nickel based super-alloys: a review. Front Mech Eng 2014;9:106–19. https://doi.org/10.1007/s11465-014-0301-2.
[57] Manjunath Patel GC, Lokare D, Chate GR, Parappagoudar MB, Nikhil R, Gupta K. Analysis and optimization of surface quality while machining high strength aluminium alloy. Measurement 2020;152:107337. https://doi.org/10.1016/j.measurement.2019.107337.
[58] Hadad M, Hadi M. An investigation on surface grinding of hardened stainless steel S34700 and aluminum alloy AA6061 using minimum quantity of lubrication (MQL) technique. Int J Adv Manuf Technol 2013;68:2145–58. https://doi.org/10.1007/s00170-013-4830-3.
[59] Pham M-Q, Yoon H-S, Khare V, Ahn S-H. Evaluation of ionic liquids as lubricants in micro milling – process capability and sustainability. J Clean Prod 2014;76:167–73. https://doi.org/10.1016/J.JCLEPRO.2014.04.055.
[60] Abukhshim NA, Mativenga PT, Sheikh MA. Heat generation and temperature prediction in metal cutting: a review and implications for high speed machining. Int J Mach Tools Manuf 2006;46:782–800. https://doi.org/10.1016/J.IJMACHTOOLS.2005.07.024.
[61] Bhirud NL, Gawande RR. Measurement and prediction of cutting temperatures during dry milling: review and discussions. J Brazilian Soc Mech Sci Eng 2017;39:5135–58. https://doi.org/10.1007/s40430-017-0869-7.
[62] Duc TM, Long TT, Chien TQ. Performance evaluation of MQL parameters using Al2O3 and MoS2 nanofluids in hard turning 90CrSi steel. Lubricants 2019;7:658. https://doi.org/10.3390/lubricants7050040.
[63] Li B, Li C, Zhang Y, Wang Y, Jia D, Yang M, et al. Heat transfer performance of MQL grinding with different nanofluids for Ni-based alloys using vegetable oil. J Clean Prod 2017. https://doi.org/10.1016/j.jclepro.2017.03.213.
[64] Said Z, Gupta M, Hegab H, Arora N, Khan AM, Jamil M, et al. A comprehensive review on minimum quantity lubrication (MQL) in machining processes using nano-cutting fluids. Int J Adv Manuf Technol 2019;105:2057–86. https://doi.org/10.1007/s00170-019-04382-x.
[65] Dong PQ, Duc TM, Long TT. Performance evaluation of MQCL hard milling of SKD 11 tool steel using MoS2 nanofluid. Metals (Basel) 2019;9. https://doi.org/10.3390/met9060658.
[66] Akhtar AMZ, Rahman MM, Kadirgama K, Maleque MA. Effect of TiO_2 and Al_2O_3-ethylene glycol-based nanofluids on cutting temperature and surface roughness during turning process of AISI 1018. In: IOP conf ser mater sci eng. 736; 2020. p. 52033. https://doi.org/10.1088/1757-899x/736/5/052033.
[67] Moura RR, da Silva MB, Machado ÁR, Sales WF. The effect of application of cutting fluid with solid lubricant in suspension during cutting of Ti-6Al-4V alloy. Wear 2015;332–333:762–71. https://doi.org/10.1016/J.WEAR.2015.02.051.
[68] Rahmati B, Sarhan AAD, Sayuti M. Morphology of surface generated by end milling AL6061-T6 using molybdenum disulfide (MoS2) nanolubrication in end milling machining. J Clean Prod 2014;66:685–91. https://doi.org/10.1016/J.JCLEPRO.2013.10.048.
[69] Kadirgama K, Abou-El-Hossein KA, Noor MM, Sharma KV, Mohammad B. Tool life and wear mechanism when machining Hastelloy C-22HS. Wear 2011;270:258–68. https://doi.org/10.1016/J.WEAR.2010.10.067.
[70] Bhatt A, Attia H, Vargas R, Thomson V. Wear mechanisms of WC coated and uncoated tools in finish turning of Inconel 718. Tribol Int 2010;43:1113–21.
[71] Batista Ponce M, Vazquez-Martinez JM, Davim JP, Salguero Gomez J. Analysis of secondary adhesion wear mechanism on hard machining of titanium aerospace alloy. Materials (Basel) 2019;12. https://doi.org/10.3390/ma12122015.

[72] Gómez-Parra A, Álvarez-Alcón M, Salguero J, Batista M, Marcos M. Analysis of the evolution of the Built-Up Edge and Built-Up Layer formation mechanisms in the dry turning of aeronautical aluminium alloys. Wear 2013;302:1209–18. https://doi.org/10.1016/j.wear.2012.12.001.

[73] Kümmel J, Gibmeier J, Müller E, Schneider R, Schulze V, Wanner A. Detailed analysis of microstructure of intentionally formed built-up edges for improving wear behaviour in dry metal cutting process of steel. Wear 2014;311:21–30. https://doi.org/10.1016/j.wear.2013.12.012.

[74] Álvarez M, Salguero J, Sánchez JA, Huerta M, Marcos M. SEM and EDS characterisation of layering TiO_x growth onto the cutting tool surface in hard drilling processes of Ti-Al-V alloys. Adv Mater Sci Eng 2011;2011:414868. https://doi.org/10.1155/2011/414868.

[75] Sarıkaya M, Yılmaz V, Güllü A. Analysis of cutting parameters and cooling/lubrication methods for sustainable machining in turning of Haynes 25 superalloy. J Clean Prod 2016;133:172–81. https://doi.org/10.1016/j.jclepro.2016.05.122.