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Comparative Analysis of Dry, Minimum Quantity Lubrication, and Nano-Reinforced Minimum Quantity Lubrication Environments on the Machining Performance of AZ91D Magnesium Alloy

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Abstract: This study investigates the machining performance of AZ91D magnesium alloy under three different cooling environments: dry, minimum quantity lubrication (MQL), and nano-reinforced MQL (NanoMQL) with multi-walled carbon nanotubes. Turning experiments were conducted on a CNC lathe with systematically varied cutting parameters, including cutting speed (150–450 m/min), feed rate (0.05–0.2 mm/rev), and depth of cut (0.5–2 mm). The machining performance was evaluated through cutting force measurements, surface roughness analysis, and tool wear examination using SEM. The results demonstrate that the NanoMQL environment significantly outperforms both dry and conventional MQL conditions, providing a 42.2% improvement in surface quality compared to dry machining and a 33.6% improvement over conventional MQL. Cutting forces were predominantly influenced by the depth of cut and the feed rate, while cutting speed showed variable effects. SEM analysis revealed that the NanoMQL environment substantially reduced built-up edge formation and flank wear, particularly under aggressive cutting conditions. The superior performance of the NanoMQL environment is attributed to the enhanced thermal conductivity and lubrication properties of carbon nanotubes, which form a protective tribofilm at the tool–workpiece interface. This study provides valuable insights for optimizing the machining parameters of AZ91D magnesium alloy in industrial applications, particularly where high surface quality and tool longevity are required.

Keywords: magnesium alloy; turning; tribology; surface roughness; wear; minimum quantity lubrication; carbon nanotubes; sustainable machining

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1. Introduction

Magnesium alloys, particularly AZ91D, have become critical materials in the automotive, aerospace, and electronics industries due to their low density, high specific strength, excellent castability, and corrosion resistance [1–3]. These properties make AZ91D especially suitable for lightweight applications where weight reduction and durability are essential, such as automotive components, portable electronic devices, and aerospace structures [4]. However, despite these advantages, the machinability of magnesium alloys presents significant challenges, primarily due to their high thermal conductivity, low melting point, and tendency to form built-up edges (BUEs) during machining [5]. These issues

often result in poor surface quality, increased tool wear, and reduced process efficiency, limiting their broader adoption in precision manufacturing [6].

To address these challenges, researchers have explored various cooling and lubrication techniques to improve the machinability of magnesium alloys. Conventional flood cooling has been widely used to reduce cutting temperatures and improve surface quality. However, this method is associated with high environmental and economic costs due to the large volumes of cutting fluid required and the subsequent disposal challenges [7,8]. As a result, alternative methods such as minimum quantity lubrication (MQL) have gained attention. MQL involves the application of a minimal amount of cutting fluid directly at the tool–workpiece interface, significantly reducing fluid consumption while maintaining effective cooling and lubrication [9]. Studies have shown that MQL can improve surface quality and reduce tool wear compared to dry machining, making it a more sustainable alternative to flood cooling [10,11].

Although the present study focuses on the turning of AZ91D magnesium alloy, several researchers have also explored its machinability in milling operations. For instance, Jouini et al. [12] reported that both dry and cryogenic high-speed milling of AZ91D can produce mirror-like surface finishes, with cryogenic cooling notably extending tool life and further enhancing surface quality. Similarly, Zagórski and Korpysa [13] systematically examined how milling parameters affect surface roughness, finding that feed per tooth is the most critical factor, while higher cutting speeds tend to reduce 3D surface roughness. Marakini et al. [14] investigated high-speed face milling of AZ91 alloy and observed that both uncoated and PVD-coated carbide inserts significantly improve surface roughness and hardness, with PVD-coated tools yielding defect-free surfaces and higher compressive residual stresses. These studies underscore the importance of optimizing cutting parameters and lubrication strategies to achieve superior surface integrity in AZ91D milling. Nevertheless, it is important to recognize that the mechanisms and outcomes of turning may differ from those in milling, due to the inherent differences between these machining processes.

Building on the success of MQL, recent advancements have focused on enhancing its performance through the incorporation of nanoparticles into the cutting fluid. NanoMQL utilizes nanoparticles such as multi-walled carbon nanotubes (MWCNTs) to improve the thermal conductivity and lubrication properties of the cutting fluid [15]. These nanoparticles form a protective tribofilm at the tool–workpiece interface, reducing friction, adhesion, and heat generation during machining [16]. Experimental studies have demonstrated that NanoMQL can significantly enhance surface quality, reduce cutting forces, and extend tool life compared to both dry and conventional MQL environments [17,18].

Despite the widespread use of AZ91D magnesium alloy in lightweight applications, its machinability under advanced cooling and lubrication techniques such as NanoMQL remains underexplored. Previous studies have primarily focused on conventional machining methods, with limited attention given to the effects of nano-reinforced cutting fluids on the machining performance of AZ91D [19]. This gap in the literature highlights the need for a comprehensive investigation into the potential benefits of NanoMQL for machining AZ91D, particularly regarding cutting forces, surface roughness, and tool wear.

Cutting forces are a critical parameter in machining, as they directly influence tool wear, surface quality, and energy consumption. Studies have shown that cutting forces are primarily affected by cutting parameters such as cutting speed, feed rate, and depth of cut, as well as the cooling and lubrication environment [9,20]. For magnesium alloys, the high thermal conductivity and low melting point exacerbate the effects of cutting forces, leading to increased tool wear and poor surface finish [21]. By reducing friction and heat generation, NanoMQL has the potential to mitigate these issues and improve the overall machinability of AZ91D [12,22].

Surface roughness is another key performance indicator in machining, as it directly impacts the functional performance of machined components, including their fatigue resistance, corrosion susceptibility, and aesthetic appeal [23]. Achieving a high-quality surface finish is particularly challenging for magnesium alloys due to their tendency to form BUE and adhere to the cutting tool [24]. Previous studies have demonstrated that NanoMQL can significantly improve surface roughness by forming a thin protective film at the tool–workpiece interface, reducing adhesion and wear [25]. However, the specific effects of NanoMQL on the surface quality of AZ91D under varying cutting parameters remain largely unexplored.

Tool wear is a major concern in machining, as it affects tool life, machining accuracy, and overall process efficiency. The wear mechanisms in magnesium alloy machining are influenced by both mechanical and thermal factors, with flank wear and crater wear being the most common types observed [26]. The use of NanoMQL has been shown to reduce tool wear by enhancing heat dissipation and minimizing adhesion at the tool–workpiece interface [27]. However, the effectiveness of NanoMQL in mitigating tool wear during the machining of AZ91D has not been thoroughly investigated, particularly under aggressive cutting conditions [28].

This study aims to address these research gaps by conducting a comprehensive analysis of the machining performance of AZ91D magnesium alloy under dry, MQL, and NanoMQL environments. The primary objectives are to evaluate the effects of these cooling and lubrication methods on cutting forces, surface roughness, and tool wear, and to identify the optimal machining parameters for achieving superior performance. By systematically varying cutting speed, feed rate, and depth of cut, this study provides valuable insights into the interactions between machining parameters and cooling environments. The findings are expected to contribute to the development of more efficient and sustainable machining processes for magnesium alloys, aligning with the growing emphasis on environmentally friendly manufacturing practices.

Although several studies have examined the machinability of magnesium alloys under dry and MQL conditions, there is a lack of systematic research directly comparing dry, MQL, and NanoMQL environments for AZ91D magnesium alloy using identical experimental parameters. In particular, the tribological and performance benefits of NanoMQL with multi-walled carbon nanotubes for this alloy have not been comprehensively reported. Therefore, this study not only aims to fill these gaps but also provides new insights into the optimization of sustainable machining processes for AZ91D.

2. Materials and Methods

2.1. Materials

AZ91D is the most widely used magnesium alloy grade (designated by the aluminum and zinc content). Aluminum serves as the primary alloying element while zinc improves strength and corrosion resistance in this magnesium-based alloy. It is employed in applications requiring lightweight components with good castability and mechanical properties. These alloys are commonly used in automotive components, portable electronic housings, power tool casings, and aerospace parts.

AZ91D magnesium alloy samples were used for experimentation. The chemical composition of this alloy consists of Al 9.21%, Zn 0.45%, Mn 0.17%, Fe 0.0018%, Be 0.00084%, Si 0.016%, Cu 0.002%, and Ni 0.00085%, and the balance is Mg element. The Brinell hardness value of the material was measured as 63 BSD. The yield strength of the AZ91D magnesium alloy was determined to be 160 MPa, and the tensile strength as 230 MPa. The material exhibits a fatigue strength of 90–110 MPa, elongation of 3%, thermal conductivity of 72 W/mK, and a melting temperature of 578 °C.

2.2. Experiments

The experiments were conducted on a Johnford TC-35 industrial CNC lathe (Johnford Machine Tool Company, Taichung, Taiwan) with a maximum power capacity of 10 kW and spindle speed of 3500 rpm. This Fanuc-operated machine features a 250 mm x-axis travel, 600 mm z-axis travel, 250 mm hydraulic chuck diameter, and a 12-position turret. Prior to testing, workpiece preparation included drilling Ø 5 mm center holes at both ends, with one end machined in the traveling center-mirror axis configuration to prevent chuck ejection during testing. Surface preparation involved removing 0.5–1.0 mm of material to eliminate potential axial misalignment, post-heat treatment oxide layers, and decarburized regions. The cutting operation employed TCMT16T304 cutting inserts with STGCR1616h11 tool holders (Sandvik Coromant, Sandviken, Sweden). Cooling was provided by a minimum quantity lubrication (MQL) system delivering 0.0036 mL of cutting oil per injection at approximately 5 bar pressure, with two injections occurring each second. Figure 1 presents a schematic representation of the MQL system's arrangement during the turning process.



Figure 1. Schematic illustration of the experimental setup.

The metalworking process utilized CUTTEX SYN-10, a biodegradable cutting oil manufactured by Belgin Oil Company (Gebze, Turkiye). This synthetic vegetable-based lubricant, enhanced with performance additives, is applied directly at the tool–material interface. The product contains no chlorine or heavy metals, making it environmentally friendly, while its light coloration facilitates workpiece visibility. Its formulation includes anti-wear and anti-corrosion additives that extend cutting tool lifespan, while its synthetic base provides longevity between oil changes and its high flash point reduces oil mist formation and fire hazards. For the NanoMQL system, this same base oil was modified with 1% by weight of MWCNTs sourced from Nanografi (Ankara, Turkiye). These 92% pure nanoparticles, measuring 8–10 nm, were thoroughly incorporated through a com-

bined process of mechanical mixing and ultrasonic homogenization, with each step lasting one hour.

Experimental investigations were performed across three distinct cooling environments (dry, MQL, and NanoMQL) with systematically varied cutting parameters. The cutting speed was tested at three levels (150, 300, and 450 m/min), combined with three feed rates (0.05, 0.1, and 0.2 mm/rev) and three cutting depths (0.5, 1, and 2 mm), as detailed in Table 1. Throughout all trials, ISO standard TCMT16T304 cutting inserts were utilized in conjunction with ISO standard STGCR1616h11 tool holders.

Table 1. Parameters and levels for machining experiments.

Parameters	Units	Levels		
		1	**2**	**3**
Cutting Speed	m/min	150	300	450
Feed rate	mm/rev	0.05	0.1	0.2
Depth of Cut	mm	0.5	1	2
Cooling environments	-	Dry	MQL	NanoMQL

2.3. Experimental Measurement Procedures

The experimental analysis incorporated multiple measurement techniques to comprehensively evaluate machining performance. Cutting force data were captured at 20 mm intervals using a KISTLER 9257B piezoelectric dynamometer (Kistler Group, Winterthur, Switzerland) capable of simultaneously measuring main cutting force (Fc), feed force (Ff), and radial force (Fr). The force signals underwent amplification via a KISTLER Type 5019 multichannel charge amplifier before transmission to a computer through an RS-232C connection, where DynoWare Type 2825A1-2 software generated the corresponding force graphics.

Surface quality assessment was conducted using a portable Mitutoyo Surftest SJ 201 roughness meter (Mitutoyo Corporation, Kawasaki, Japan), with data collected from three equidistant positions (120° apart) around each workpiece to ensure representative sampling. This evaluation is critical as surface characteristics significantly influence component performance attributes including fatigue resistance, corrosion susceptibility, and operational longevity. Manufacturing engineers recognize that surface irregularities often serve as initiation sites for fractures and corrosion processes, though achieving optimal surface finish values typically involves challenging and cost-intensive processes.

A detailed examination was carried out using the Scanning Electron Microscope (SEM) (JEOL JSM-6060LV, JEOL Ltd., Tokyo, Japan) facilities at Gazi University, Faculty of Technology, Department of Metallurgy and Materials Engineering, to detect deterioration of the cutting tools.

The flank wear (VB) was measured from SEM images using the scale bar as reference, following the procedure described in ISO 3685 for turning operations [29]. The reliability of this method is supported by recent studies, which show that automated image analysis algorithms and manual measurements (e.g., using ImageJ) yield very similar results, with relative errors as low as 2.5% for common magnifications [30]. The ImageJ software used for measurements was obtained from the official website (https://imagej.nih.gov/ij/, accessed on 12 May 2025) [31].

3. Results

3.1. Analysis of Machining Forces

Table 2 and Figure 2 present the cutting force data obtained from machining AZ91D magnesium alloy in a dry environment. Analysis of these results reveals that cutting

forces increase significantly with greater cutting depths and feed rates, while cutting speed variations produce less pronounced effects on force magnitudes. The minimum cutting force was recorded at parameters of 300 m/min cutting speed, 0.05 mm/rev feed rate, and 0.5 mm cutting depth (60.86 N resultant force). Conversely, maximum cutting force occurred at 450 m/min cutting speed, 0.2 mm/rev feed rate, and 2 mm cutting depth (234.42 N resultant force).

Table 2. Force values measured during the dry-cutting process of AZ91D magnesium alloy.

Exp No.	Cutting Speed	Feed Rate	Depth of Cut	F_x (N)	F_y (N)	F_z (N)	F_{result} (N)
1	150	0.05	0.5	28.36	23.75	51.84	63.685
2	150	0.05	1	52.22	23.64	69.41	90.020
3	150	0.05	2	91.93	20.44	102.85	139.453
4	150	0.1	0.5	30.23	23.74	59.38	70.735
5	150	0.1	1	57.37	24.41	85.82	106.077
6	150	0.1	2	100.97	23.51	135.7	170.769
7	150	0.2	0.5	31.36	27.14	72.78	83.767
8	150	0.2	1	67.35	24.59	115.64	136.064
9	150	0.2	2	98.67	25.02	183.17	209.554
10	300	0.05	0.5	28.7	19.95	49.82	60.858
11	300	0.05	1	58.9	26.27	71.04	95.948
12	300	0.05	2	89.29	21.92	101.17	136.706
13	300	0.1	0.5	31.04	27.38	61.04	73.750
14	300	0.1	1	64.42	24.65	88.94	112.552
15	300	0.1	2	105.51	22.37	136.72	174.141
16	300	0.2	0.5	30.1	24.91	74.49	84.115
17	300	0.2	1	61.92	32.95	114.06	133.901
18	300	0.2	2	116.78	27.82	187.79	222.882
19	450	0.05	0.5	30.46	24.2	50.42	63.684
20	450	0.05	1	48.83	19.42	66.75	84.953
21	450	0.05	2	98.91	21.44	102.89	144.323
22	450	0.1	0.5	31.87	25.43	60.83	73.230
23	450	0.1	1	54.74	23.74	84.2	103.197
24	450	0.1	2	107.99	22.99	136.02	175.191
25	450	0.2	0.5	41.12	30.4	71.89	88.222
26	450	0.2	1	59.36	29.23	111.94	130.033
27	450	0.2	2	131.53	30.6	191.62	234.424

Previous studies on dry machining of AZ91D magnesium alloys have consistently reported substantial force increases with greater cutting depths and feed rates [32]. Regarding cutting speed effects, the literature presents mixed findings, with some researchers documenting force reductions at higher speeds [33], while others report minimal influence [34]. Our experimental results similarly show inconsistent cutting speed effects, with forces decreasing in some trials and increasing in others as cutting speed rises.

This variable response to cutting speed can be attributed to two competing mechanisms: thermal softening of the workpiece material at higher speeds, which tends to reduce cutting forces, and material adhesion to the cutting tool edge, which increases cutting resistance and consequently elevates forces [35]. The specific balance between these phenomena appears to vary across different parameter combinations in the current study.

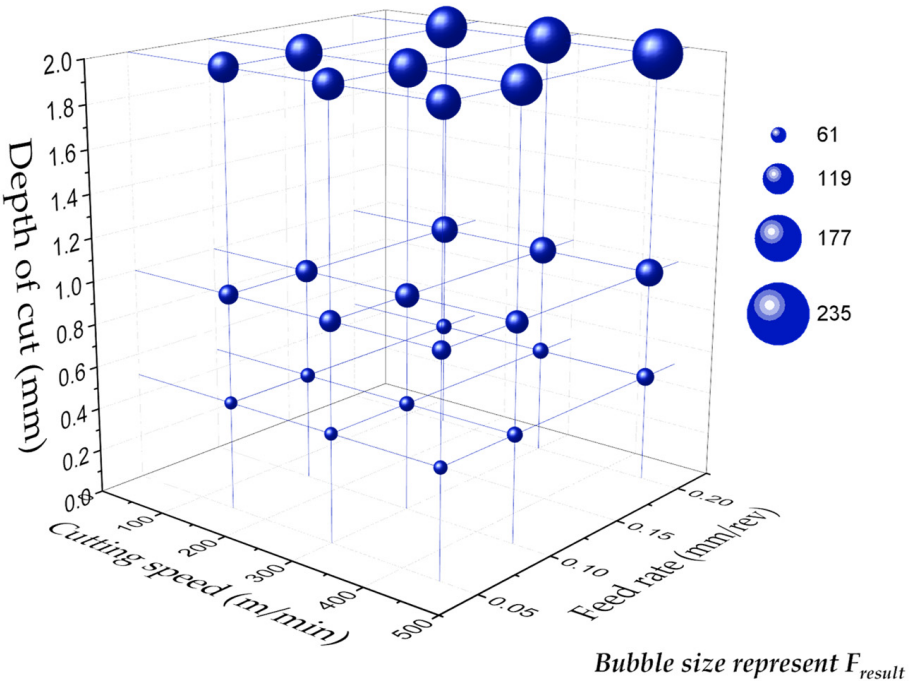


Figure 2. Force values required for machining AZ91D magnesium alloy in a dry environment.

3.2. Surface Roughness Evaluation

Table 3 and the graphics are shown in Figures 3–5 present the surface roughness values obtained from machining AZ91D magnesium alloy under dry, MQL, and NanoMQL environments. Analysis of these results reveals significant variations in surface quality across different cutting parameters and cooling conditions.

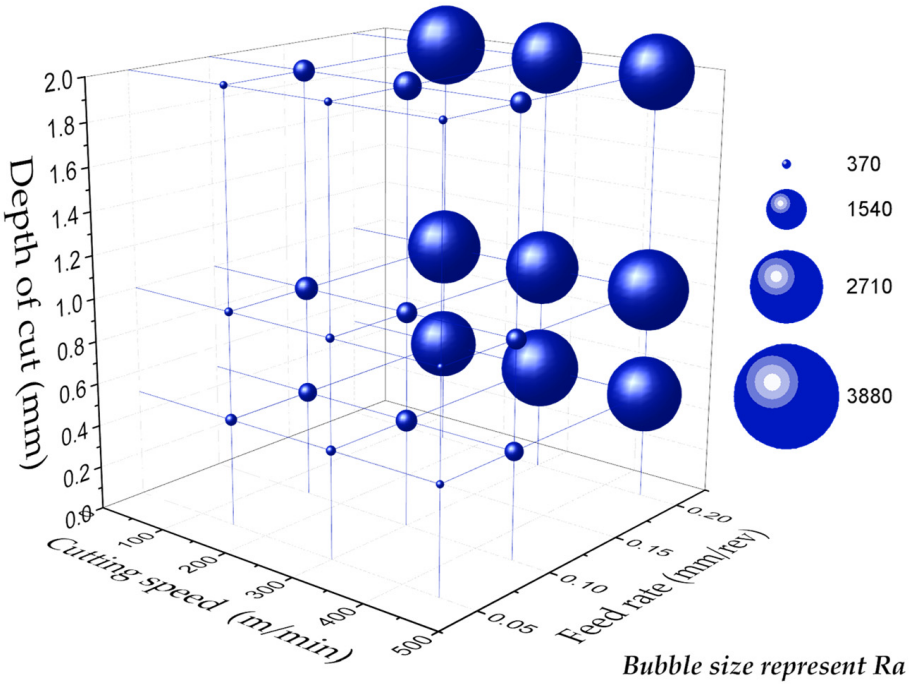


Figure 3. Surface roughness graph obtained by machining AZ91D magnesium alloy in a dry environment.

Table 3. Surface roughness (Ra) values obtained by machining AZ91D magnesium alloy under dry, MQL, and NanoMQL environments.

Cutting Speed	Feed Rate	Depth of Cut	Ra (Dry, µm)	Ra (MQL, µm)	Ra (NanoMQL, µm)
150	0.05	0.5	0.587	0.322	1.910
150	0.05	1	0.405	0.356	2.660
150	0.05	2	0.399	0.360	2.386
150	0.1	0.5	0.933	0.966	4.393
150	0.1	1	1.137	0.986	3.784
150	0.1	2	1.007	0.940	4.018
150	0.2	0.5	3.353	3.042	8.098
150	0.2	1	3.703	3.128	8.424
150	0.2	2	3.897	3.084	9.965
300	0.05	0.5	0.492	0.348	2.535
300	0.05	1	0.421	0.423	2.578
300	0.05	2	0.382	0.389	2.208
300	0.1	0.5	1.01	0.954	3.766
300	0.1	1	0.964	0.958	3.827
300	0.1	2	1.251	1.121	4.308
300	0.2	0.5	3.833	3.053	8.463
300	0.2	1	3.557	3.168	8.429
300	0.2	2	3.386	2.924	8.809
450	0.05	0.5	0.391	0.380	2.110
450	0.05	1	0.39	0.397	2.600
450	0.05	2	0.377	0.387	2.160
450	0.1	0.5	0.885	0.893	3.744
450	0.1	1	0.946	0.964	3.032
450	0.1	2	0.921	0.842	3.959
450	0.2	0.5	3.571	3.062	8.190
450	0.2	1	3.815	3.210	7.929
450	0.2	2	3.498	2.993	8.728

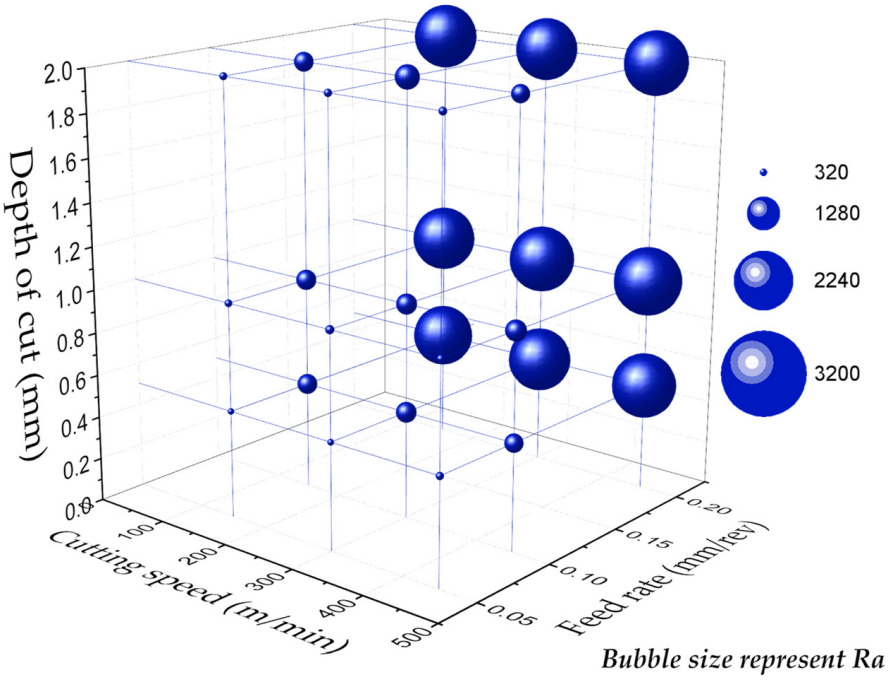


Figure 4. Surface roughness graph obtained by machining AZ91D magnesium alloy in MQL environment.

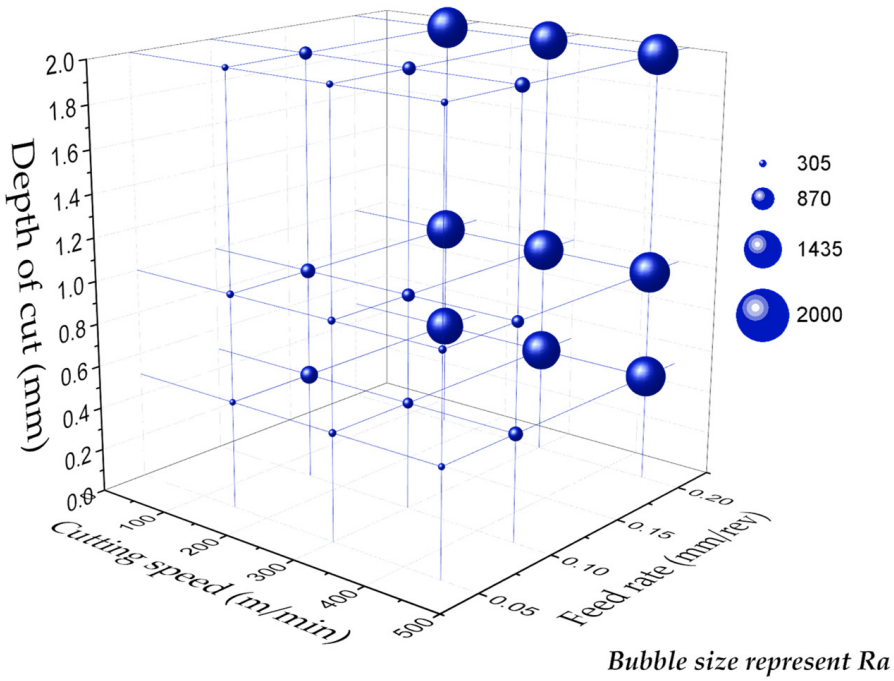


Figure 5. Surface roughness graph obtained by machining AZ91D magnesium alloy in multi-walled carbon-nanotube-reinforced MQL environment.

In dry machining conditions, surface roughness decreases with decreasing feed rate, which aligns with established machining theory [36]. Generally, increasing cutting speed leads to improved surface finish, with the best surface quality (Ra = 0.377 µm) achieved at 450 m/min cutting speed, 0.05 mm/rev feed rate, and 2 mm cutting depth. The poorest surface finish (Ra = 3.897 µm) occurred at 150 m/min cutting speed, 0.2 mm/rev feed rate, and 2 mm cutting depth. This relationship between cutting speed and surface quality can be attributed to reduced built-up edge formation at higher speeds [37].

Figure 3 illustrates the three-dimensional representation of surface roughness values obtained in the dry machining environment. The bubble chart clearly demonstrates the significant influence of feed rate on surface roughness, with larger bubbles (indicating higher Ra values) predominantly appearing at the 0.2 mm/rev feed rate position. The visualization confirms that the combination of high feed rate and low cutting speed produces the roughest surfaces, while the combination of high cutting speed and low feed rate yields the smoothest surfaces. The size gradient of the bubbles effectively represents the magnitude of surface roughness across the experimental parameter space.

When applying minimum quantity lubrication, surface roughness similarly increases with higher feed rates. The effect of cutting speed shows a non-linear pattern, with roughness increasing as speed rises from 150 to 300 m/min, then decreasing as speed further increases to 450 m/min. The optimal surface quality (Ra = 0.322 µm) was obtained at 150 m/min cutting speed, 0.05 mm/rev feed rate, and 0.5 mm cutting depth. The roughest surface (Ra = 3.210 µm) resulted from parameters of 450 m/min cutting speed, 0.2 mm/rev feed rate, and 1 mm cutting depth. Compared to dry machining, MQL generally provides superior surface finish, with an average improvement of 12.9% [10].

Figure 4 presents the three-dimensional bubble chart for surface roughness values in the MQL environment. Similar to the dry machining results, the chart shows a clear correlation between feed rate and surface roughness, with the largest bubbles concentrated at the 0.2 mm/rev feed rate. However, the overall bubble sizes are noticeably smaller compared to the dry environment chart, visually confirming the improved surface finish achieved with MQL. The distribution pattern also reveals the non-linear effect of cutting

speed, with medium cutting speeds (300 m/min) showing slightly larger bubbles than both lower and higher speeds at equivalent feed rates and cutting depths.

The nano-reinforced MQL environment demonstrates that surface roughness increases with higher feed rates, consistent with the other environments. Cutting speed shows a different pattern, with roughness decreasing as speed increases from 150 to 300 m/min, then remains relatively stable between 300 and 450 m/min. The finest surface quality (Ra = 0.308 μm) was achieved at 450 m/min cutting speed, 0.05 mm/rev feed rate, and 2 mm cutting depth, while the poorest finish (Ra = 2.001 μm) occurred at 150 m/min cutting speed, 0.2 mm/rev feed rate, and 2 mm cutting depth. Notably, NanoMQL provides significantly better surface quality compared to both dry and conventional MQL environments, with improvements of 42.2% and 33.6%, respectively [8].

Figure 5 displays the surface roughness graph obtained by machining AZ91D magnesium alloy in a multi-walled carbon-nanotube-reinforced MQL environment. The most striking feature of this visualization is the substantially smaller bubble sizes compared to both dry and conventional MQL charts, particularly at the 0.2 mm/rev feed rate position. This visual representation effectively illustrates the superior surface finish achieved with NanoMQL across all parameter combinations. The bubble distribution pattern confirms that, while feed rate remains the dominant factor affecting surface roughness, its negative impact is significantly mitigated by the nano-enhanced lubricant. Additionally, the chart shows more consistent bubble sizes across different cutting speeds, suggesting that NanoMQL provides more stable machining conditions regardless of speed variations.

The superior performance of NanoMQL can be attributed to the enhanced thermal conductivity and lubrication properties of carbon nanotubes, which effectively reduce friction at the tool–workpiece interface and improve heat dissipation from the cutting zone [27]. This is particularly beneficial for magnesium alloys like AZ91D, which are prone to built-up edge formation and poor surface finish due to their high thermal conductivity and low melting point [38,39]. The nanoparticles in the cutting fluid create a thin protective film between the tool and workpiece, reducing adhesion and improving machining stability [16].

3.3. Tool Wear Analysis

The wear mechanisms occurring during the machining of AZ91D magnesium alloy were examined using SEM micrographs. These images provide critical insights into the tool degradation patterns under different cooling conditions. Figures 6 and 7 present SEM images of tool wear after machining in dry, MQL, and NanoMQL environments at different cutting parameters.

Figure 6 shows the SEM images obtained from experiments conducted at moderate cutting conditions (cutting speed: 150 m/min, feed rate: 0.05 mm/rev, and depth of cut: 0.5 mm). Under these conditions, flank wear was observed in all three environments, though with varying severity. The dry machining condition (Figure 6a) exhibited the most pronounced flank wear, followed by the MQL environment (Figure 6b), while the NanoMQL environment (Figure 6c) showed the least wear. This pattern can be attributed to the superior cooling and lubrication properties of the nano-enhanced cutting fluid, which effectively reduces friction and heat generation at the tool–workpiece interface [40].

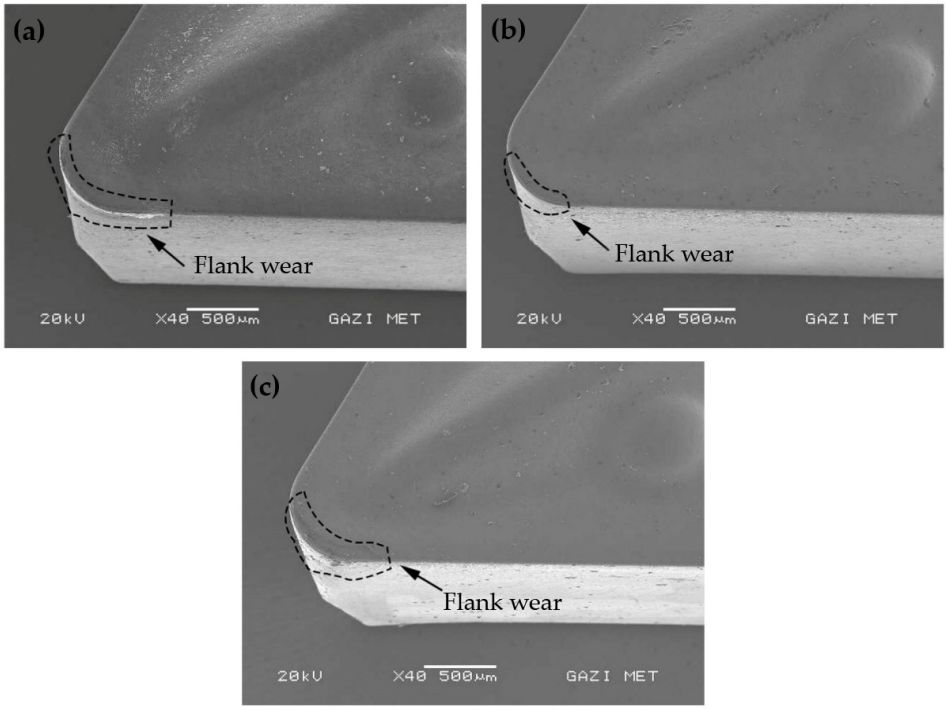


Figure 6. SEM images obtained from experiments performed in different environments: (**a**) dry, (**b**) MQL, and (**c**) NanoMQL. Turning parameters: cutting speed 150 m/min, feed rate 0.05 mm/rev, and depth of cut 0.5 mm.

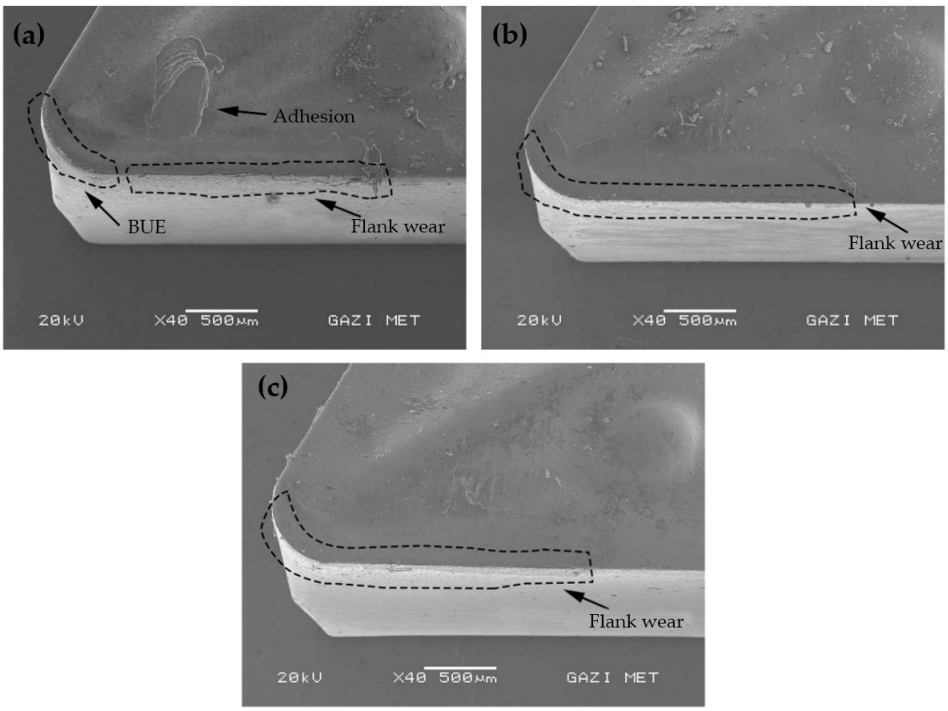


Figure 7. SEM images obtained from experiments performed in different environments: (**a**) dry, (**b**) MQL, and (**c**) NanoMQL. Turning parameters: cutting speed 450 m/min, feed rate 0.2 mm/rev, and depth of cut 2 mm.

Figure 7 presents SEM images from experiments performed at more aggressive cutting parameters (cutting speed: 450 m/min, feed rate: 0.2 mm/rev, and depth of cut: 2 mm). Under these severe conditions, significant differences in wear mechanisms were observed. In the dry environment (Figure 7a), both built-up edge (BUE) formation and adhesion were

evident alongside extensive flank wear. The presence of BUE is particularly detrimental as it alters the effective tool geometry and can lead to poor surface finish [2]. In contrast, the MQL environment (Figure 7b) showed reduced BUE formation but still exhibited considerable flank wear. The NanoMQL environment (Figure 7c) demonstrated the least severe wear pattern with minimal adhesion and more uniform flank wear distribution.

The depth of cut was found to have the most significant impact on tool wear, while cutting speed and feed rate had comparatively less influence within the parameter ranges studied. This finding aligns with previous research on magnesium alloy machining, which indicates that the depth of cut directly affects the contact area between the tool and workpiece, thereby increasing mechanical and thermal loads on the cutting edge [41].

The superior performance of the NanoMQL environment can be attributed to the multi-walled carbon nanotubes' ability to form a protective tribofilm at the tool–workpiece interface. This film reduces direct contact between the tool and workpiece materials, thereby minimizing adhesion and friction [42]. Additionally, the enhanced thermal conductivity of the nano-enhanced fluid facilitates more efficient heat dissipation from the cutting zone, preserving the tool's hardness and wear resistance properties [43].

These results are consistent with findings by Wang et al. [11], who reported that nano-enhanced cutting fluids significantly reduced tool wear when machining magnesium alloys due to the rolling and sliding effects of nanoparticles at the contact interface. Similarly, Sharma et al. [44] observed that carbon-nanotube-enhanced cutting fluids provided superior performance in terms of tool life and wear resistance compared to conventional cooling methods when machining lightweight alloys.

As shown in Table 4, the average flank wear values measured under each lubrication condition clearly demonstrate the superior performance of NanoMQL compared to both dry and conventional MQL environments. These findings are in agreement with those of previous studies, confirming that the use of nano-reinforced lubricants can significantly enhance tool life during the machining of magnesium alloys. The substantial reduction in flank wear observed with NanoMQL can be attributed to several synergistic effects provided by the nano-additives. The presence of MWCNTs in the lubricant improves the formation and stability of a lubricating film at the tool–workpiece interface, effectively reducing direct metal-to-metal contact and, consequently, friction and adhesive wear. Furthermore, the high thermal conductivity of MWCNTs enables more efficient heat dissipation from the cutting zone, lowering the thermal load on the cutting edge and minimizing thermal softening and diffusion wear mechanisms. In addition, these nano-additives can act as nanosized ball bearings, further reducing friction and promoting smoother chip flow. Collectively, these effects not only decrease the rate of tool wear but also contribute to improved surface finish and dimensional accuracy of the machined parts. Similar mechanisms and benefits of nano-reinforced lubricants have been reported in the literature for various machining operations involving difficult-to-cut materials [28,45]. Therefore, the superior performance of NanoMQL observed in this study is consistent with the growing body of evidence supporting the adoption of nanofluid-based lubrication strategies in advanced manufacturing.

Table 4. Average flank wear (VB) under different lubrication conditions.

Lubrication Condition	Average Flank Wear (VB, μm)
Dry	163 ± 4
MQL	94 ± 7
NanoMQL	58 ± 3

The superior performance of NanoMQL in turning operations can be attributed to the presence of multi-walled carbon nanotubes in the lubricant. These nanoparticles enhance the lubricating film strength, reduce friction at the tool–workpiece interface, and improve heat dissipation during turning. As a result, the tool experiences lower thermal and mechanical loads, leading to reduced wear. This mechanism is consistent with previous findings in the literature [46,47]. The effectiveness of different cooling and lubrication strategies in turning operations is primarily related to their ability to reduce friction and dissipate heat at the tool–workpiece interface. Under dry conditions, there is no external medium to carry away heat or reduce friction, resulting in higher tool temperatures and accelerated wear. MQL introduces a small amount of lubricant in the form of a fine mist, which partially reduces friction and provides some cooling, leading to moderate improvements in tool life and surface quality.

NanoMQL, in which multi-walled carbon nanotubes are dispersed in the lubricant, offers additional benefits. The MWCNTs act as nanosized ball bearings, further reducing friction at the interface. They can also form a protective tribo-film on the tool surface, which minimizes direct contact between the tool and the workpiece, thereby reducing adhesive and abrasive wear. Moreover, the high thermal conductivity of MWCNTs enhances heat dissipation from the cutting zone, keeping the tool temperature lower and further extending tool life. These mechanisms have been reported in several recent studies [42,48,49].

4. Conclusions

This comprehensive investigation into the machining of AZ91D magnesium alloy under dry, MQL, and NanoMQL environments has yielded several significant findings with important implications for industrial applications.

The cutting force analysis revealed that the depth of cutting and the feed rate are the primary factors influencing force magnitudes during machining, with cutting forces increasing substantially as these parameters increase. Cutting speed demonstrated a more complex relationship with cutting forces, showing variable effects that can be attributed to the competing mechanisms of thermal softening and material adhesion. The minimum cutting force (60.86 N) was achieved at a moderate cutting speed (300 m/min) with low feed rate and depth of cutting; meanwhile, the maximum force (234.42 N) occurred at high values of all three parameters.

Surface roughness measurements demonstrated the superior performance of the NanoMQL environment, which provided a 42.2% improvement over dry machining and a 33.6% improvement over conventional MQL. The feed rate consistently emerged as the most influential parameter affecting surface quality across all environments, with higher feed rates producing rougher surfaces. The finest surface finish (Ra = 0.308 μm) was achieved in the NanoMQL environment at a high cutting speed (450 m/min), a low feed rate (0.05 mm/rev), and a large depth of cut (2 mm). This exceptional performance can be attributed to the enhanced lubrication and cooling properties of the carbon-nanotube-reinforced cutting fluid.

Tool wear analysis through SEM imaging revealed significant differences in wear mechanisms across the three environments. The NanoMQL environment consistently demonstrated reduced flank wear and minimal built-up edge formation compared to both dry and MQL conditions. Compared to dry cutting, NanoMQL reduced flank wear by approximately 64.4%. Compared to conventional MQL, the reduction was about 38.3%. This was particularly evident under aggressive cutting parameters, where the dry environment exhibited extensive adhesion and BUE formation. The protective tribofilm formed by carbon nanotubes at the tool–workpiece interface effectively minimized direct contact

between materials, reducing friction and adhesion while enhancing heat dissipation from the cutting zone.

These findings collectively establish that nano-reinforced MQL represents a superior approach for machining AZ91D magnesium alloy, particularly in applications requiring high surface quality and extended tool life. The optimal machining parameters identified in this study (high cutting speed, low feed rate, and moderate–high depth of cut with NanoMQL) provide valuable guidelines for industrial implementation. Furthermore, the environmentally friendly nature of the biodegradable cutting fluid used in this study, combined with the minimal quantity application, aligns with sustainable manufacturing principles.

Future research should explore the long-term effects of carbon nanotube concentration on machining performance and investigate the potential for further optimization through the combination of nano-enhanced cutting fluids with advanced tool coatings. Additionally, the economic implications of implementing NanoMQL systems in industrial settings should be evaluated to provide a comprehensive cost–benefit analysis.

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