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REGULAR PAPER

Comparison the Effect of MQL, Wet and Dry Turning on Surface Topography, Cylindricity Tolerance and Sustainability

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Abstract

The increasing needs for the production of high quality parts require the use of new techniques to produce parts with higher precision. One of these modern techniques is minimum quantity lubricant (MQL) machining. In this paper, the effects of MQL, wet and dry machining on surface characteristic and geometric tolerances in turning of parts made of AISI 1045 steel were investigated. The influences of machining parameters i.e. feed rate and cutting speed as well as MQL parameters, namely air pressure and flow rate on surface topography, cutting force and cylindricity tolerance were studied. In addition, dry, wet, and MQL machining were compared to study the performance of different cooling systems. In the final step, the Pugh matrix approach was implemented to compare different cooling strategies in terms of sustainable production. According to the obtained results, MQL machining significantly improved the output parameters in AISI 1045 steel turning. By using MQL system, not only was the topography of machined surfaces improved and parts with tighter tolerances produced, but sustainability criteria were also improved. Based on sustainability assessment results, MQL turning was superior to wet and dry conditions in terms of the environmental impact, operator heath, manufacturing economy and production efficiency.

Keywords Turning · MQL · Surface topography · Cylindricity Tolerance · Cutting force · Sustainability assessment

1 Introduction

The surface characteristics and geometric accuracy of parts have been regarded as important and influential output parameters in machined parts. International Organization for Standardization (ISO) established a unified approach for the assessment of surface properties such as geometrical tolerances and surface quality, under 'Geometrical Characterization Specification for Products' (GPS Standards). The establishment of the GPS standard presents a very significant validation approach to guarantee the quality of parts produced by machining processes [1–3].

The increasing needs for the production of high quality parts require the use of new machining techniques to produce parts with higher precision. One of these modern techniques is minimum quantity lubricants (MQL) machining, which improves machining output parameters [4]. Machining with minimum quantity lubricant or near dry machining is an alternative technique for traditional wet and dry machining. In a MQL system, a minimal amount of lubricant (< 500 cc/h) is used. The lubricant is mixed with compressed air in a MQL nozzle and sprayed on cutting zone using atomization process. In spite of the name, the oil/lubricant droplets are not atom-sized, however, their size are ranged between 10–60 µm [5].

Research studies on MQL machining have been proved the numerous benefits of this technology [6]. Astakhov studied the principal, theory and directions of future studies in MQL cutting in a comprehensive research [7]. In recent years, many research studies have also been conducted in the area of surface quality as well as dimensional and geometrical accuracy of machined parts. Leppert studied the effect cooling conditions on surface waviness and roughness in machining of C45 steel [8]. The results indicated that lubrication and cooling systems significantly influence surface

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roughness and waviness. However, the results showed that the impact of the cooling and lubricating techniques in a large extent depend on the applied cutting parameters, namely the cutting speed and feed rate. Sartori et al. investigated solid lubricant-assisted MQL machining with different cooling strategies in turning of Ti6Al4V [9]. According to their results, in terms of surface quality, dry cutting presented the worst result, while the best surface finish achieved in MQL machining with PTFE particles. The use of the solid lubricant-assisted MQL approach determined the best result, as reductions in surface quality were equal to 44%, 36% and 29% compared to the dry, MQL and wet strategies, respectively. Masoudi et al. studied the influence of MQL machining on surface roughness in turning of AISI 1045 steel. According to their results, in MQL machining by using two MQL nozzles on both rake and flank faces, lower surface roughness was observed [10]. They declared that oil mist on both faces prevents the chip adhesion on tool edges when two MQL nozzles were used. Two MQL nozzles decreased the friction and heat generated on the tool's flank and rake faces and consequently reduced surface roughness.

Cho et al. proposed a mathematical model for the geometrical tolerances of machined parts [11]. The developed model presented an advanced geometrical tolerance analysis in cylindrical parts. The model was verified for both turning and cylindrical grinding processes. Based on their results, in addition to cutting parameters, model's performance was highly depended on spindle error motions. Musthafa et al. optimized machining parameters in turning of Al2017 for surface quality and geometric tolerances [12]. According to their results, feed rate was the most influential parameter affecting cylindricity tolerance in turned parts. The minimum workpiece cylindricity error was 19 µm in the feed rate of 0.15 mm/rev, depth of cute of 0.5 mm and cutting speed of 2500 rev/min. According to their results, change in the diameter of workpiece had a considerable effect on cylindricity and dimensional precision. Dhar et al. studied the effect of MQL machining on dimensional accuracy and temperature in machining of AISI-1040 steel [13]. They compared their results with dry cutting and cutting with soluble oil as coolant. They announced that minimum quantity lubricant condition reduces cutting temperature and increases dimensional inaccuracy depending on the levels of feed rate and cutting speed. They also declared that chip formation and chip–tool interaction become more favorable under MQL condition.

According to the literature, it has been found that little research studies have been reported for analyzing the effect of machining parameters on the surface topography and geometrical accuracy in cutting processes. This deficiency is especially felt in the study of MQL machining on these critical output parameters. Generally, engineering and scientific issues of machining processes do not adequately address surface topography. Surface analysis is limited to the roughness parameters such as Rz or Ra while studying the topography of machined surface could result in better understanding of process parameters [14]. In addition, the geometrical assessment of machined parts demands more advanced quality measurements such as cylindricity and roundness tolerances. Therefore, the aim of the present paper is to study the influence of MQL machining on the surface characteristic (topography and roughness) and the cylindricity tolerances in machined parts made of AISI 1045 steel. In addition, dry, wet and MQL machining were compared in order to study the performance of MQL machining on the output parameters. In the final step, the Pugh matrix approach was used to compare different cooling conditions in terms of sustainability assessment.

2 Experimental Procedure

Turning experiments were carried out on a manual lathe (TN50BR model, Tabriz). The cutting insert used in the experiments was a tungsten carbide insert (TNMA 160,404-Iscar) with the rake angle of 0^o and the clearance angle of 15^o. In order to prevent the effect of tool wear on the accuracy of results, each test was done with a new insert. The process variables studied were feed rate, cutting speed, air pressure of MQL system, and MQL flow rate. The different levels considered for machining and MQL parameters in the experiments are presented in Table 1.

The experiments were performed on the cylindrical parts made of AISI 1045 steel. The geometry of the cylindrical parts had two diameters. The greatest diameter, which was 60 mm with the length of 25 mm, was clamped by the chuck. All machining experiments and measurements were done on the section with 45 mm in diameter and the length of 75 mm. By clamping the larger diameter by the chuck, it could be ensured that any changes in cylindricity tolerance are not due to the pressure of the chuck.

The main components of the MQL setup used in the present research were the air compressor, oil reservoir, precise pump, manometer, directional control valve, inlet and outlet air pressure control, oil flow control, frequency valve and MQL nozzle. The precise pump transmits an

Table 1 Different levels considered for machining and MQL parameters

Parameter	Level			Unit
	1	2	3	
Cutting speed	50	70	100	m/min
Feed rate	0/08	0/12	0/16	mm/rev
Flow rate	30	70	110	ml/h
Pressure	3	5	7	bar

adaptable amount of oil (less than 200 mL/h) to the MQL nozzle. The frequency valve calibrates the rate of oil transmission via the precise pump. The oil is sent to the MQL nozzle through the flow control, which atomizes the lubricant to droplets sizing around 10–45 µm. The lubricant utilized in the MQL setup was ester oil (Behran-RS-1642). The flash point of the used oil was 210 °C with density of 886 kg/m^3 at 15 °C and a kinematic viscosity of 39 m^2/s at 40 °C. All experiments were done by two MQL nozzles spraying on both flank and rake faces. In wet condition, oil flow rate was 1.5 l/h.

A dynamometer (9257b-Kistler), a multichannel amplifier and a computer data acquisition system were used for cutting force measurement during the experiments. The force measurement system was placed on the turret below the tool holder. In order to determine surface quality, a surface roughness measurement machine (Hommel-T550) was used. Also, in order to study surface topography in different cutting conditions, a 3D nano-focus optical microscope (Bruker-GTK) was utilized. For the measurement of cylindricity tolerance, a form measurement instrument (Hommel-F4004 model) was used. Figure 1 shows the schematic diagram of the developed MQL and the measurement setups.

3 Results and Discussion

3.1 Surface Topography Results

Surface texture and topography are significant elements in the quality assessment of machined parts. To evaluate the effect of cutting speed on surface topography, three different machining tests were performed in dry condition. MQL machining is more efficient in low cutting speed i.e. below 100 m/min [8]. At low cutting speeds, the penetration of oil mist to cutting zone is more convenient; hence the lubricating and cooling effect of oil exceed the influence of raised friction and temperature at tool-chip interface. Accordingly, three different cutting speeds namely 50, 70 and 100 m/min (spindle speeds of 355, 500 and 710 rev/min) were used to investigate the effect of cutting speed on surface topography. Experiments were carried out with a constant feed rate of 0.08 mm/rev and the depth of cut was 1 mm. Figure 2 shows the topography of the machined surfaces and the values of surface roughness obtained at three cutting speeds.

Figure 2 clearly shows the significant effect of cutting speed on the machined surface topography. By increasing cutting speed, the quality of the machined surface improved and smother surface was achieved. At the cutting speed of 50 m/min, the topography of surface was rough with deep peaks and valleys. At this cutting speed, the roughness value

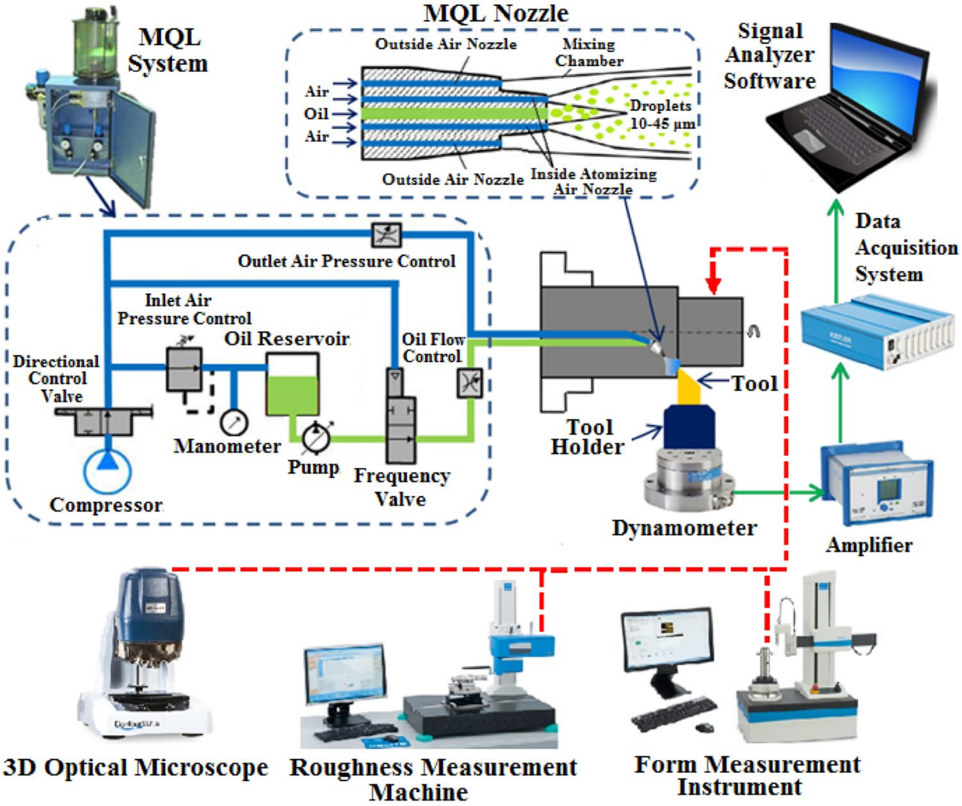

Fig. 1 Schematic diagram of the developed MQL setup and the measurement systems

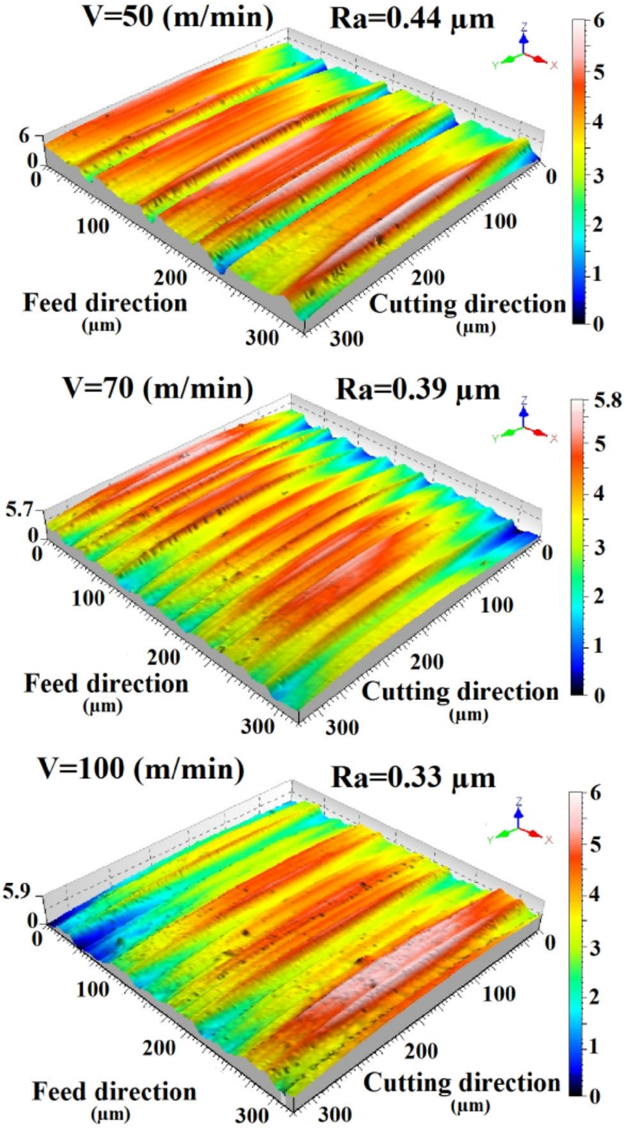

Fig. 2 Effect of cutting speed on surface topography

of 0.44 µm was obtained in surface roughness measurements. With increasing cutting speeds from 55 to 100 and 160 m/min, surface quality was improved and the topography of the machined surfaces indicates that the depth of valley and peaks were reduced and smoother features on surface were created. At the cutting speeds of 70 and 100 m/min, surface roughness values were 0.39 and 0.33 µm, respectively, which indicate 19 and 31% reduction relative to the cutting speed of 50 m/min. Better surface quality in higher cutting speeds is mainly due to a drop in flow stress and the ease of plastic deformation in material. This phenomenon is caused by an increase in temperature at cutting zone, which decrease friction and hence reduction in surface roughness [15].

In the next step, the effects of flow rate and air pressure in MQL system were investigated to study the effect of MQL parameters on surface topography. To study the influence of air pressure, all other input parameters were considered constant in the experiments. According to the results presented in the previous section, all tests were performed at the cutting speed of 100 m/min, depth of cut of 1 mm and feed rate of 0.08 mm/rev. Also flow rate of 70 ml/h was selected on the MQL system. Figure 3 shows the topography of four machined surfaces with air pressure of 0 (dry machining), 3, 5 and 7 bar. According to the results, it can be mentioned that the use of MQL machining improved the quality of the machined surfaces. With increasing air pressure, the surface roughness has decreased and surface topography improved. The Ra values at air pressure of 3, 5, and 7 bar were 0.28, 0.26 and 0.23 µm, respectively, which represent the decrease of 15, 21 and 30% compared to dry machining (air pressure of 0 bar).

By the reaction of workpiece material with oil mist in cutting area during MQL machining, a transitional layer of lubricant was created that separates the surfaces of tool and workpiece and consequently reduces the friction in cutting zone. In other words, a layer with low shear strength between the workpiece/chip and cutting tool was formed and subsequently eliminates the zone of severe friction and adhesion in cutting zone.

In the experiments, the penetration rate of oil mist increased with an increase in air pressure that resulted in better formation of lubricant layer at the chip-tool interface. Accordingly, friction and adhesion were reduced that appeared in surface with lower surface irregularities and defects.

In order to evaluate the effect of MQL flow rate on surface quality, three experiments in MQL condition with different flow rates i.e. 30, 70 and 110 ml/h were performed and compared with dry machining condition (flow rates of 0 ml/h). Turning tests were performed at the cutting speed of 100 m/min, depth of cut of 1 mm, feed rate of 0.08 mm/rev and the air pressure of 7 bar. Figure 4 represents the effect of flow rate on surface topography and roughness. The surface roughness in the flow rate of 30, 70 and *110* ml/h were measured as 0.26, 0.24 and 19 µm, respectively, which indicates a reduction of 21, 27 and 42% compared with dry cutting.

Figure 5 shows the microscopic image of machined surfaces as well as the corresponding roughness profiles in different flow rates. As shown in Figs. 4 and 5, an increase in flow rate decreased the surface roughness and improved surface topography; however, the influence of flow rate on surface roughness was much higher than air pressure as peaks and valleys were more flattened and the lower surface roughness values (Ra) were recorded. In MQL cutting as oil mist supplied to both flank and rake faces, the adhesion of chip to the rake face of tool and machined surface reduced and consequently surface quality improved. Increasing the flow rate reduced the friction at the tool-chip interface by

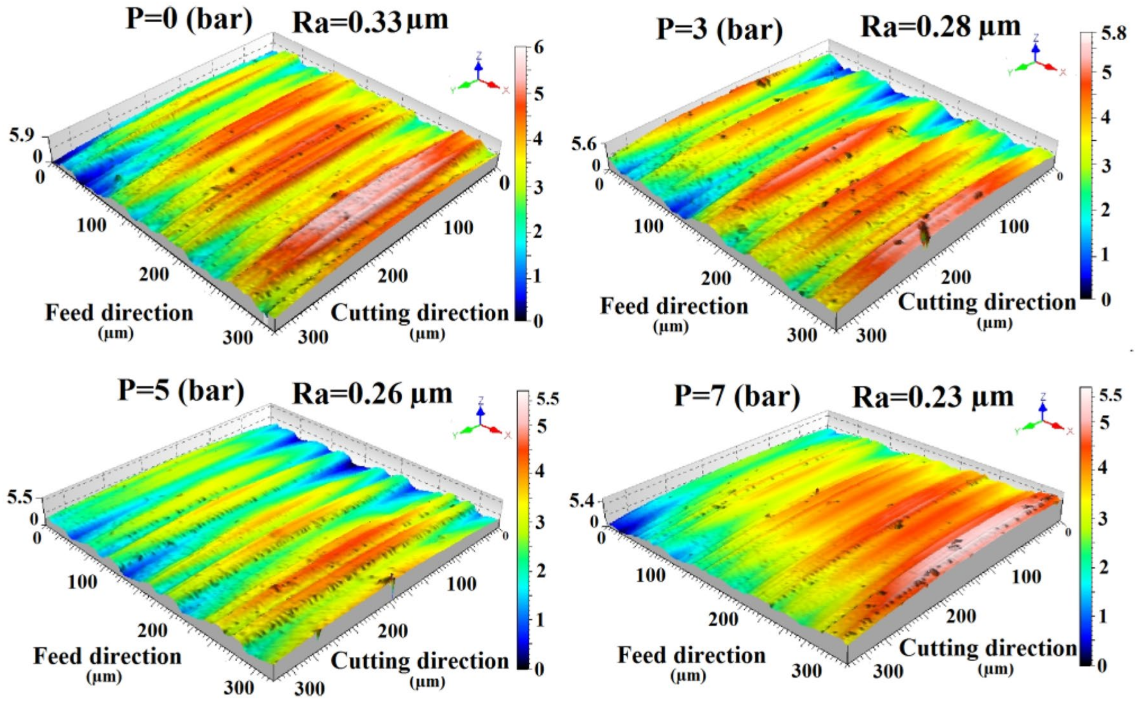

Fig. 3 Effect of MQL air pressure on surface topography

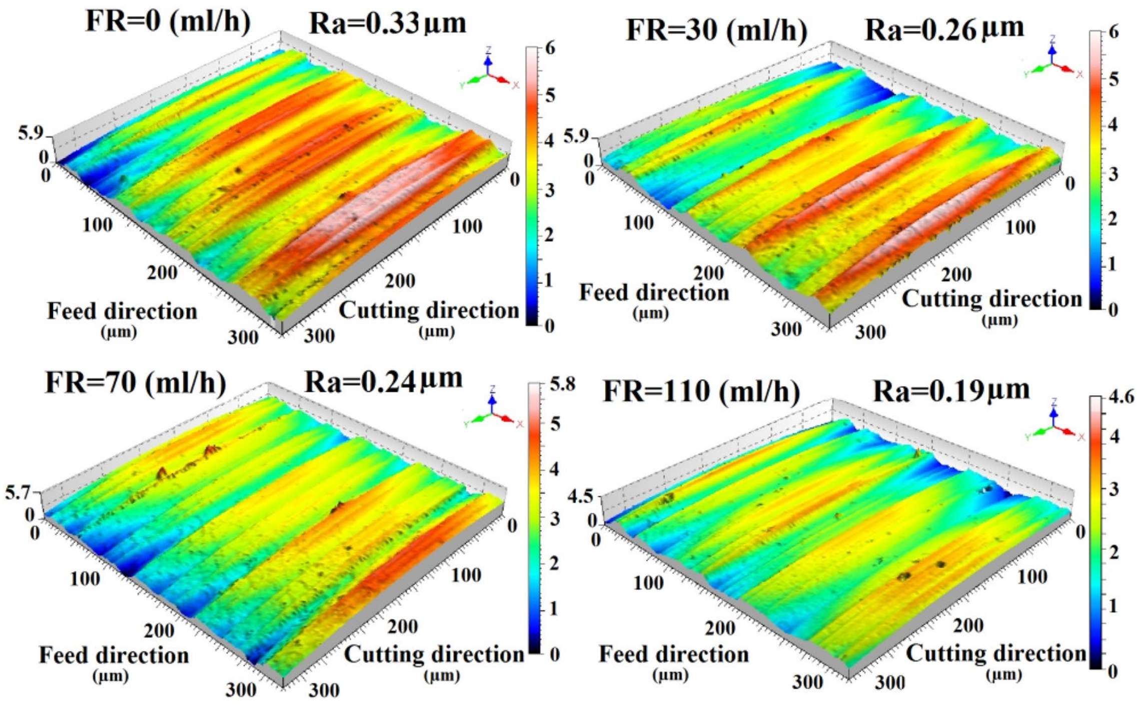

Fig. 4 Effect of MQL flow rate on surface topography

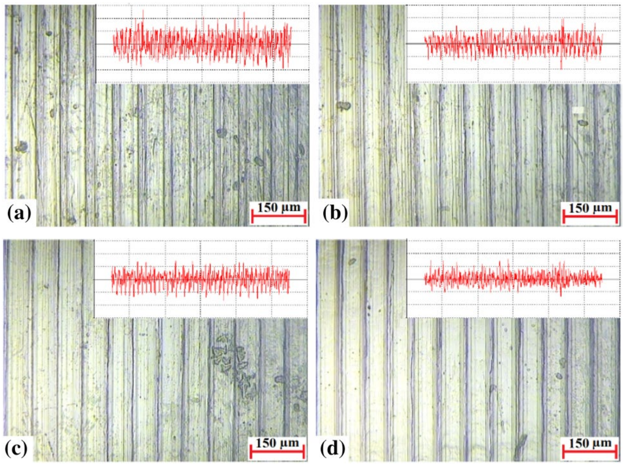

Fig. 5 Microscopic image of machined surfaces and the corresponding roughness profiles in the flow rates of: **a** 0 (dry cutting), **b** 30, **c** 70, and **d** 110 ml/h

supplying more lubricant at cutting zone, which facilitates cutting and reduces surface roughness.

In the next step, turning tests were conducted to compare MQL with wet and dry conditions. Three turning tests with different feed rates of 0/08 0.12 and 0.16 mm/rev were performed in MQL, wet and dry machining conditions. In MQL condition, based on the results obtained previously, the air pressure of 7 bar and flow rate of 110 ml/h were adjusted. The cutting speed was 100 m/min and depth of cut fixed at 1 mm. In wet condition, oil flow rate was 1.5 l/h. Figure 6 shows the results of surface topography in MQL, wet and dry machining under different feed rates. According to the results obtained in different cooling conditions, the surface roughness increased with increasing feed rate. Increasing in Ra values with a raise in feed rate is mainly due to more physical contact between workpiece and tool that raise the friction and machining force. In addition, an increase in feed rate leads to severe plastic deformation on machined surface and creates uninform surface texture.

MQL machining in all three feed rates led to the improvement of surface quality. In three feed rates of 0.08, 0.12 and 0.16 mm/rev, the values of Ra in MQL machining decreased by 37, 20, and 23%, respectively, in comparison with dry cutting. However, the surface quality of the machined surfaces in wet condition was superior to dry cutting and was inferior in comparison with MQL condition. These results are in accordance with the observations found by Leppert [8], that MQL machining is more efficient in lower cutting speeds and feed rates as the penetration rate

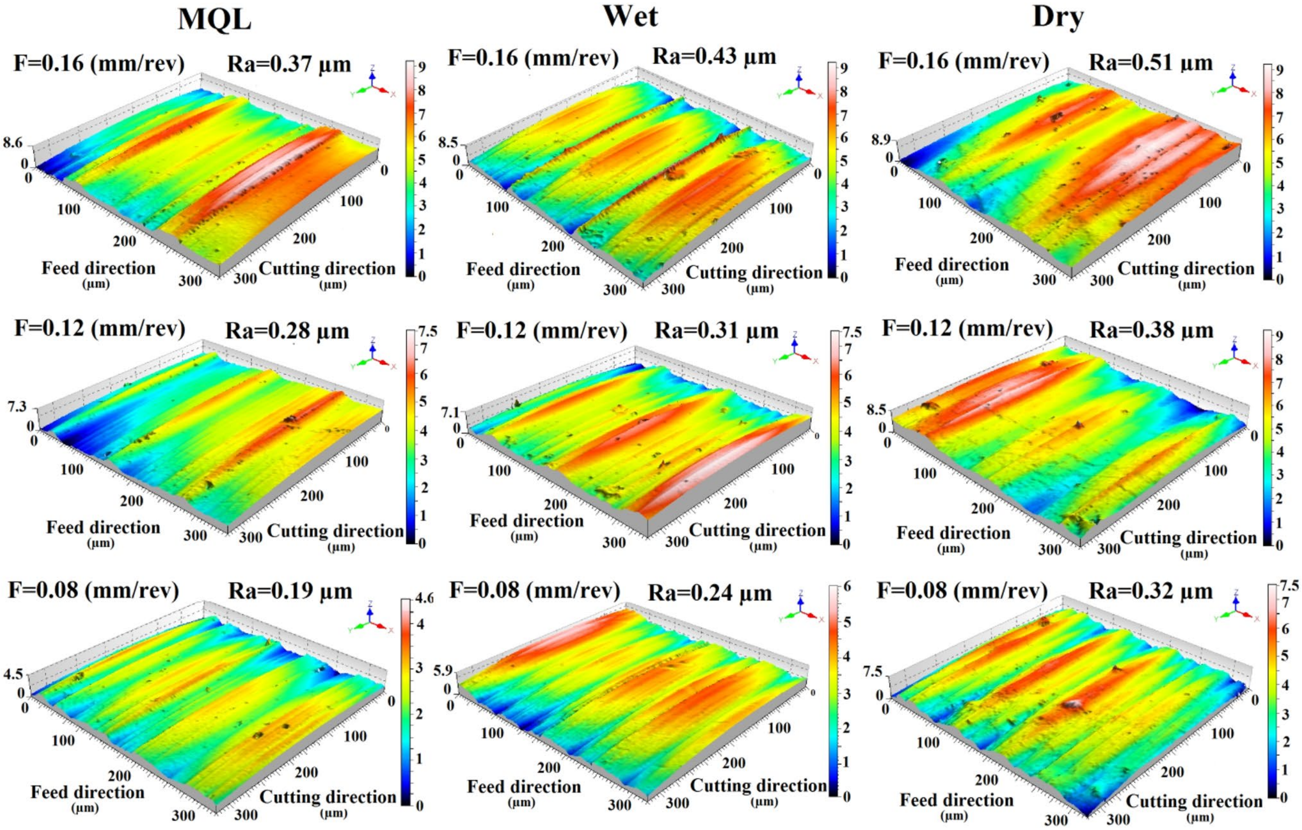

Fig. 6 Surface topography in MQL and dry machining under different feed rates

of oil mist will be increased in lower cutting speed and feed rate. The surface topography of MQL machined surfaces were presented by smother surface with fewer cleavages and scrapes, although traces of material side flow and local scratches were visible. These results have confirmed the significant influence of MQL machining on the improvement of machined surface quality.

The improvement of machined surface topography in MQL machining could be due to several reasons. Firstly, in MQL system, the micro droplets of oil with high pressure and velocity easily penetrate at the chip/tool interface and significantly reduce friction coefficient. Secondly, the cooling effect of oil mist jet could reduce the adhesion of workpiece material on tool surface. In addition, the embrittlement effect of the lubricant that is a physics-based phenomenon reduces the value of the strain needed for the fracture of chips. Chips' embrittlement is mainly due to the decomposition of the oil mist and is comparable to the hydrogen embrittlement that weakens the material plasticity. According to the Rebinder effect [16], it is confirmed that absorbed lubricant during turning creates a film that prevent the closing of micro cracks in chips due to plastic deformation of material. Lower energy is required for material removal, since each micro crack in cutting zone and chip serves as a stress concentrator. Clearly, lower cutting force is needed in MQL machining in comparison with dry machining, which ultimately enhance machinability and reduce surface roughness.

Studying surface topography by using a 3D nano-focus optical microscope in this research and comparing with Ra values show that the parameters such as Ra and Rz cannot completely define the surface properties. In the measurement of surface roughness, Ra is defined as the mean roughness of surface, so that the total area in upper and lower sections of an average line is calculated at a specified length. The area is expressed in the form of a rectangle and the rectangle width is considered as Ra value. In other words, the Ra value is calculated by using following equation:

$$\mathrm{Ra} = \frac{1}{l}\int_{0}^{l} |z(x)|dx \tag{1}$$

in which l is evaluation length and $z(x)$ is the profile height function. The concept behind Ra calculation is shown in Fig. 7a. Accordingly, surfaces with a completely different

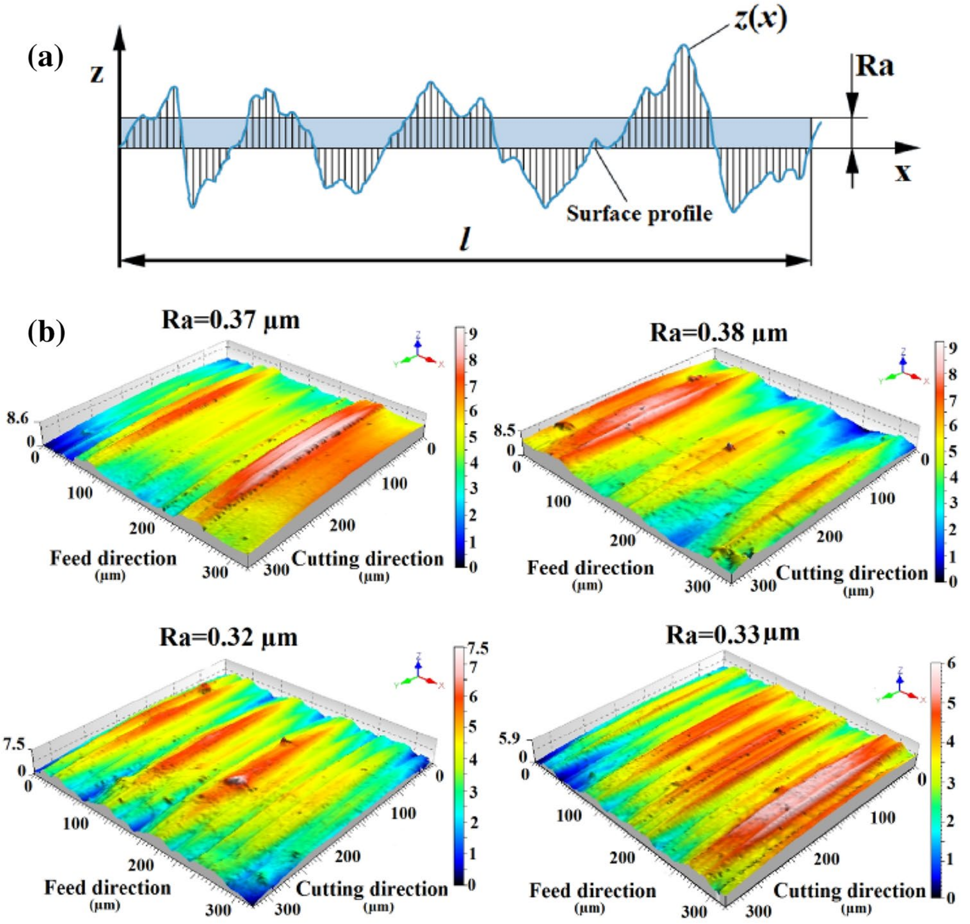

Fig. 7 **a** Concept behind Ra calculation, **b** machined surfaces with almost same roughness and different topography

topography may have the same surface roughness value (Ra). This issue is well illustrated in Fig. 7b. As shown in this figure, almost same roughness values were achieved for two surfaces while their topography and texture were completely different. These results clearly show that in the study of machined surfaces, using the parameters such as Ra and Rz are not sufficient.

3.2 Cylindricity Results

Geometric tolerance is one of the most important output parameters in evaluating the quality of machined parts. In many cases, machined parts are approved by quality control units in terms of size and dimensional accuracy. However, some parts faced with problems during assembly operations due to deviation form of a theoretical form and failure to meet the required geometric tolerances. One of the most important tolerances in evaluating the quality of turned parts is cylindricity tolerance that actually is a combination of the straightness and roundness tolerances [17].

After surface roughness and topographic measurements, the cylindricity tolerance was measured in all parts by using the form measurement machine. All conditions of the machining tests were the same as the previous section. The maximum and minimum cylindricity tolerances measured in parts were 10.8 and 7.3 µm that are shown in Fig. 8 in the forms of two-dimensional and three-dimensional profiles.

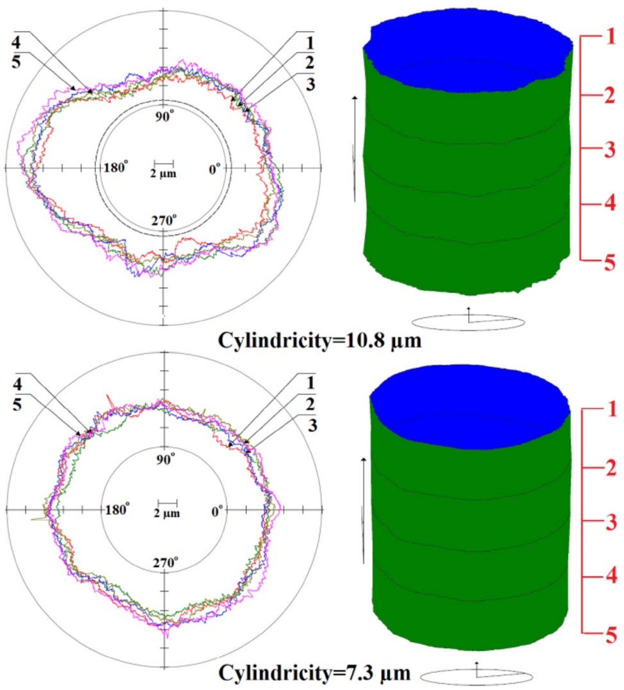

Fig. 8 Two-dimensional and three-dimensional profiles of the maximum and minimum cylindricity tolerances in the experiments

Figure 9 shows the effect of the investigated parameters on cylindricity tolerance and cutting force. As shown in Fig. 9a, in the three cutting speeds of 50, 70 and 100 m/min, main cutting forces were 215,183 and 166 N, respectively. These results are in accordance with the cutting theory that cutting force will decrease with an increase in cutting speed. These results are mainly due to a drop in flow stress and the ease of plastic deformation in material with an increase in temperature, reducing friction and machining force [18].

Geometric tolerance measurement results show that the values of cylindricity tolerance in parts were reduced with increasing cutting speed. These results show the direct effect of cutting force on cylindricity tolerance. In the cutting speeds of 50, 70 and 100 mm/min, the cylindricity tolerances were 10.8, 10.2 and 9.6 µm, respectively. By increasing the cutting speed from 50 to 70 and 100 m/min, the cutting force reduced by 15 and 23%, while the corresponding reduction for the cylindricity tolerances were 6 and 11%. In Fig. 9b, c, the effect of MQL parameters on cylindricity and cutting force are shown. According to Fig. 9b, in MQL machining with the air pressure of 3 bar and the flow rate of 70 ml/h, cutting force decreased from 166 to 134 N in comparison with dry cutting (the air pressure of 0). With increasing air pressure in the MQL system from 3 to 5 and 7 bar, the cutting force decreased slightly and the measured cylindricity tolerances were 8.1 to 8.3 and 7.6 µm, respectively. According to Fig. 9c, by increasing flow rate, both output i.e. the cutting force and cylindricity were reduced. The cylindricity tolerance at the flow rate of 30, 70 and 110 ml/h were 7.8, 7.6 and 7.3 µm. Comparing Fig. 9b, c shows that the effect of flow rate on cutting force and cylindricity is higher than air pressure in MQL machining. The minimum value of cylindricity tolerance was 7.3 µm at the flow rate of 110 ml/h with the air pressure of 7 bar.

Figure 9d shows the results of comparison between dry, wet and MQL machining in three different feed rates. Cutting force and cylindricity increased in all cooling conditions with an increase in feed rate. These results indicate a higher plastic deformation rate by increasing feed rate that resulted in increasing cutting force and cylindricity. According to results, in all feed rates i.e. 0.8, 0.12, and 0.16 mm/rev, both cutting force and cylindricity were reduced in MQL turning in comparison with dry and wet conditions. Also, wet machining caused reduction in cylindricity and cutting force, however, MQL machining was more efficient than wet cutting in terms of decreasing cylindricity and cutting force. According to the results, feed rate and cutting speed have much greater influence on cutting force and cylindricity in comparison with the MQL parameters. Comparing the results of experiments performed in dry and MQL machining shows that the maximum differences in cutting force and cylindricity were 32 and 25% respectively, while the change in MQL conditions (i.e. change in air pressure and flow rate)

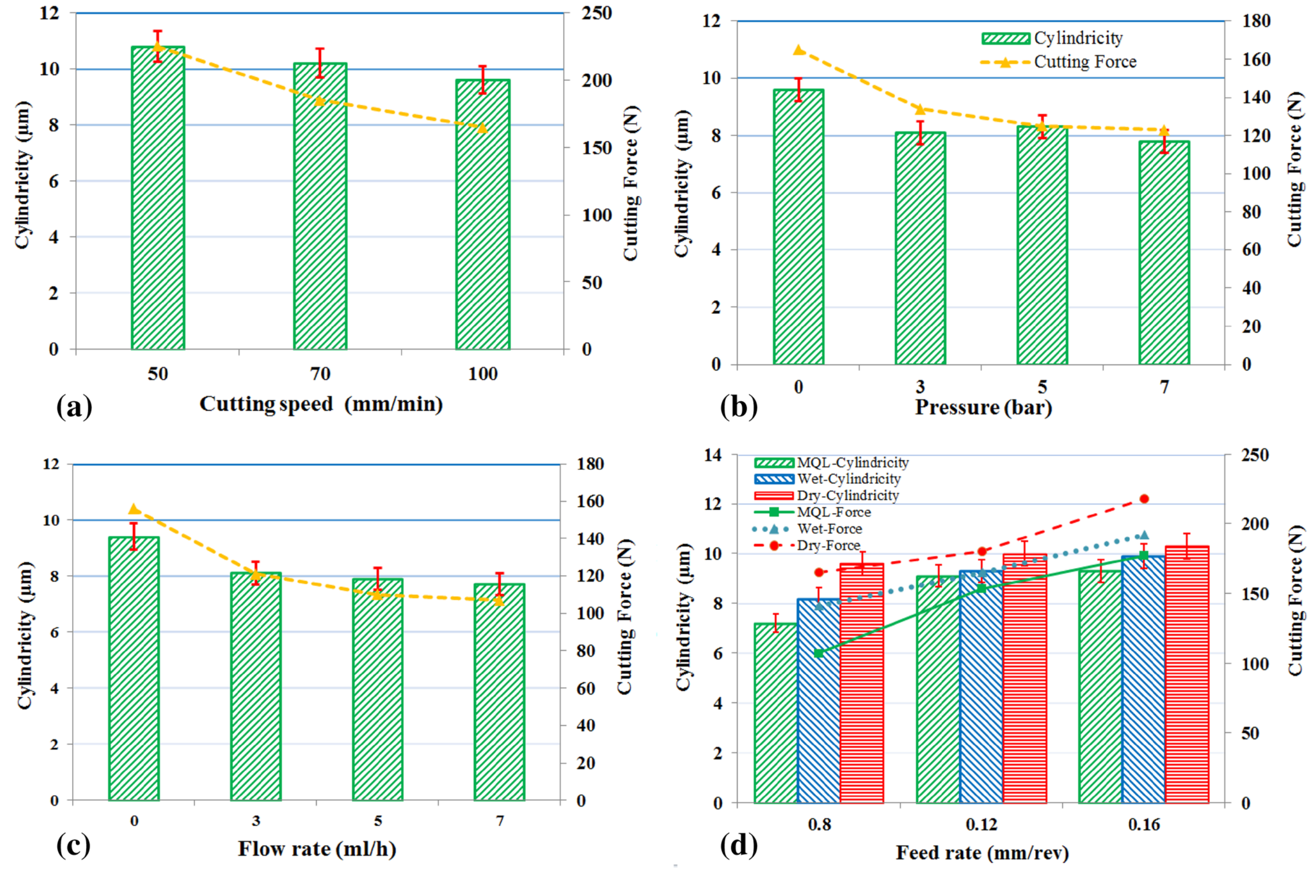

Fig. 9 Effect of machined and MQL parameters on cylindricity and cutting force

caused the maximum 12 and 8% reduction in cutting force and cylindricity. In fact, an increase in feed rate and cutting speed influenced cylindricity error and cutting force in different ways, including accelerating tool wear, formation of a built-up edge, increasing thermal distortion, changing the elastic deformation of workpiece and increasing radial spindle error.

Results provided in Fig. 9 demonstrate that MQL machining provided remarkable benefit in reducing cylindricity error in comparison with dry and wet machining. This occurred for several reasons, including reduction in the tool's wear, cutting force and the thermal expansion of workpiece in MQL machining. Dimensional and geometrical errors in turned parts are mainly due to inducing high mechanical loads, thermal expansion as the workpiece temperature rises during machining and increasing auxiliary flank wear of cutting tool. Therefore, in this case, MQL machining had the remarkable advantages in reducing these three sources of error, thereby reducing cylindricity tolerance.

In Fig. 10 measured cutting forces in the experiments are shown from the smallest to the highest values by using a bar graph and the corresponding cylindricity tolerance of each test is shown as a linear graph. According to the results obtained in this figure, a direct correlation between cutting force and cylindricity tolerance could be found as the value of cylindricity in the parts raised by increasing cutting force. By increasing cutting force, high mechanical pressures are induced on machined surface that appears as residual stress, distortion and non-uniform cylindrical surfaces. Consequently, in the experiments with higher cutting force, bigger cylindricity tolerances were measured.

One of the main reasons for variation in geometric tolerances of machined parts is machining-induced residual stresses. In a cutting process, a high volume of plastic deformation occurs at cutting region that results in generation of high mechanical pressures on machined surfaces. On the other hand, the major part of energy used in plastic deformation in machining appears as high temperature in cutting zone. The thermal and mechanical loads applied on workpiece surface lead to undesirable changes and inducing high levels of residual stresses.

Another mechanism for creating residual stress is microstructural changes on machined subsurface if the generated temperature be high enough. The interaction of these three complex mechanisms determines the final state of machining-induced residual stresses that results in the creation of

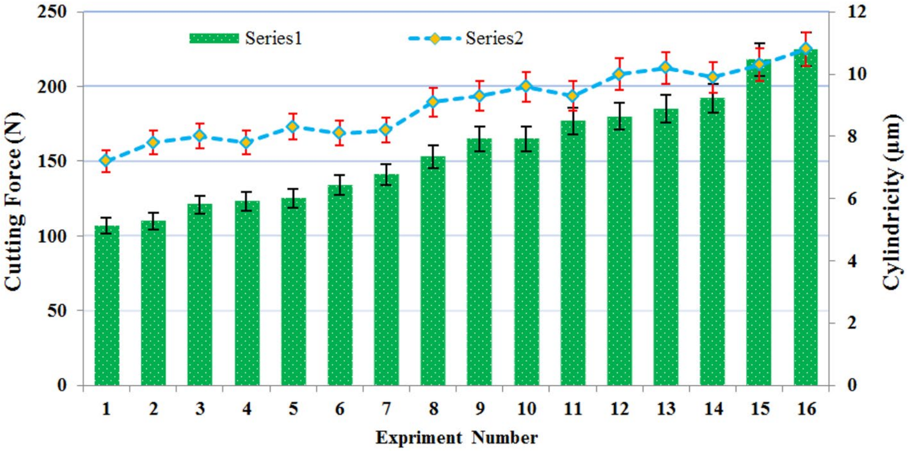

Fig. 10 Variations in cylindricity with increase in cutting force

a very thin layer (about 80–150 µm) with a high level of residual stress [19]. In nearly all of the research studies in the field of MQL machining, lower cutting forces and temperature have been reported in comparison with dry machining [20]. In one of the limited research done to investigate the influence of MQL condition on residual stresses, Maruda et al. announced that the depth of the microstructure change in turning of AISI 1045 reduced from 15.4 to 7.4 µm in MQL machining in comparison with dry cutting [21]. Therefore, in MQL machining the three main sources of residual stresses namely mechanical and thermal loads as well as microstructural changes will be reduced. These conditions lead to reduce the level of residual stress, consequently reducing the distortion and geometric tolerances of parts that is in accordance with the results obtained in the presented research. The obtained results here clearly show that the use of minimum quantity lubrication system can increase the accuracy of geometric tolerances especially the cylindricity tolerance in turned parts. Therefore, using MQL system especially in the machining of precise parts, which are used in assembly collections, is very advantageous and beneficial.

3.3 Sustainability Assessment Through Pugh Matrix Approach

In the concept of clean production, sustainability assessment is of great importance. Predominantly, the term sustainability assessment is a complex appraisal approach that is based on decision and policy making according to various parameters that include economical, environmental, technical and social conditions and transcends a pure technical or scientific evaluation [22]. In other words, in addition to evaluating technical parameters in sustainability assessment, the environmental aspects of a manufacturing process including environmental impact, the operator health, lubricant price and recycling are assessed. In the present study, Pugh matrix approach (PMA) was used for sustainability assessment in three modes of cooling system in machining including dry, wet, and MQL conditions. PMA is a decision-matrix method that compares a number of candidates based on which best candidate meets a set of criteria. This methodology determines the best candidate through the quality assessment of several alternative candidates based on specific qualitative parameters. PMA works based on pair wise matrix with priority on the comparison of several elements or desired qualities in a special situation. In order to achieve the best or ideal results, special weights with reference to numerical numbers are allocated to each quality parameter. The principle and basic steps of the Pugh matrix approach are as bellow:

Step 1 Defining the criteria: in this step, special weights will be selected, defined and established.

Step 2 Defining the datum criteria: The mean indicator with all basic performances will be selected as the datum or base criteria.

Step 3 Comparison step: In this step, the relative weights (in terms of their preference and importance) will be assigned to every quality parameters. For example, “+ 1” will be assigned for better outcomes and “− 1” for worse results. In a similar way, for more important parameters, a larger number will be given, for example “+ 4” and “− 4”.

Step 4: Final step: in the final step, all assigned numbers will summed up with each other and the superior criterion will be chosen [23].

In the present study, the sustainability assessment in turning of parts made of AISI 1045 steel with different cooling systems was appraised according to the combination of the environmental, economic and technical factors including: environmental impact, the operator health, lubricant price, lubricant recycling and disposal, surface roughness and topography, cylindricity tolerances and cutting force. Table 2 represents Pugh matrix comparison for different cooling systems. According to this table, for the environmental factors i.e. environmental impact and operator health the weight of “4” was allocated, while for the economic factors, which are

Table 2 Pugh matrix comparison for different cooling systems

Sustainability assessment factors	Weight	Dry	Wet	MQL
Environmental impact	4w	S	– 4	+3
Operator health	4w	S	– 4	+ 2
Lubricant price	3w	S	– 4	+ 1
Lubricant recycling	3w	S	– 2	+ 2
Surface roughness	2w	S	+ 1	+ 2
Cylindricity tolerances	2w	S	+ 1	+ 2
Cutting force	2w	S	+ 1	+ 2
Total +	–	0	+ 3	+ 14
Total –	–	0	– 14	0
Score	–	0	– 11	14

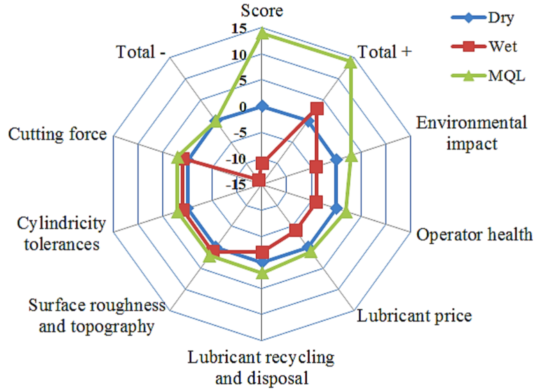

Fig. 11 Comparing the environmental, economical and technical aspects of different cooling systems

lubricant price and lubricant recycling, the weight of “3” was assigned. For the technical factors, i.e. surface roughness, cylindricity tolerances and cutting force the weight of “2” was allocated. In addition, dry condition has been referred as the baseline or datum.

In dry machining, turning was conducted without using cutting fluid, while in wet turning, the maximum amount of lubricant was used. However, the minimum amount of lubricant with compressed air was used in MQL condition. Consequently, in MQL condition the environmental impact and operator health are safer in terms of harmful constituents and pollutants than wet turning. Accordingly, the score of “+ 3” was given to MQL condition, while “– 4” was given to wet turning for the environmental impact factors. Also the score of “+ 2” was given to MQL condition for the operator health factor, while “– 4” was provided to wet turning. This is because the fact that the extensive oil used in wet turning contains potentially harmful chemical components and is environmentally damaging. The lubricant used in machining are difficult to recycle and expensive to dispose. In addition, exposure to cutting fluids and lubricants could cause the skin disease such as dermatitis and folliculitis, as well as the respiratory diseases such as asthma, bronchitis, allergies and in some cases cancer [20]. As mentioned earlier, for the economic factors i.e. lubricant price and lubricant recycling, the weight of “3” was assigned. In wet turning experiments, roughly 35 Ls of oil were used, whereas in MQL experiments nearly 4.5 Ls of oil were consumed which means that the consumption rate of oil in wet condition was nearly 7.5 times higher than MQL condition. Hence, the score of “+ 2” was given to MQL condition, while “– 4” was given to wet turning for the lubricant price factor. Clearly, more cost should be invested for lubricant recycling and disposal in wet turning in comparison with MQL condition. Accordingly, the score of “+ 2” was given to MQL condition, while “– 2” was given to wet turning for the lubricant recycling factor. According to the experimental results, MQL machining was superior to wet condition in terms of surface roughness and topography, cylindricity tolerances and cutting force. However, wet turning recorded superior results in comparison with dry cutting. Consequently, the score of “+ 2” was given to MQL condition, while “+ 1” was given to wet turning for all technical factors. Based on the calculation provided in Table 2, MQL condition achieved the maximum score of 14 points followed by the wet condition with the total score of – 11. Figure 11 represents a radar chart according to data provided in Table 2. According to Fig. 11 and Table 2, wet turning is not a suitable cooling system in terms of sustainability assessment in comparison with MQL condition. In addition to better performance in achieving lower surface roughness, cylindricity and cutting force, MQL machining is superior in terms of sustainability and cleaner production.

4 Conclusion

In the present paper, the effect of MQL machining on the surface characteristic and geometric tolerances in turning of parts made of AISI 1045 steel was investigated. The influence of machining and MQL parameters on surface topography and roughness as well as cutting force and cylindricity tolerance were studied. Dry, wet and MQL machining were compared to study the performance of MQL machining on the output parameters. In the final step, the Pugh matrix approach was used to compare different cooling conditions in terms of sustainability assessment. The following conclusions can be drawn from the obtained results:

- The results showed that both machining and MQL parameters influence surface roughness and topography. In MQL machining the quality of machined surfaces were smother and fewer dents and scrapes created in comparison with dry and wet conditions. The penetration of oil mist into cutting zone increased with increasing flow rate and air pressure and a lubricant layer with low shear strength was formed which resulted in lower friction coefficient and adhesion on the tool/chip interface. However, the change in machining parameters has led to more variation in surface quality than the change in MQL parameters. The study of surface topography in machined surfaces showed that the Ra roughness parameter cannot completely represent all surface properties and surfaces with the same Ra values could have a completely different topography.

- By increasing cutting speed and feed rate, the cylindricity tolerance of turned parts increased. Lower cutting force and cylindricity were measured in MQL machining than dry and wet conditions that indicates MQL machining improved cutting efficiency and parts with higher precision produced. Study of two MQL parameters i.e. flow rate and the air pressure represented that by increasing both parameters, cylindricity tolerances were reduced. However, the flow rate had a greater influence on cylindricity tolerances. Comparing cutting force and cylindricity tolerance clarified that a direct correlation between these two output parameters exists as the values of cylindricity in the parts increased by increasing cutting force. In MQL machining, due to reduced cutting force and thermal gradient, the level of residual stresses will be less than dry machining. Therefore, parts with lower deviations in geometric tolerances were achieved.
- Sustainability assessment approach based on the Pugh matrix approach demonstrated that MQL turning was superior to wet and dry conditions in terms of the environmental impact, operator heath, manufacturing economy and production efficiency. In other words, not only does the MQL condition improve the economic and technical aspects of the machining process, but it also moderates the problems associated with the environment and the operator health.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Muhammad, I., Khatoon, T., Ullah, S. M. S., & Ko, T. J. (2018). Development of Empirical Model for Biomachining to Improve Machinability and Surface Roughness of Polycrystalline Copper. *International Journal of Precision Engineering and Manufacturing-Green Technology,5*(2), 201–209.
2. Chu, W. S., Kim, M. S., Jang, K. H., Song, J. H., Rodrigue, H., Chun, D. M., et al. (2016). From design for manufacturing (DFM) to manufacturing for design (MFD) via hybrid manufacturing and smart factory: A review and perspective of paradigm shift. *International Journal of Precision Engineering and Manufacturing-Green Technology,3*(2), 209–222.
3. Yonehara, M., Matsui, T., Kihara, K., Isono, H., Kijima, A., & Sugibayashi, T. (2004). Evaluation method of surface texture by surface roughness based on geometrical product specifications (GPS). *Materials Transactions,45*(4), 1019–1026.
4. Nam, J., & Lee, S. W. (2018). Machinability of titanium alloy (Ti-6Al-4V) in environmentally-friendly micro-drilling process with nanofluid minimum quantity lubrication using nanodiamond particles. *International Journal of Precision Engineering and Manufacturing-Green Technology,5*(1), 29–35.
5. Pereira, O., Rodríguez, A., Barreiro, J., Fernández-Abia, A. I., & de Lacalle, L. N. L. (2017). Nozzle design for combined use of MQL and cryogenic gas in machining. *International Journal of Precision Engineering and Manufacturing-Green Technology,4*(1), 87–95.
6. Pervaiz, S., Anwar, S., Qureshi, I., & Ahmed, N. (2019). Recent advances in the machining of titanium alloys using minimum quantity lubrication (MQL) based techniques. *International Journal of Precision Engineering and Manufacturing-Green Technology*, *6*(1), 133–145.
7. Astakhov, V. P. (2009). Metal cutting theory foundations of near-dry (MQL) machining. *International Journal of Machining and Machinability of Materials,7*(1–2), 1–16.
8. Leppert, T. (2011). Effect of cooling and lubrication conditions on surface topography and turning process of C45 steel. *International Journal of Machine Tools and Manufacture,51*(2), 120–126.
9. Sartori, S., Ghiotti, A., & Bruschi, S. (2018). Solid Lubricant-assisted minimum quantity lubrication and cooling strategies to improve Ti6Al4V machinability in finishing turning. *Tribology International,118*, 287–294.
10. Masoudi, S., Vafadar, A., Hadad, M., & Jafarian, F. (2018). Experimental investigation into the effects of nozzle position, workpiece hardness, and tool type in MQL turning of AISI 1045 steel. *Materials and Manufacturing Processes,33*(9), 1011–1019.
11. Cho, N., & Tu, J. (2001). Roundness modeling of machined parts for tolerance analysis. *Precision Engineering,25*(1), 35–47.
12. Mustafa, A. Y., & Ali, T. (2011). Determination and optimization of the effect of cutting parameters and workpiece length on the geometric tolerances and surface roughness in turning operation. *International Journal of Physical Sciences,6*(5), 1074–1084.
13. Dhar, N. R., Islam, M. W., Islam, S., & Mithu, M. A. H. (2006). The influence of minimum quantity of lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel. *Journal of Materials Processing Technology,171*(1), 93–99.
14. Balasundaram, M. K., & Ratnam, M. M. (2014). In-process measurement of surface roughness using machine vision with sub-pixel edge detection in finish turning. *International Journal of Precision Engineering and Manufacturing,15*(11), 2239–2249.
15. Huang, S., Lv, T., Wang, M., & Xu, X. (2018). Effects of machining and oil mist parameters on electrostatic minimum quantity lubrication–EMQL turning process. *International Journal of Precision Engineering and Manufacturing-Green Technology,5*(2), 317–326.
16. Dureja, J. S., Singh, R., Singh, T., Singh, P., Dogra, M., & Bhatti, M. S. (2015). Performance evaluation of coated carbide tool in machining of stainless steel (AISI 202) under minimum quantity lubrication (MQL). *International Journal of Precision Engineering and Manufacturing-Green Technology,2*(2), 123–129.

17. Saadatbakhsh, M. H., Imani, H., Sadeghi, M. H., & Farshi, S. S. (2017). Experimental study of surface roughness and geometrical and dimensional tolerances in helical milling of AISI 4340 alloy steel. *The International Journal of Advanced Manufacturing Technology,93*(9–12), 4063–4074.
18. Masoudi, S., Gholami, M. A., Iariche, J. M., & Vafadar, A. (2017). Infrared temperature measurement and increasing infrared measurement accuracy in the context of machining process. *Advances in Production Engineering and Management,12*(4), 353–362.
19. Masoudi, S., Amirian, G., Saeedi, E., & Ahmadi, M. (2015). The effect of quench-induced residual stresses on the distortion of machined thin-walled parts. *Journal of Materials Engineering and Performance,24*(10), 3933–3941.
20. Faga, M. G., Priarone, P. C., Robiglio, M., Settineri, L., & Tebaldo, V. (2017). Technological and sustainability implications of dry, near-dry, and wet turning of Ti-6Al-4V alloy. *International Journal of Precision Engineering and Manufacturing-Green Technology,4*(2), 129–139.
21. Maruda, R. W., Krolczyk, G. M., Michalski, M., Nieslony, P., & Wojciechowski, S. (2017). Structural and microhardness changes after turning of the AISI 1045 steel for minimum quantity cooling lubrication. *Journal of Materials Engineering and Performance,26*(1), 431–438.
22. Yoon, H. S., Kim, M. S., Jang, K. H., & Ahn, S. H. (2016). Future perspectives of sustainable manufacturing and applications based on research databases. *International Journal of Precision Engineering and Manufacturing,17*(9), 1249–1263.
23. Mia, M., Gupta, M. K., Singh, G., Królczyk, G., & Pimenov, D. Y. (2018). An approach to cleaner production for machining hardened steel using different cooling-lubrication conditions. *Journal of Cleaner Production,187*, 1069–1081.

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