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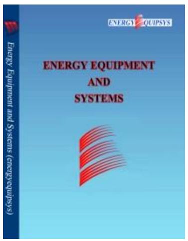

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Experimental investigation on the environmentally friendly turning of Al7075 using ultrasonic nozzle-minimum quantity lubrication (UN-MQL) system

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ABSTRACT

In this experimental work, the effects of cutting fluid and different cutting parameters on surface roughness, tool wear, and chip morphology during turning of Al7075-T6 were investigated. Machining experiments have been done in different environments such as dry, wet, minimum quantity lubrication (MQL) as well as a homemade ultrasonic nozzle- minimum quantity lubrication (UN-MQL). Ultrasonic vibrations can be used to effectively atomize the cutting fluid into fine and uniform-sized droplets and smaller spray angles with a larger spray deposition distance. The MQL system and machining parameters were evaluated by the design of experiments (DOE) method which allows us to carry out the optimization analysis by performing a relatively small number of experiments while determining the influence on the machining performance using the analysis of variance technique. In the second step, an optimization of the machining parameters was sought using signal-to-noise ratio analysis. Therefore, the response surface methodology was determined in a regression analysis, which was used to model the influence of the parameters on the performance. The fine droplets produced by the UN-MQL system penetrate effectively into the machining zone. Finally, the chip morphology, tool wear and surfaces of the machined parts were examined using optical microscopy to identify the chip formation mechanism in different machining conditions. Cutting tool wear were also examined using the SEM tests to quantify the tool wear zones under specific process parameters. Experimental results show that applying UN-MQL system reduces the surface roughness and tool wear by up to 30% in comparison to the conventional MQL system.

Keywords: Minimum Quantity Lubrication, Machining, Ultrasonic Nozzle, Chip Formation, Surface Roughness.

1. Introduction

Turning is a widely used criterion for assessing the productivity of machine tools and machine components [1]. For a workpiece surface, surface roughness is a significant quality indicator [2]. A good surface can help with fatigue strength, corrosion resistance, assembly tolerance, wear rate, coefficient of friction, cleanability, thermal resistance, and aesthetics, among other things [3]. In other words, lubricant is widely utilized in all industries to cool and lubricate the tool-workpiece interface to improve machinability. Despite the extensive application of cutting fluids in various processes, academics and companies are progressively attempting to reduce cutting fluid consumption [4]. In 2005, the number of

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lubricants used in machining was about 38 Mt, with an expected growth of 1.2 percent over the next decade. Mineral-based cutting fluids account for over 85% of all cutting fluids used worldwide. The rising usage of mineral and petroleum-based oil has several negative environmental consequences as well as major health risks. According to reports, skin contact with cutting fluids caused around 80% of all occupational illnesses among operators. Cutting fluids can have irritating or allergic qualities due to their complex makeup. Toxic and less biodegradable cutting fluids have generated a slew of techno-environmental issues as well as major health issues, including lung cancer, respiratory disorders, dermatological, and genetic diseases[5]. The majority of machining processes are reliant on having access to a coolant-lubricant system. Under their cooling and lubricating qualities, such cutting fluids clearly improve machining performance [6]. These cutting fluids have been employed in a flood or wet cooling mode, which involves injecting a huge amount of fluid into the cutting zone. However, only a small portion of the coolant lubricant is usable in wet cooling. As a result, wet cooling is a costly, ineffective, health-threatening, and non-environmentally friendly method of machining. As a result, the relatively novel concepts of dry machining [7], and coolant application known as MQL [8] and UN-MQL [9] have emerged. Except for some aluminum alloys, dry machining can be used for conventional machining on steels, steel alloys, and cast irons. Nonetheless, in dry-cutting conditions, strong friction between the tool and the workpiece greatly raises the temperature, resulting in increased abrasion, diffusion, and oxidation. The workpiece also receives a lot of heat, which makes it difficult to obtain tight tolerances and causes metallurgical damage to the surface layer. To determine the ideal conditions for dry cutting, turning tests were carried out with varying cutting speed, feed, and tool nose radius, with and without the use of cutting fluid. They came to the conclusion that using cutting fluids in wet cooling can extend tool life. Dry cutting, on the other hand, used less energy and produced a better surface finish [7]. Aerosols are oil droplets dispersed in a jet of air in the MQL technique, and oil droplets transported by the air fly straight to the tool working area, providing the necessary cooling and lubricating actions [10]. The jet begins to break up immediately after exiting the nozzle hole, forming a conical spray (spray cone angle (φ)) that becomes increasingly diluted downstream of the nozzle. Near the spray axis, the majority of the oil mass and larger drops are concentrated, while the outlying spray zones contain less oil mass and smaller drops. As a result of the interaction with the surrounding air, droplet velocities are greatest along the spraying axis and diminish in the radial direction [11]. Using a newly built and constructed ultrasonic nozzle–minimum quantity lubrication (UN-MQL) configuration, the effect of ultrasonic vibration applied to the MQL nozzle tip has been examined in the UN-MQL technique. The novel UN-MQL system has been shown to have a significant impact on synergistically increased atomization behavior (compressed air generates the primary atomization in the air+oil mixture area of the nozzle due to the Venturi effect, and the supplementary atomization is also improved due to the high-frequency vibration at the ultrasonic nozzle tip (resonant surface), Fig. 1). The UN-MQL system uses far less lubrication than the traditional MQL method. This lowers machining costs while also lowering health and environmental dangers to the operator. Furthermore, UN-MQL system lubrication performance, hence improving the technical and economic elements of machining operations (lower compressed air and cutting oil consumption, finer droplets, uniform distribution of droplets, the area covered by the droplets, lower waste of cutting oil). When compared to the traditional MQL system, the cutting oil droplets in the UN-MQL system are smaller and more evenly distributed. UN-MQL turning was used to improve the surface roughness [9].

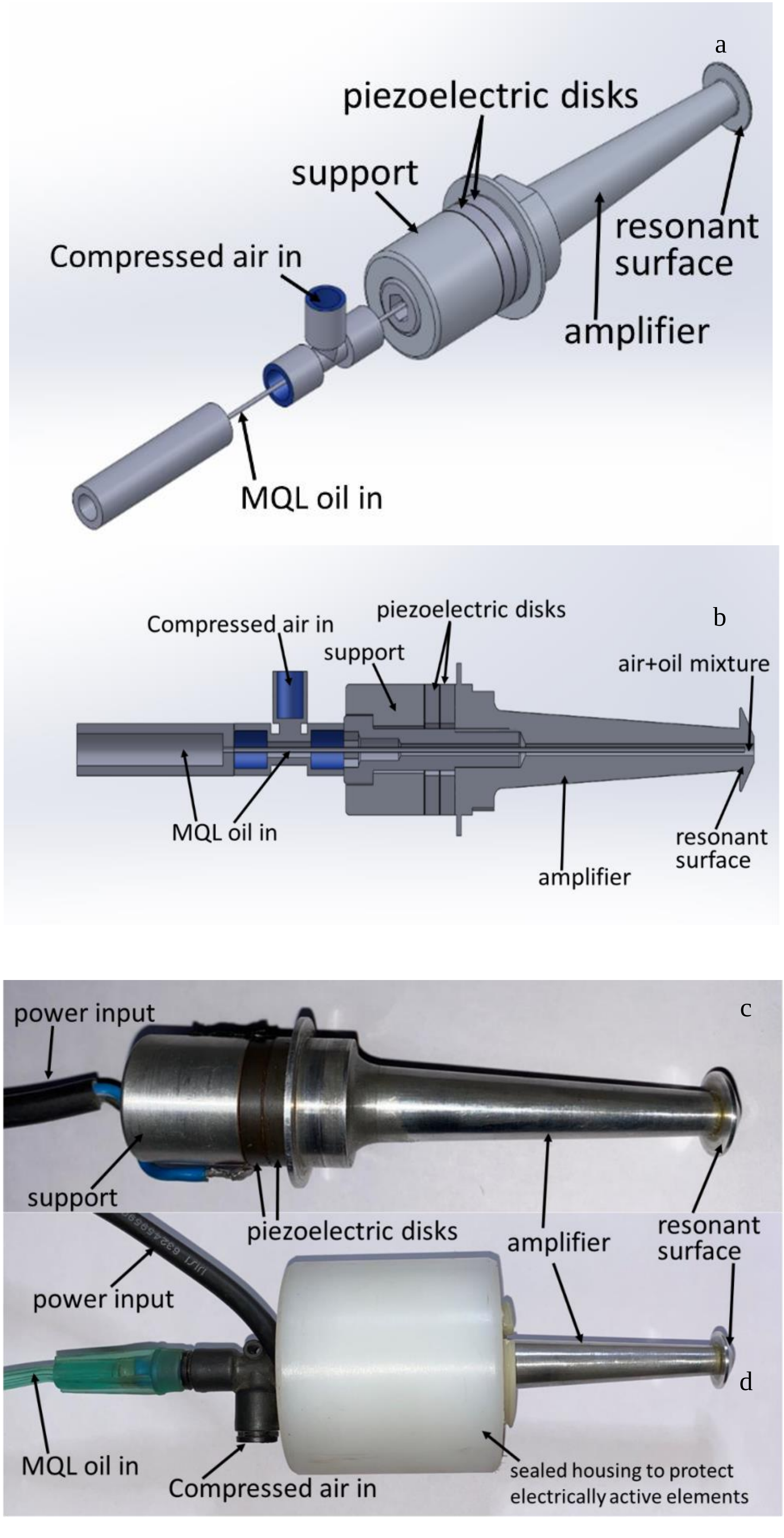


Fig. 1. ultrasonic nozzle-MQL (UN-MQL) system; a, b) Schematic and detailed design, c, d) manufactured, assembled, and sealed nozzle [9]

Tosun and Huseyinoglu [12] studied the impact of minimum quantity lubrication (MQL) in terms of surface roughness in the milling of Aluminum 7075-T6. MQL and flood were also utilized as the lubrication techniques in the experiments. The flow rates of 5 and 1000 ml/min were kept in MQL and flood, respectively. The result showed that the ratio of MQL of 1:10 technique led to lower roughness values due to effective lubrication at the work-tool interface. They concluded that the surface roughness in the cutting under MQL decreased as spindle speed was increased. Kouam et al. [13] analyze the impact of lubrication of minimum quantity lubrication (MQL) at flow rates of 1.75 and 3 ml/min and dry when turning of the aluminum alloy 7075-T6. Surface roughness and chip formation were chosen as the response variables. They observed that the MQL flow rate of 1.75 ml/min gives the lowest surface roughness than the MQL flow rate of 3 ml/min and the dry. In terms of chip formation, the flow rate of 3 ml/min at a cutting speed of 657 m/min shows more long chips compared to the flow rate of 1.75 ml/min and dry as shown in Fig. 2. It concluded that the best lubrication was 1.75 ml/min. Cakir et al. [14] study the optimum conditions on the cutting speed and feed rates using MQL technology when turning aluminum 7075-T6. Four different flow rates which are 0.25, 0.45, 0.90 and 3.25 ml/min were applied along with cutting speed and feed rates. They concluded that the surface roughness value is increased when increasing the feed rate and the surface roughness values will be decreased when increasing the flow rate. However, the surface quality not has a severe effect though the cutting speed was increased. It has been observed that the impact of the flow rate on the surface quality was influenced at a high feed rate. It can be seen that there are different results in the termination of the flow rate amount of MQL between Kouam et al. [13] and Cakir et al. [14].

This paper presents, for the first time, the comparative performance of environmentally friendly machining towards surface quality and chip formation when turning of aluminum alloy 7075-T6 using an ultrasonic nozzle-MQL (UN-MQL) system. In addition, an investigation on the influence of machining parameters on tool wear was carried out. In other words, this research, to the best of the authors knowledge, demonstrates the first attempt to investigate and optimize the process parameters of turning operation of aluminum alloy 6026-T9 under wet, dry, MQL and UN-MQL conditions using vegetable oil. The main reason for selecting this alloy for investigation was driven by its new class of aluminum alloys which is extensively used in automotive, machined parts, electrical, and electronic industries and shows excellent strength and superior corrosion resistance. This alloy is also suitable for biomedical applications and energy equipment which requires good corrosion properties. Nowadays, the automotive industries start to evaluate its potential as a superior alternative to common alloys such as 6061 and 6082. Also, this type of alloy may be used to replace the 6082 or 6081 alloys, particularly where extensive machining is required for finished parts. Therefore, this study will help in generating detailed machining data related to aluminum alloys and can be used as the benchmark to compare other materials by the following novelties:

1. Investigation of the effects of turning parameters (cutting speed and feed rate) on the machining performance of 7075-T6 aluminum alloy (surface roughness, tool wear, chip formation and surface morphology).
2. Environmentally friendly machining of 7075-T6 aluminum alloy applying UN-MQL system.
3. Applying analysis of variance (ANOVA to study the effect of process parameters on surface roughness.
4. Compare the machining of 7075-T6 aluminum alloy using different coolant-lubricant conditions such as dry machining, wet, MQL and UN-MQL techniques.

2. Experimental setup

The range of cutting parameters and cutting fluid conditions was selected based on the machine's ability, preliminary tests, Jiangxi company brochure (the used tools manufacturer company in this experiment) [15], previous works data [9] as well as the recommendation of standard machining data book for turning processes [16] as listed in

Table 1 and 2. TCGX 16T380-AC carbide tool insert with the composition of micro columnar Ni+Co+TiCN was used in this machining operation. This insert is suitable for free-cutting alloy aluminum workpieces. Because of the softness of aluminum alloy, turning requires the use of a tool with high hardness and strength to good wear, according to the mentioned properties in the composition of the selected tool for turning aluminum, the addition of 6% cobalt to the other components reduces the number of fine grains to a density of 14.83 g/cm3 and increases the hardness[15].

Figure 2 shows the lathe, workpiece, and UN-MQL system used in the experiments. An ultrasonic generator provides the mechanical energy required to create the vibrations in the nozzle. While the ultrasonic generator is switched off, the nozzle will be changed to the conventional MQL system working with the Venturi effect. The atomized droplets are focused and injected into the grinding zone with the help of compressed air.

Table 1. machining conditions

Machining parameter	**Level**			
Cutting speed, $V_c\ (m/min)$	265	630	930	1300
Feed, $f(mm/rev)$	0.052	0.99	0.199	0.3
Depth of cut, $a_p(mm)$	1			
Air pressure for MQL, (bar)	3			
MQL oil flow rate, (ml/h) (vegetable oil; viscosity=18 m^2/s, and ρ=850 kg/m^3)	30			

Table 2. MQL technique parameters

Air pressure (bar)	3	
MQL oil Flow rate (ml/h)	30	
Method	MQL	UMQL
Wettability, A (%)	3.5	9

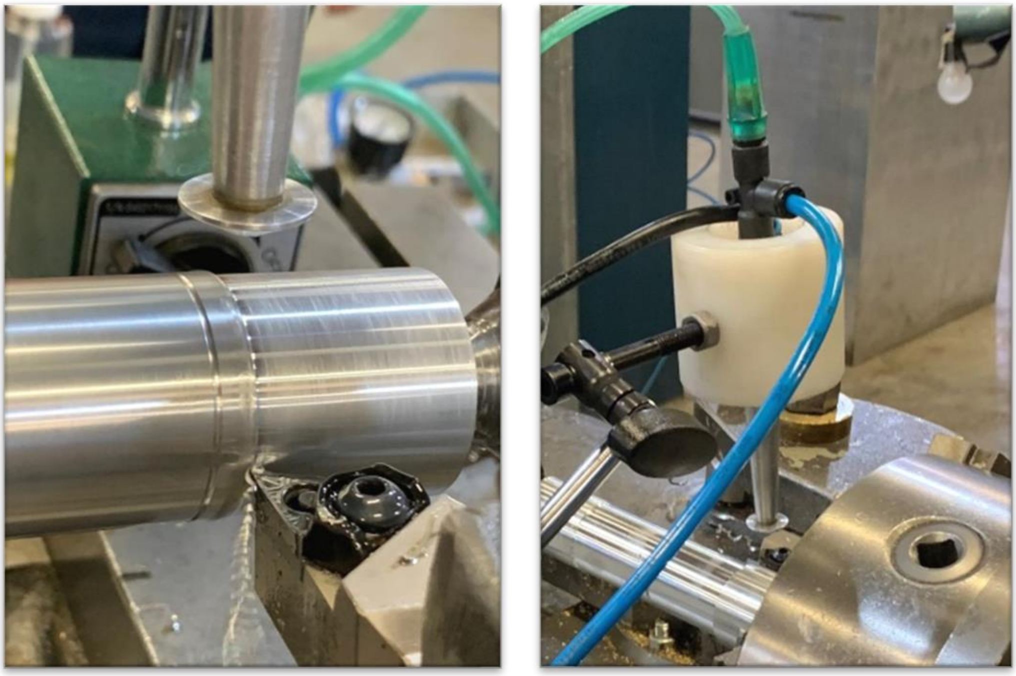


Fig. 2. experimental setup

Table 3. chemical properties of Al7075-T6 alloy[18]

Elements	Al	Zn	Mg	Cu	Fe	Cr	Mn	Ti	Si
Contribution (%)	88.76	5.6	2.4	1.6	0.5	0.24	0.3	0.2	0.4

Table 4. mechanical properties of Al7075-T6 alloy[18]

Parameters	Unit	Level
Density	g/cc	2.81
Elastic modulus	Gpa	71.7
Poisson's ratio	-	0.33
Coefficient of thermal expansion	$\mu m/mc^{-1}$	25.2
Thermal conductivity	w/mk	130
Specific heat capacity	J/gc	0.96

A shaft of Al7075-T6 alloy with a length of 30mm and a diameter of 30 mm was machined for each experiment. The following are the main reasons for selecting this material: Widespread use in the military, medical, and installation industries, Reasonable price, Adequate toughness and strength, Significant abrasion resistance and Low density compared to other ferrous and non-ferrous metals, particularly in the aerospace industry[17]. Table 3 and 4 show the qualitative, chemical, and mechanical properties of this alloy. The cutting fluid used in the experiments during wet machining was soluble oil and for MQL and UN-MQL conditions was olive oil which is environmentally friendly. The major reasons for using olive oil are divided into the following points: safety at work due to the absence of producing toxic gases, no early smoking in high-temperature working conditions and suitable viscosity compared to other vegetable oils.

A full factorial design is applied, so many experimental runs have been conducted for each Turning method of this study such as Dry, Wet, MQL and UN-MQL processes. But Taguchi orthogonal array was employed to minimize the number of experiments. Accordingly, Taguchi's L16 orthogonal array was used to design the experiments of each method of Turning with 2 factors such as cutting speed and feed rate and 4 levels for dry and wet, meanwhile, 3 factors such as cutting speed, feed rate and wettability percentage for MQL and UN-MQL. All selection range of factors are referred in Table 1 and Table 2. A surface roughness measuring instrument (model T8000; Hommel Werke profilometer) was used to measure the surface roughness of the workpieces after machining (according to DIN EN ISO 3274:1998). To ensure the accuracy of the results, the surface roughness of each workpiece was measured three times at three different angles and the average was reported. The surface morphology of the workpieces and chips as well as the tool wear were observed using a digital microscope (DigiMicro manufactured by DNT Company), which possesses a maximum magnification of 200 times. In addition, tool wear investigation of some experiments was performed on a Philips model XL Series (XL30). Furthermore, based on all studies and analyses, the optimal point was determined as the better as well as efficient parameters and method for turning Al7075-T6 by comparing predicted and experimental studies at the optimal cutting conditions using signal-to-noise (S/N) ratio between the results of UN-MQL and MQL tests.

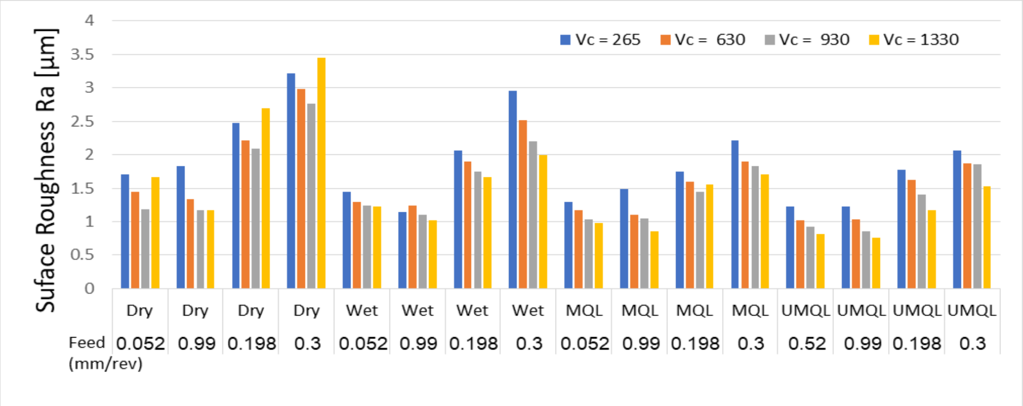
3. Results and discussion

3.1 Analysis of surface roughness

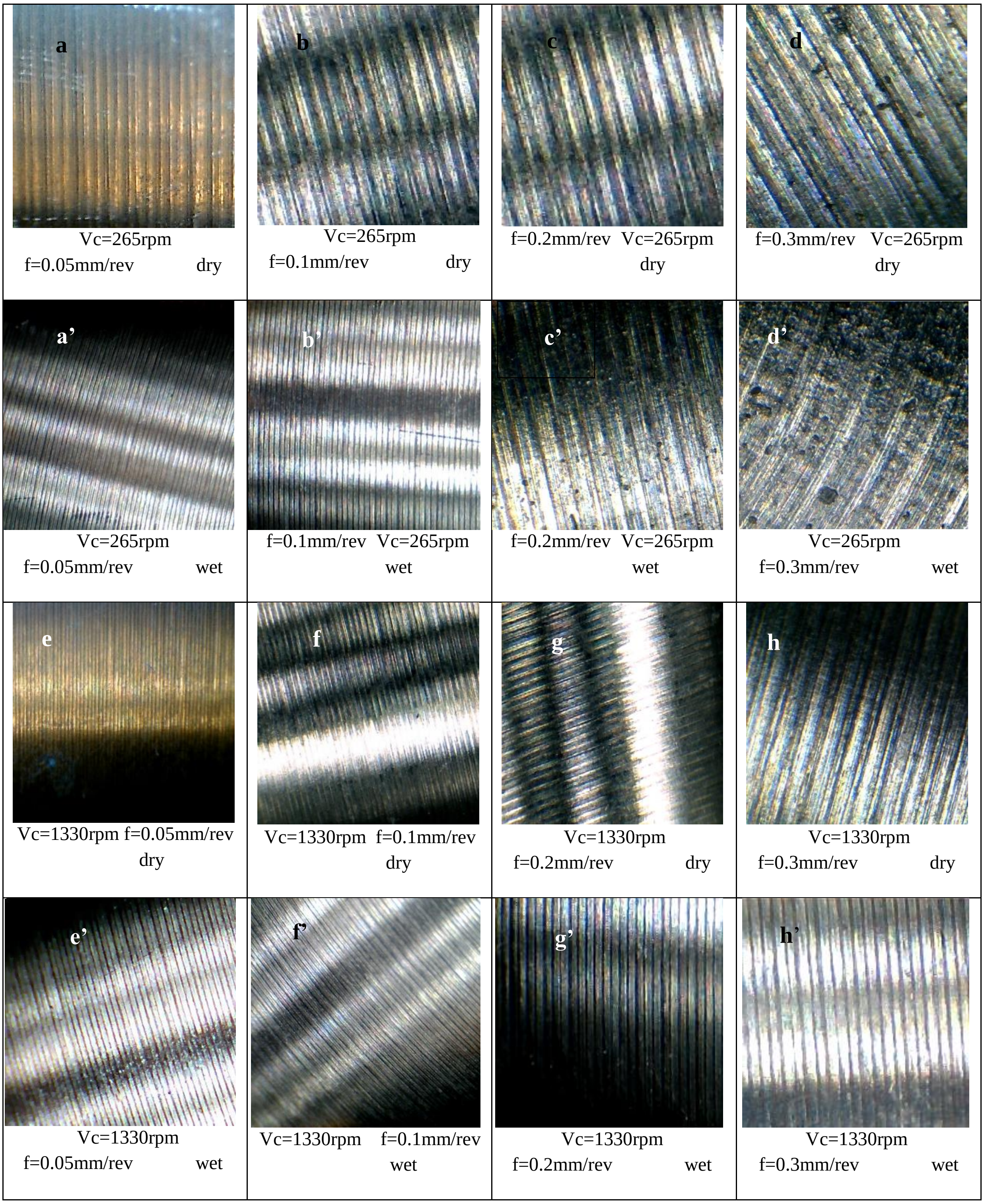
Figure 3 shows the surface roughness variation using different cutting conditions. Fig. 3 shows that as cutting speed increases, surface roughness decreases. It was observed that feed rate had a greater influence than cutting speed on surface roughness. It can also be seen that increasing the cutting speed in dry turning increased surface roughness by increasing the cutting tool wear and cutting forces, resulting in an increase in friction and cutting temperature. Fig. 3 shows that the UN-MQL machining technique strongly reduced the roughness of the machined surfaces over that of the conventional dry, MQL and continuous fluid machining conditions. It can be seen that lubrication during machining generally reduces surface roughness because it decreases the friction and plowing forces. However, the UN-MQL system performed better than the wet, dry and conventional MQL conditions because the high-pressure air containing uniformly distributed small oil droplets caused the lubricant to more thoroughly coat the contact surface between the tool and workpiece and facilitated the cutting. On the other hand, increasing lubrication (decreasing tool-chip-workpiece interface friction) increased the shear plane angle and decreased the chip thickness (increased chip thickness ratio). Reducing the chip thickness decreased the shear plane area and initial deformation zone and reduced the energy required for material removal and the cutting force. Increasing the feed rate increased the machining tangential force which increased the power consumption of the machine. Furthermore, increasing the feed rate increased the friction coefficient between the tool and the workpiece, which increased the cutting force. It can be concluded that machining with UN-MQL system is a better choice in terms of reducing surface roughness and better surface quality. The results indicated that machining with MQL is promising because the consumption of lubricants in the MQL method is 7-fold less than with continuous lubrication. This decreases the risk of disease for the machine operator and environmental pollution.

3.2 Analysis of surface morphology

The obvious differences in the morphology of surfaces machined with different coolant-lubricant types suggest a considerable influence of the MQL techniques on the chip-formation mechanisms (Figures 4 and 5). Analysis of the results of applying dry, wet and MQL techniques indicated that the application of cutting fluid with UN-MQL system to the turning process resulted in a performance superior to that of the conventional methods, possibly by providing greater lubricant penetration efficiency into the machining zone. From the results of surface roughness (Fig. 3), and surface morphology (Figures 4 and 5), it is considered that the oil mist supplied to the cutting zone applying UN-MQL system lowers the total natural contact length due to the cooling/lubricating effect of air that results in chip up-curling that decreases the contact length. The oil droplets decrease the friction at the sliding region which is observed as thinner clad material at the sliding region on the tool for UN-MQL. In general, the wider chips are the result of side flow that can make the surface finish worse for dry cutting in comparison to MQL turning. A change from dry to MQL can result in benefits due to shorter contact length but a change from emulsion to MQL should be evaluated in terms of other parameters such as surface finish, forces, temperature and so on. Furthermore, with regard to the surfaces of the machined specimens (Figs. 4 and 5), it can be observed that there are hardly any side flows and defects on surfaces machined by applying MQL technique. However, surfaces generated under dry and fluid conditions are characterized by side flow and more surface damage. It can be seen that in these conditions, lower thermal damages and material side flow can be observed when using MQL technique.



Figu. 3. variation in surface roughness with different process parameters under various turning operations



Vc=265rpm f=0.05mm/rev dry

Vc=265rpm f=0.1mm/rev dry

f=0.2mm/rev Vc=265rpm dry

f=0.3mm/rev Vc=265rpm dry

Vc=265rpm f=0.05mm/rev wet

f=0.1mm/rev Vc=265rpm wet

f=0.2mm/rev Vc=265rpm wet

Vc=265rpm f=0.3mm/rev wet

Vc=1330rpm f=0.05mm/rev dry

Vc=1330rpm f=0.1mm/rev dry

Vc=1330rpm f=0.2mm/rev dry

Vc=1330rpm f=0.3mm/rev dry

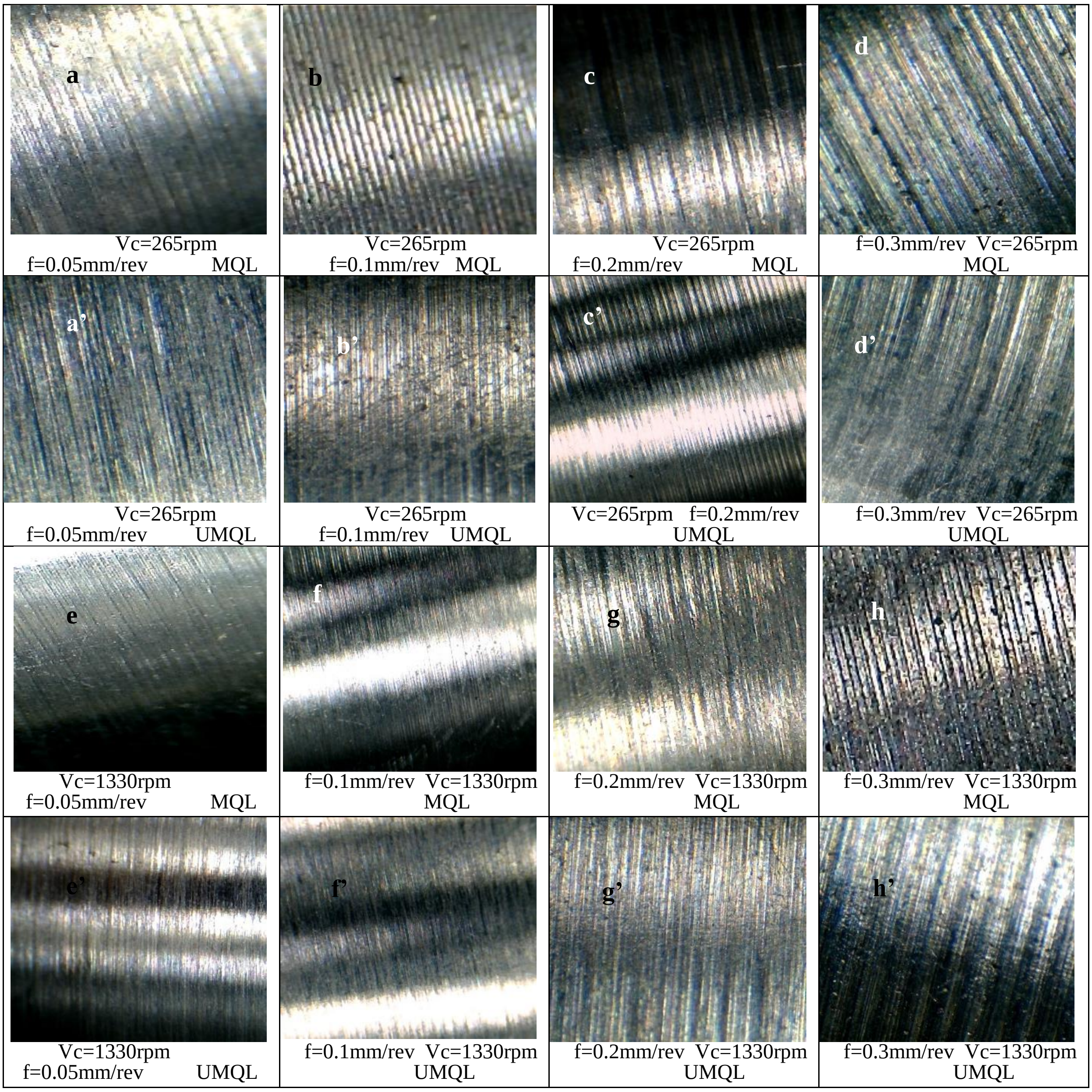
Vc=1330rpm f=0.05mm/rev wet

Vc=1330rpm f=0.1mm/rev wet

Vc=1330rpm f=0.2mm/rev wet

Vc=1330rpm f=0.3mm/rev wet

Fig. 4. workpiece surface in dry (a-h) and wet (a'-h') turning



Vc=265rpm f=0.05mm/rev MQL

Vc=265rpm f=0.1mm/rev MQL

Vc=265rpm f=0.2mm/rev MQL

f=0.3mm/rev Vc=265rpm MQL

Vc=265rpm f=0.05mm/rev UMQL

Vc=265rpm f=0.1mm/rev UMQL

Vc=265rpm f=0.2mm/rev UMQL

f=0.3mm/rev Vc=265rpm UMQL

Vc=1330rpm f=0.05mm/rev MQL

f=0.1mm/rev Vc=1330rpm MQL

f=0.2mm/rev Vc=1330rpm MQL

f=0.3mm/rev Vc=1330rpm MQL

Vc=1330rpm f=0.05mm/rev UMQL

f=0.1mm/rev Vc=1330rpm UMQL

f=0.2mm/rev Vc=1330rpm UMQL

f=0.3mm/rev Vc=1330rpm UMQL

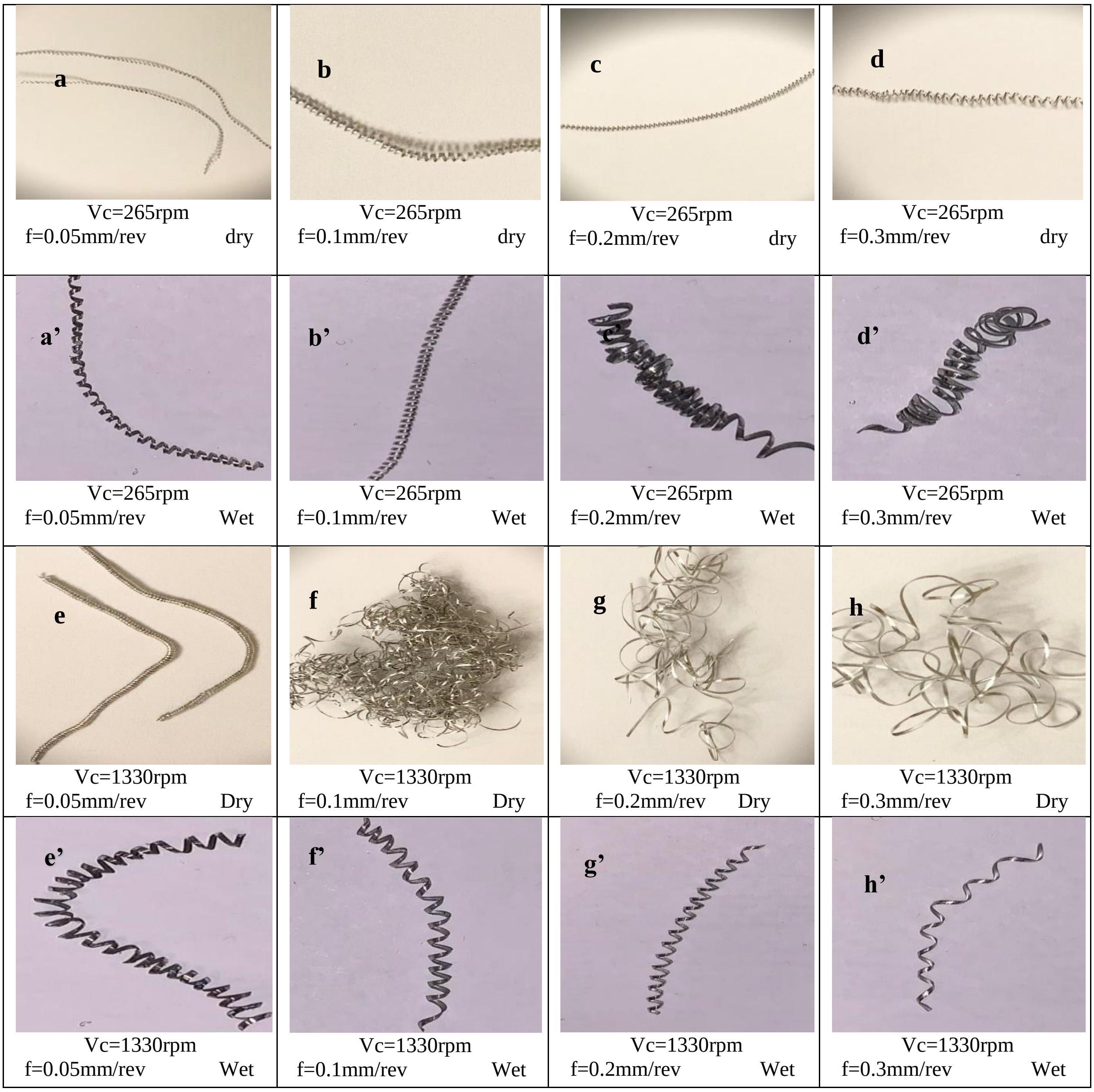
Fig. 5. workpiece surface in MQL (a-h) and UMQL (a'-h') turning

3.3 Analysis of chip formation

Under different machining conditions, different chip forms are formed (Figures 6 and 7). It is obvious that long chips, like ribbon chips, snarled chips and flat helical chips, are disadvantageous and can endanger persons, tools, workpieces, and the machine tool. Short chips, like discontinuous chips and spiral chip segments, can cause problems in the transport from the material separation zone or if the operator is not adequately protected. Spiral chips and helical chip segments are the most favorable. The formation of the different chip forms depends greatly on the friction conditions in the contact area between the chip and the rake face, the cutting parameters and the material properties. The feed influences the chip compression ratio, i.e., the chip thickness, and thus the chip deformability. Therefore, the chip forms highly depend on the feed. The cutting speed has an essential influence on the temperatures in the chip formation zone due to heat conduction and convection. Higher cutting speeds lead to higher chip formation temperatures.

Chips are divided into ten types in [19], which are then divided into three groups: good, acceptable, and unfavorable chips. Nakayama [20] attempted to categorize chips theoretically but provided no information on how to test the three essential parameters involved, namely chip flow angle, up-curl radius, and side curl radius. In [21] a chip-shape classification based on membership values has been proposed. Using so-called fuzzy membership values, chip breakability was quantitatively weighted. However, no compelling evidence was provided to support the assignment of fuzzy membership values to a certain chip form or size.

It is indicated from Figures 6 and 7 that in MQL machining of Al 7075-T6, the chip forms are regular, non-snarled and non-convoluted, and this can lead to significant lamellae as well as a fine segmentation to continuous chip types. Applying UN-MQL to the turning process provides greater lubricant penetration efficiency into the machining zone, results in lower energy required at the shear plane and tool-chip friction zones, greater shear plane angle and consequently better chip formation (Fig. 7).



Vc=265rpm f=0.05mm/rev dry

Vc=265rpm f=0.1mm/rev dry

Vc=265rpm f=0.2mm/rev dry

Vc=265rpm f=0.3mm/rev dry

Vc=265rpm f=0.05mm/rev Wet

Vc=265rpm f=0.1mm/rev Wet

Vc=265rpm f=0.2mm/rev Wet

Vc=265rpm f=0.3mm/rev Wet

Vc=1330rpm f=0.05mm/rev Dry

Vc=1330rpm f=0.1mm/rev Dry

Vc=1330rpm f=0.2mm/rev Dry

Vc=1330rpm f=0.3mm/rev Dry

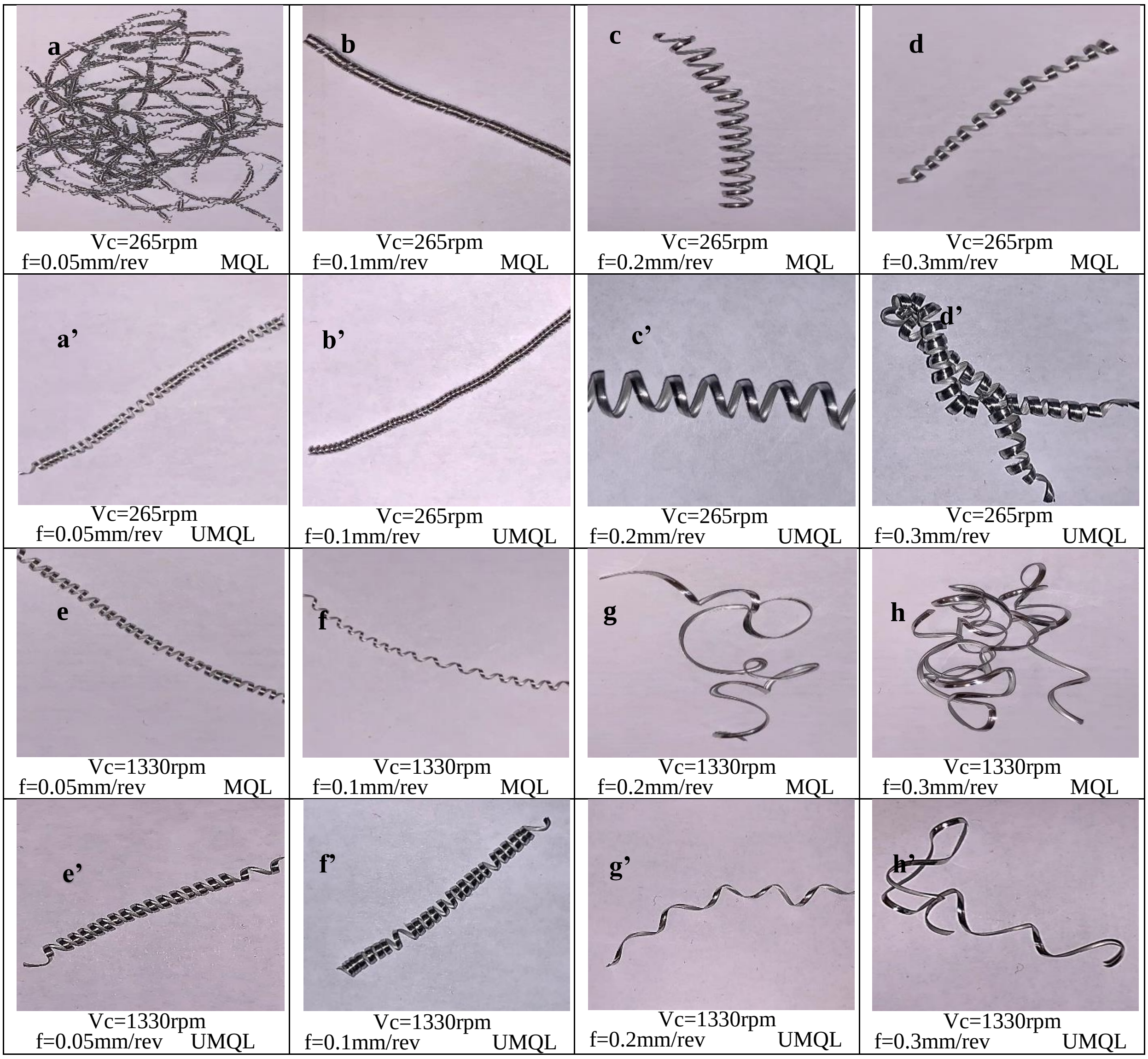
Vc=1330rpm f=0.05mm/rev Wet

Vc=1330rpm f=0.1mm/rev Wet

Vc=1330rpm f=0.2mm/rev Wet

Vc=1330rpm f=0.3mm/rev Wet

Fig. 6. chip forms in dry(a-h) and wet (a'-h') turning

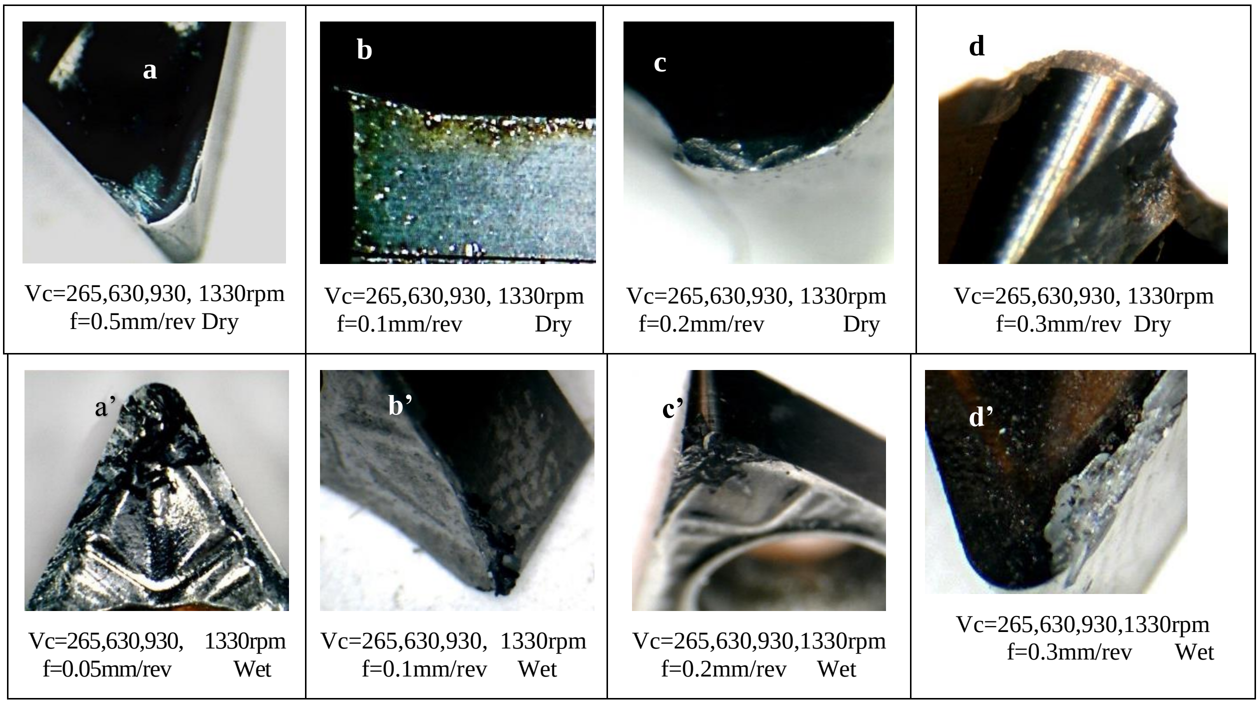


Vc=265rpm f=0.05mm/rev MQL
Vc=265rpm f=0.1mm/rev MQL
Vc=265rpm f=0.2mm/rev MQL
Vc=265rpm f=0.3mm/rev MQL
Vc=265rpm f=0.05mm/rev UMQL
Vc=265rpm f=0.1mm/rev UMQL
Vc=265rpm f=0.2mm/rev UMQL
Vc=265rpm f=0.3mm/rev UMQL
Vc=1330rpm f=0.05mm/rev MQL
Vc=1330rpm f=0.1mm/rev MQL
Vc=1330rpm f=0.2mm/rev MQL
Vc=1330rpm f=0.3mm/rev MQL
Vc=1330rpm f=0.05mm/rev UMQL
Vc=1330rpm f=0.1mm/rev UMQL
Vc=1330rpm f=0.2mm/rev UMQL
Vc=1330rpm f=0.3mm/rev UMQL

Fig. 7. chip forms in MQL (a-h) and UMQL (a’-h’) turning

3.4 Analysis of cutting tool wear

Figure 8-11 shows the tool wear micrograph at the flank side and nose radius of used tools under different cutting conditions for 5min machining time. As shown in Fig. 10, MQL and UN-MQL machining techniques caused lower damage at the flank face of the cutting tool in comparison with the dry and wet machining operations. In all machining conditions build-up edge and abrasive wear on the cutting edge and flank face can be easily seen, however, in wet and dry the levels of these defects were higher in comparison to MQL and UN-MQL machining processes. Another reason behind these results could be the temperature reduction in the MQL cutting. In fact, in the MQL machining due to the lower temperature in the tool-chip-workpiece interface and improving cutting conditions, the thermomechanical forces on the tool’s edge significantly reduced and consequently, lower tool wear and better surface roughness were achieved. Under dry and wet machining at f=0.2 and 0.3 mm/rev, the cutting edge has been broken which demonstrates the effect of the cutting lubricants on the reduction of pressure, contact temperatures and friction on the tool edge. In UN-MQL technique negligible wear was observed (Figs. 10 and 11). Indeed, in the cutting process absorbed lubricant films on tool surface significantly reduce friction and adhesion and prevent forming of micro cracks. The micro-cracks in tool surface act as a stress concentrator and increase the potential risk of cutting-edge fracture. UN-MQL condition provides a long steady state wear which means thermal softening and oil droplets penetration at the tool-workpiece-chip interface reduced the risk of high tool wear rate. It can be concluded that the high rate of tool wear may be a reason for high cutting and friction temperatures and forces and consequently higher surface roughness in the wet, dry and machining in the ambient temperature.



Vc=265,630,930, 1330rpm f=0.5mm/rev Dry

Vc=265,630,930, 1330rpm f=0.1mm/rev Dry

Vc=265,630,930, 1330rpm f=0.2mm/rev Dry

Vc=265,630,930, 1330rpm f=0.3mm/rev Dry

Vc=265,630,930, 1330rpm f=0.05mm/rev Wet

Vc=265,630,930, 1330rpm f=0.1mm/rev Wet

Vc=265,630,930,1330rpm f=0.2mm/rev Wet

Vc=265,630,930,1330rpm f=0.3mm/rev Wet

Fig. 8. tool wear in dry (a-d) and wet (a’-d’) turning

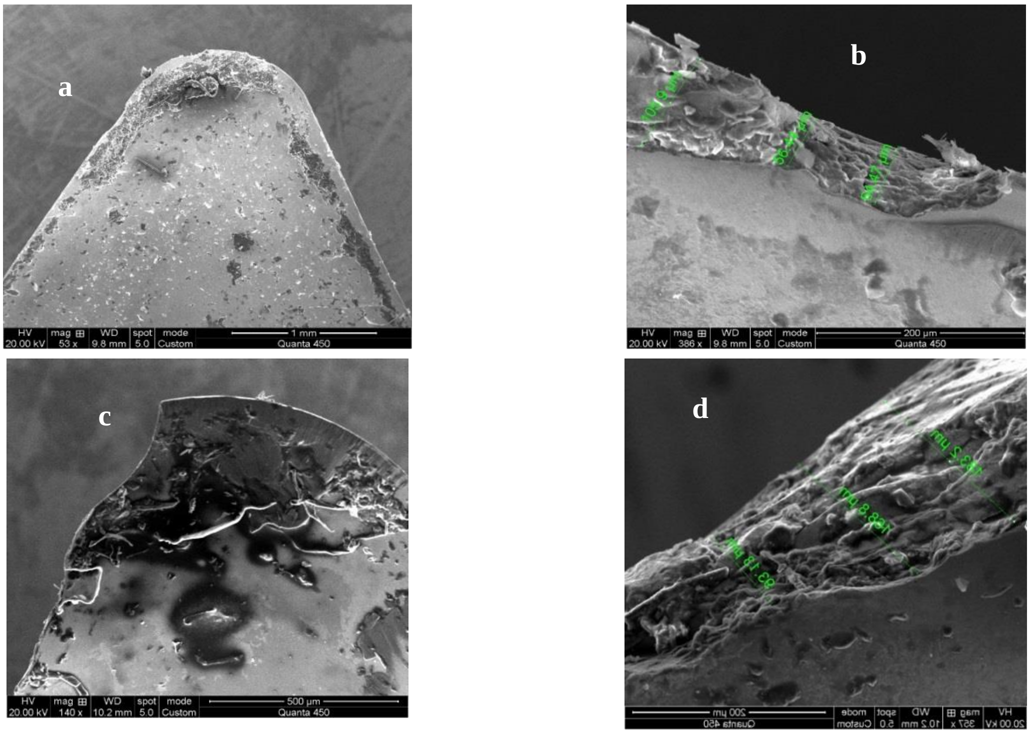
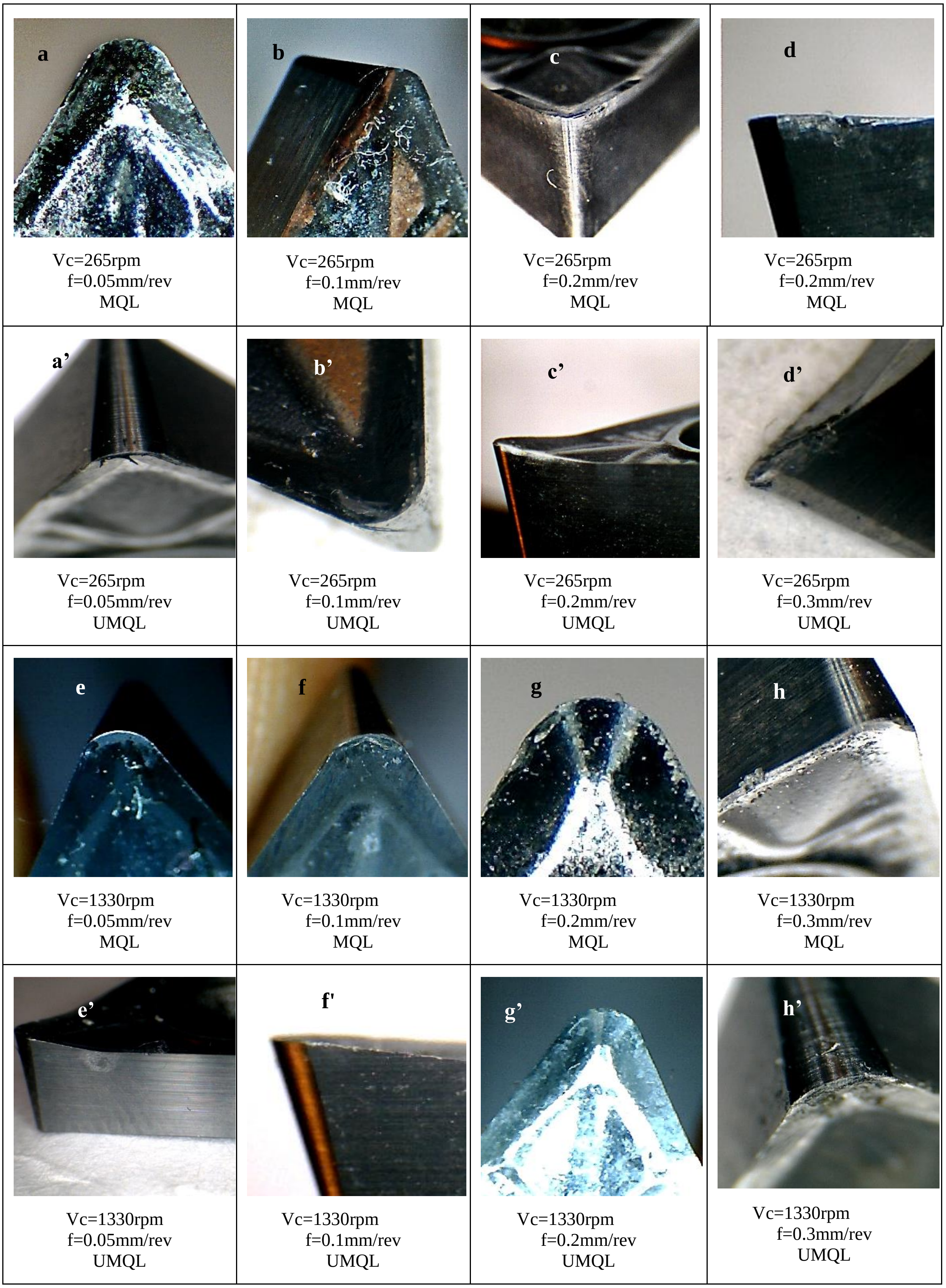


Fig. 9. SEM micrographs of tool wear area in wet (a,b) and dry (c,d) turning



a: Vc=265rpm f=0.05mm/rev MQL

b: Vc=265rpm f=0.1mm/rev MQL

c: Vc=265rpm f=0.2mm/rev MQL

d: Vc=265rpm f=0.2mm/rev MQL

a’: Vc=265rpm f=0.05mm/rev UMQL

b’: Vc=265rpm f=0.1mm/rev UMQL

c’: Vc=265rpm f=0.2mm/rev UMQL

d’: Vc=265rpm f=0.3mm/rev UMQL

e: Vc=1330rpm f=0.05mm/rev MQL

f: Vc=1330rpm f=0.1mm/rev MQL

g: Vc=1330rpm f=0.2mm/rev MQL

h: Vc=1330rpm f=0.3mm/rev MQL

e’: Vc=1330rpm f=0.05mm/rev UMQL

f': Vc=1330rpm f=0.1mm/rev UMQL

g’: Vc=1330rpm f=0.2mm/rev UMQL

h’: Vc=1330rpm f=0.3mm/rev UMQL

Fig. 10. tool wear in MQL (a-h) and UMQL (a’-h’) turning

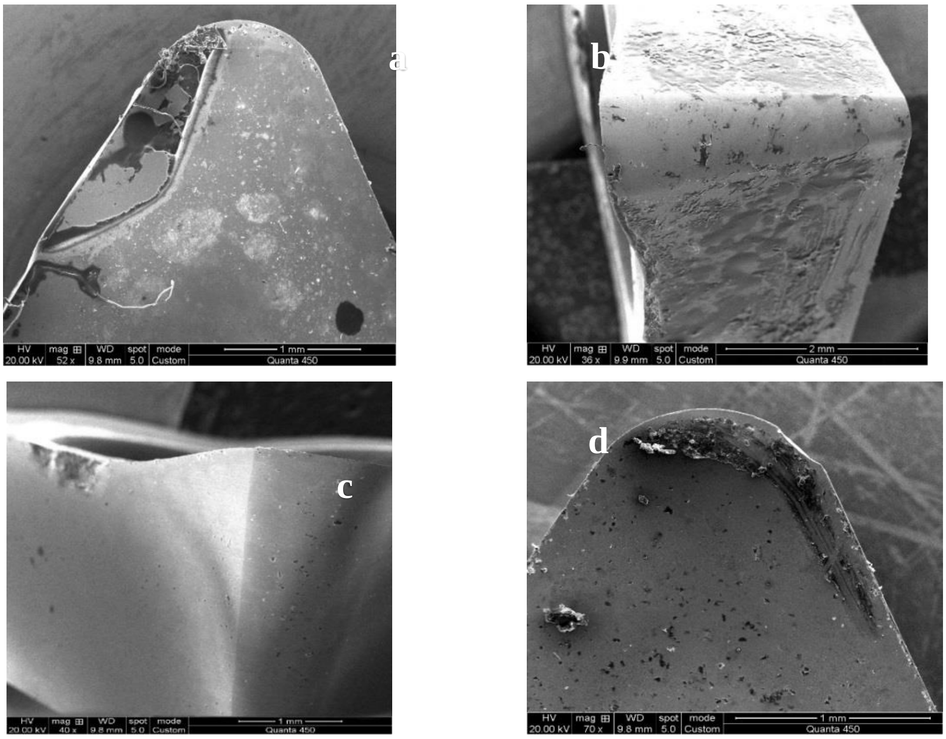


Fig. 11. The views of wear area in MQL (a,b) and UN-MQL (c,d) turning

4. Optimization

4.1 Influence of machining parameters

Table 5 shows the experimental results of surface roughness during turning the Al 7075-T6 with TCGX 16T380-AC carbide tool inserts in both MQL and UMQL cutting environments. This experiment has been designed with Taguchi L16 orthogonal array to reduce all 32 tests that must be conducted. In this table for the values of cutting parameters, i.e., 1330 rpm cutting speed, 0.05 mm/rev feed and 0.09 A, a minimum (0.81 μm) value of Ra is observed (run no. 13). For run no. 4, Ra is maximal (2.07 μm) at 265 rpm, 0.2 mm/rev, 0.09, cutting speed and feed, and A respectively.

Table 5. Experimental results for L16 orthogonal array in both MQL and UMQL turning

Run No.	Vc	Feed	Wettability (A)	Ra (μm)
1	265	0.05	0.035	1.29
2	265	0.1	0.09	1.22
3	265	0.2	0.035	1.75
4	265	0.3	0.09	2.07
5	630	0.05	0.09	1.02
6	630	0.1	0.035	1.10
7	630	0.2	0.09	1.63
8	630	0.3	0.035	1.90
9	930	0.05	0.035	1.03
10	930	0.1	0.09	0.85
11	930	0.2	0.035	1.44
12	930	0.3	0.09	1.86
13	1330	0.05	0.09	0.81
14	1330	0.1	0.035	0.85
15	1330	0.2	0.09	1.17
16	1330	0.3	0.035	1.70

4.2 Signal-to-noise (S/N) ratio

The S/N ratio is the mean-to-standard deviation ratio. It is used to determine how far a quality characteristic deviates from its desired value [22]. According to the Taguchi technique, the signal-to-noise ratio (S/N) can be employed as a quantitative analytical tool. Because in this experiment, lower surface roughness and tool wear values are sought, the signal-to-noise ratio is selected as $S/N = -10\log(\frac{1}{n}\sum_{i=1}^{n} yi^2)$ where n is the number of experiments and yi is the observed value. The bigger the S/N ratio, the better the performance in obtaining the optimal process parameters.

Based on the experimental results, the S/N ratio is calculated as shown Table 5, where Vc represents the cutting speed, Feed represents the feed rate, A represents the wettability. The highest S/N ratio value can be used to determine the ideal level of process parameters [23]. ANOVA was used to discover the design characteristics that have a significant impact on the response values.

The Signal to Noise (S/N) ratio was used to examine the effects of each factor level on the quality features. The S/N ratio is plotted against the test level for each control parameter, as shown in Figure12 and 13, where depicts surface roughness. The ideal cutting parameters for surface roughness were identified using the S/N ratio analysis in Fig. 12 and 13: cutting velocity 1330 rpm (level 4), feed rate 0.1 mm/rev (level 2), and A 0.09 (level 2).

Table 6 shows the ANOVA results of surface roughness to determine the percentage contribution of each parameter on surface roughness. It was observed that the feed rate is the more significant cutting parameter affecting the surface roughness. ANOVA results showed that feed rate, cutting speed, and wettability are affecting the surface roughness by approximately 81.3%, 16.9%, and 0.045% respectively.

The response table for means of Ra (Table 8) and main effects plots for means of Ra (Fig. 12) show that the mean Ra changes as the cutting parameters, i.e., cutting speed, feed, and wettability, have various behavior. Furthermore, Feed is the most influential element for Ra, since it has the highest delta value (0.877) and is listed first in Table 8. Similarly, A has the least influence on Ra because it has the smallest delta value (0.0540) and is rated third.

Table 6. Analysis of variance (ANOVA) for surface roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Vc	3	0.43267	0.144223	31.96	0.001	16.9%
Feed	3	2.08747	0.695823	154.20	0.003	81.3%
A	1	0.01156	0.011556	2.56	0.014	0.045%
Error	8	0.03610	0.004512			
Total	15	2.56779				

Table 7. Response Table for Signal-to-Noise Ratios

Level	Vc	Feed	A
1	3.77979	0.20256	2.51210
2	2.70467	0.06705	1.99680
3	1.85066	3.40887	
4	0.68269	5.47343	
Delta	3.09710	5.54048	0.51530
Rank	2	1	3

Table 8. Response Table for Means

Level	Vc	Feed	A
1	1.583	1.038	1.383
2	1.413	1.005	1.329
3	1.295	1.498	
4	1.133	1.883	
Delta	0.450	0.877	0.054
Rank	2	1	3

4.3 Confirmation Experiments

After determining the optimal level, the following equation can be used to forecast the best response:

$$y_{predicted} = y_m + \sum_{i=1}^{n}(y_i - y_m) \qquad (1)$$

where y_m denotes the total mean S/N ratio, y_i denotes the mean S/N ratio at the ideal level, and n denotes the number of primary design elements that influence quality features. The goal of this confirmation experiment is to confirm that the quality features have improved. On the basis of [24].

According to Fig. 12 and 13, the ideal cutting parameters for surface roughness are V4F2A2, where V is cutting speed, F is feed rate, and A is wettability. As a result, the S/N ratio prediction is estimated as 1.8964, as shown in Table 9 and Fig. 14. The S/N value for the conformation experimental result at the V4F2A2 level is 3.3964, which is close to the predicted value.

The desired regression equation model is developed to predict Ra during MQL and UMQL turning of Al7075-T6 with TCGX 16T380-AC carbide tool insert, using the relevant experimental data from Table 5 and by computing the values of various parameters through MINITAB software. Equation 2 represents the response surface model to the sample data for Ra.

$$\text{Ra} = 1.379 - 0.000590\,\text{Vc} + 2.04\,\text{f} - 1.53\,\text{A} + 4.00\,feed^2 - 0.000243\,\text{Vc}\times\text{feed} - 0.00161\,\text{Vc}\times\text{A} + 4.78\,\text{feed}\times\text{A} \qquad (2)$$

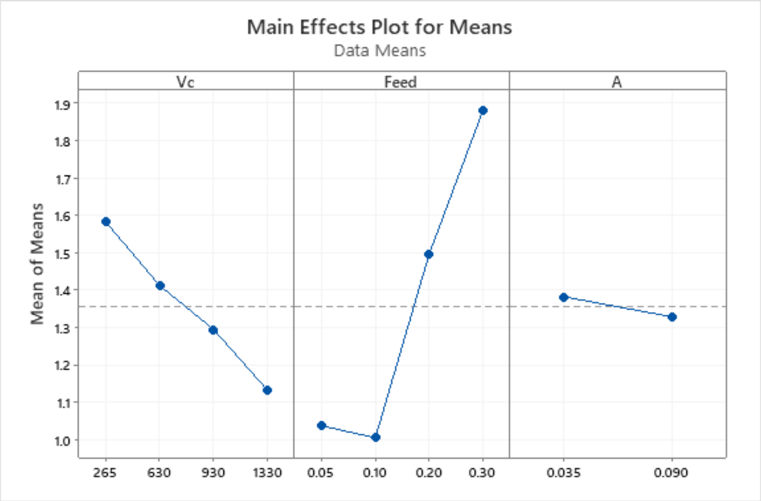


Fig. 12. Main effect plot for means (Ra)

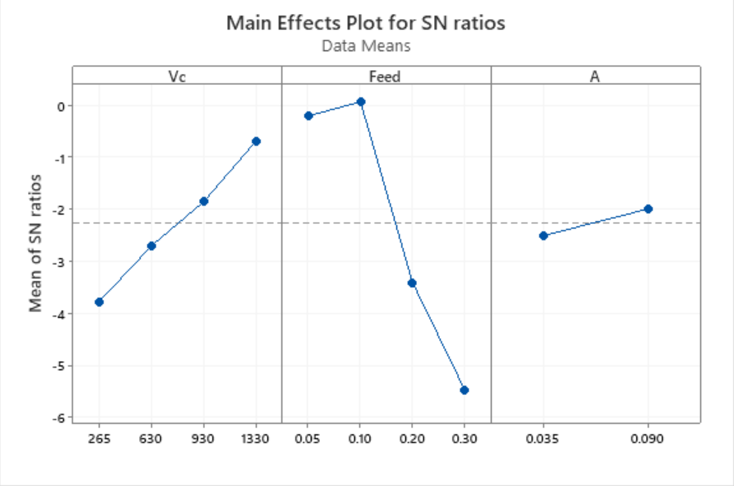


Fig. 13. Main effect plot for SN ratios (Ra)

Table 9. Result of confirmation experiment for surface roughness

Confirmation test for surface roughness			
	Initial	**Prediction**	**Experiment**
Parameter level	V3F2A1	V4F2A2	V4F2A2
S/N ratio	0.2131	1.8964	3.3964
improvement		3.1833	

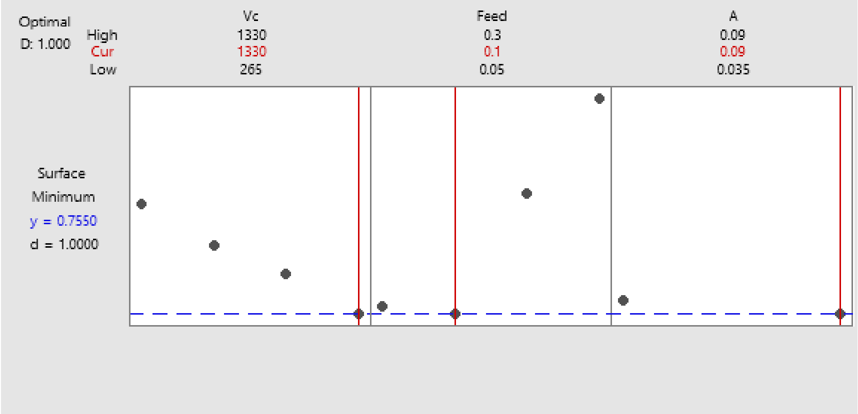


Fig. 14. Response of optimization

5. Conclusions

In this paper, the turning of Al7075-T6 has been investigated experimentally at different machining environments as well as different cutting parameters. The main results can be explained as:

1. The machining performance at a higher cutting speed value of 1330 m/min and feed rate values of 0.1 mm/rev under MQL and UN-MQL conditions is better in comparison to other machining parameters and environment conditions.
2. The UN-MQL nozzle by applying high-pressure air contained uniformly dispersed small oil droplets allowing the lubricant to more thoroughly coat the contact surface between the tool and workpiece and eased cutting. As a result, compared to the dry, MQL, and continuous fluid machining conditions, the UN-MQL machining technique significantly reduced the roughness of the machined surfaces.
3. Increasing the feed rate increased the machining tangential force, which increased the machine's power consumption. Increasing the feed rate also raised the friction coefficient between the tool and the workpiece, which increased the cutting force and caused the surface roughness to increase. Surface roughness, on the other hand, reduces as cutting speed increases.
4. It is considered that the oil mist delivered to the cutting zone via the UN-MQL system reduces the total natural contact length due to the cooling/lubricating impact of air, which causes chip up-curling and so reduces the contact length.
5. There are very few flaws on surfaces machined using the MQL process. Surfaces formed in dry and fluid conditions, on the other hand, exhibit higher surface damage. Lower thermal damages and defects can be noted when employing the MQL approach in these settings.
6. Using UN-MQL in the turning process increases the efficiency of lubricant penetration into the machining zone, resulting in less energy required at the shear plane and tool-chip friction zones, a greater shear plane angle, and, as a result, improved chip formation.
7. Build-up edge and abrasive wear on the cutting edge and flank face can be seen in all machining circumstances, although the levels of these defects were higher in wet and dry machining processes

compared to MQL and UN-MQL machining processes.

8. The UN-MQL condition provided steady-state wear, which means that thermal softening and oil droplet penetration at the tool-workpiece-chip interface lower the possibility of excessive tool wear rate. It may be deduced that the high rate of tool wear may be a cause of high cutting and friction temperatures and forces, and hence higher surface roughness in wet, dry, and ambient temperature machining.
9. Results of ANOVA revealed that feed rate and cutting speed are significant parameters for surface roughness. The feed rate (P = 81.3%) is the most influencing factor in determining the multiple performance characteristics. Cutting speed (P=16.9%) and Wettability (0.045%) stands at the second and last influential factors.
10. From the confirmation test, the optimal parameters for Ra were obtained at a feed rate of 0.1 mm/rev, cutting speed of 1330 rpm and wettability of 9%.
11. The experimental test demonstrated good agreement between the predicted and experimental values for surface roughness.

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