A Comparative Analysis of Chip Shape, Residual Stresses, and Surface Roughness in Minimum-Quantity-Lubrication Turning with Various Flow Rates

Morteza Sadeghifar
Mahshad Javidikia (mahshad.javidikia.1@ens.etsmtl.ca)
Ecole de technologie superieure
Victor Songmene
Mohammad Jahazi

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Abstract

In this research, an experimental investigation was carried out to investigate the interaction between various turning parameters and different Minimum Quantity Lubrication (MQL) flow rates and compare their effects on chip shape and surface integrity characteristics in low speed turning and high speed turning of AA6061-T6. The turning parameters included cutting speed, feed rate, and depth of cut. The flow rates comprised 3.5, 10, and 15 *ml/min*, and the surface integrity characteristics consisted of average arithmetic surface roughness, height peak from the valley, axial and hoop surface residual stresses. The results showed that cutting conditions including cutting speed, feed rate, and depth of cut affected chip shape, while MQL flow rate had no impact on chip shape. The lowest values of cutting speed, feed rate, and depth of cut, equal to 145 *m/min*, 0.07 *mm/rev*, and 0.66 *mm*, respectively, resulted in the smallest residual stresses for all the flow rates. Moreover, the smallest surface roughness parameters were obtained at the lowest feed rate (0.07 *mm/rev)* for all the flow rates, whereas there were high interaction effects between cutting speed and flow rate and depth of cut and flow rate. Finally, turning with the minimum quantity lubrications of 3.5 and 10 *ml/min*, respectively, are suggested to obtain the best overall surface integrity characteristics. These lower values of flow rate are suitable to reduce machining costs, protect the environment, and preserve machinist's health. Since most of the previous research studies focused on the comparison of the turning environments including dry, MQL, wet, and cryogenic and only a few research works on the comparative analysis of MQL turning with different flow rates were carried out, the results of the present research can be utilized as a reference for future works in this field.

1. Introduction

AA6061-T6 is one of the most widespread of the 6000 series aluminum alloys. It has high strength, good workability, light weight and high resistance to corrosion, which makes it a suitable alloy for aerospace components [1]. Turning operations are frequently used in the aerospace and automotive industries to produce the final shape of aluminum parts [2]. Dry turning is commonly conducted due to respecting the environment, preserving the machinist's health and reducing the turning costs. However, it can produce high machining temperature. In wet turning, cutting fluids are used not only to reduce the generated temperature in the workpiece and tool, but also to decrease the friction at the tool-workpiece-chip interfaces [3, 4]. However, high flow rates of cutting fluids are hazardous to the machinist health and the environment and also increase the machining costs. To avoid all of these problems, another lubrication mode such as minimum quantity lubricant is commonly utilized. This method provides clean machining and eliminates the problems owing to traditional dry and wet turning processes. The most important privilege of MQL system is that a lubricant with small flow rates is directly applied to the contact area, avoiding the thermal shock of the cutting tool, and consequently, improves the surface quality. In addition, machining processes are accompanied by the formation of chips. The chip forms in machining process are classified based on their geometrical appearance including shape. It is known that long or tangled chips can deleteriously affect the tool life and the surface quality of the machined parts. Therefore, the study of chip shape is essential.

As reported by the review articles [5–9], the majority of the previous research works focused on the investigation of the effect of turning environments including dry, MQL, wet, and cryogenic on chip shape and surface integrity, while in contrast only a few analyses were performed to study various MQL flow rates in turning processes.

Kouam et al. [10] compared the influences of cutting speed, feed rate, and MQL flow rate on chip shape and surface roughness in MQL turning AA7075-T6. They found that a lower flow rate of MQL could provide shorter chips and better surface roughness in comparison with a higher flow rate. Çakır et al. [11] analyzed the impact of cutting speed, feed rate, and MQL flow rate on surface roughness induced by turning AA2024 and AA7075. The results showed that surface roughness parameters diminished with MQL flow rate. Niknam and Jalali [12] investigated the effect of cutting speed, feed rate, and MQL flow rate on average surface roughness in MQL turning of AA 6061-T6 and AA 7075-T6. They found that feed rate had a significant influence on surface roughness. Furthermore, a larger flow rate enhanced surface quality. Davim et al. [13] conducted MQL turning of brass to study the impact of cutting speed, feed rate, and MQL flow rate on chip shape and surface roughness. The results showed that chip shape was not affected by MQL flow rate, while surface roughness increased with feed rate and decreased with flow rate.

Sivaiah [14] examined the influence of cutting speed, feed rate, depth of cut, and MQL flow rate on surface roughness in machining of 15 – 5 PH stainless steel. They reported that surface roughness rose with feed rate and depth of cut, while it considerably decreased with MQL flow rate. Gürbüz et al. [15] investigated the impacts of cutting speed, feed rate, and MQL flow rate on surface roughness in machining of AISI 4140 steel. They concluded that an increase in flow rate had no significant influence on surface roughness. In addition, they found that surface roughness increased and generally decreased with an increment in feed rate and in cutting speed, respectively. Ji et al. [4] examined the effect of MQL with various flow rates on residual stresses induced by orthogonal turning of AISI 4130 steel. The results demonstrated that MQL flow rate slightly affected residual stresses at the machined surface.

According to the above literature review, most of the previous research studies compared the influence of turning environments including dry, MQL, wet, and cryogenic on chip shape and surface integrity. In addition, a few studies were carried out to analyze the impact of MQL flow rate on chip shape and surface integrity characteristics especially residual stresses in turning of AA6061-T6, specifically for a broad range of turning parameters from low speed turning (LST) to high speed turning (HST). Accordingly, the present research study aimed at investigating the influence of turning parameters and different flow rates of MQL on chip shape and surface integrity including arithmetic average surface roughness, maximum height of the profile, axial surface residual stress (ASRS), and hoop surface residual stress (HSRS) in LST and HST of AA6061-T6.

2. Experimental Methods

MQL Turning tests were carried out using a MAZAK CNC machine as illustrated in Figs. 1(a) and (b). Turning tests for seven cutting conditions given in Table 1 were conducted and three values of flow rate listed in Table 2 were used. The workpiece was a 75-mm diameter and 120-mm length cylinder made of AA6061-T6. The cutting insert was designated as ISO CNMG 120408-THM. A KENNAMETAL DCLNR 2020 K12 tool holder was used to hold the cutting inserts. Fresh inserts were utilized for each machining test to result in the same conditions for the experiments. A Tecnolub system model SLS1.2-2 was employed for MQL turning tests, as displayed in Fig. 1(c). The cutting fluid was an eco-friendly biodegradable vegetable oil called Microkut 400, whose viscosity is 37 (mm^2/s) [12]. This lubricant improves health and safety at the workstation and is also harmless to the environment.

The perthometer Mitutoyo SJ-410 was utilized to measure surface roughness characteristics as illustrated in Fig. 2. A Gaussian filter was employed to select the sampling length and the evaluation length as 0.8 and 4 mm, respectively. As portrayed in Figs. 3(a) and (b), a Pulstec μ-X360n XRD machine was used to measure hoop and axial residual stresses. The characteristics of the Pulstec machine and the constants and parameters used for residual stress measurements are explained in [16] and [17], respectively. Surface roughness and residual stress characteristics were captured at two points at the distance of 3 cm from one edge of the component and were then averaged.

3. Results And Discussion

The experiments were carried out in order to investigate the effects of different turning parameters and flow rates on chip shape and surface integrity. The arithmetic average surface roughness (R_a), the maximum height of the profile $\left(R_t\right)$, the axial surface residual stress (σ_a), and the hoop surface residual stress (σ_h) were measured to examine the interactions among the turning parameters including cutting speed, feed rate, and depth of cut and MQL with three flow rates. Each measurement was carried out twice and the values were averaged in order to obtain more accurate results.

3.1. Interaction between MQL flow rate and cutting speed

Test Nos. 1, 3, and 7, with a fixed feed rate of 0.19 mm/rev and a fixed depth of cut 1.5 mm, were carried out to study the influence of various flow rates of MQL and cutting speed on chip shape and surface integrity. Table 3 contains a comparison of chip shapes for various flow rates and cutting speed. According to ISO 3685 – 1977, the chips produced in metal machining processes are classified based on their sizes and shapes [18]. As seen in this table, short washer-type helical chips were produced at the cutting speeds of 145 and 650 m/min (LST) for all the MQL flow rates, whereas snarled ribbon chips were generated at the cutting speed of 1155 m/min (HST). Hence, it is observed that chip shape changed from LST to HST, while it remained unchanged for all the flow rates. The latter is in agreement with the results found by Davim et al. [13], where chip shape produced by turning of brasses did not change with MQL flow rate.

Figure 4(a) shows that the cutting speed of 145 m/min provided the lowest σ_a for all the flow rates. Furthermore, the largest value of σ_a, equal to 120 MPa, was found at the cutting speed of 1155 m/min in MQL1 mode, whereas the lowest value of σ_a, equal to 64 MPa, was obtained at 145 m/min for MQL2 mode. Therefore, turning with MQL2 at the cutting speed of 145 m/min is recommended to obtain small values of σ_a.

Figure 4(b) displays that the cutting speed of 145 m/min provided the lowest σ_h for all the flow rates, similar to σ_a. Moreover, the highest value of σ_h, equal to 161 MPa, was achieved at the cutting speed of 1155 m/min in MQL1 mode, whereas by contrast the smallest value of σ_h around 38 MPa was obtained at 145 m/min for MQL1 and MQL3 modes. As a result, MQL1 and MQL3 turning at 145 m/min are suggested to capture small values of σ_h.

It is worth mentioning that the dissimilar behavior of σ_a for the three flow rates can be attributed to interactions among machining parameters [19, 20]. This is known as interaction effects, when the influence of one variable (machining parameter) on the response (σ_a) depends on the level of another variable(s) [20, 21]. The interaction effect can be seen in Fig. 4(a), in which the dashed lines are not parallel.

In a turning process, a rise in cutting speed increases both the plastic work and the frictional work [22, 23], resulting in higher amounts of the generated heat, and therefore, an increase in temperature and residual stresses [19, 24]. In contrast, an increment in cutting speed increases material removal rate (MRR), which augments the heat evacuation, and as a result, can decrease temperature [25] and residual stresses [19, 22–24]. The competition between these two mechanisms reveals the level of residual stresses. For the first range of cutting speed, the first mechanism took place for all the examined flow rates, where higher residual stresses were measured with increasing cutting speed. In the second range of cutting speed, the two phenomena had almost the same contributions to the generation of residual stresses for MQL2 and MQL3, while the first phenomenon dominated in MQL1.

Figure 5(a) illustrates that the cutting speed of 650 m/min provided the lowest R_a for MQL3 lubrication mode. Moreover, the values of R_a were almost the same for all the flow rates at the highest cutting speed. Therefore, flow rate had almost no effect on R_a at HST. In addition, the largest value of R_a , equal to 1.653 μm, was observed at the cutting speed of 145 m/min in MQL2. Consequently, MQL turning with the flow rate of 15 ml/min and the cutting speed of 650 m/min is recommended to reach small values of R_a.

Figure 5(b) portrays that the values of R_t were almost the same for all the flow rates at the highest cutting speed. As a result, similar to R_a, flow rate did not affect R_t at HST. It can therefore be concluded that in HST, flow rate had no impact on surface roughness parameters. In addition, the highest value of R_t, equal to 6.869 μm, was obtained at the cutting speed of 145 m/min in MQL2 mode, while the smallest value of R_t, equal to 5.008 $\mu m,$ was obtained at 650 m/min for MQL3. Therefore, similar to R_a, MQL turning with the flow rate of 15 ml/min and the cutting speed of 650 m/min is recommended to reduce R_t. As mentioned earlier, the interaction effects between cutting speed and flow rate are clearly observed.

3.2. Interaction between MQL flow rate and feed rate

The influence of lubrication flow rates and feed rate on surface integrity was analyzed for Test Nos. 1, 2, and 4, whose cutting speed and depth of cut were kept fixed at 650 m/min and 1.5 mm, respectively. The changes in chip shape with flow rate and feed rate are presented in Table 4. As observed in this table, for all the three flow rates, snarled ribbon chips were produced at the feed rate of 0.07 mm/rev, short washer-type helical chips formed at the feed rate of 0.19 mm/rev, and connected arc chips were generated at the feed rate of 0.31 mm/rev. It is therefore concluded that chip shape changed with feed rate, but remained the same with the variation of flow rate. These results are in agreement with the results reported in [13] for turning of brass.

Figure 6(a) shows that the highest value of σ_a, around 166 $MPa,$ occurred at the feed rate of 0.31 mm/rev in MQL3 mode, while the smallest value of σ_a, equal to -20 MPa, took place at the feed rate of 0.07 mm/rev in MQL1 mode. Therefore, MQL turning with the flow rate of 3.5 ml/min at the feed rate of 0.07 mm/rev is proposed to obtain small values of σ_a.

Figure 6(b) displays that the largest σ_h, equal to 153 MPa, occurred at the feed rate of 0.19 mm/rev in MQL3 mode, whereas the smallest σ_h around 35 MPa was obtained at the lowest feed rate, equal to 0.07 mm/rev, for MQL1 mode. Thus, MQL turning with the flow rate of 3.5 ml/min at the feed rate of 0.07 mm/rev is suggested to obtain small values of σ_h.

The above findings could be analyzed in terms of heat generated at tool-chip contact surface interactions under different machining parameters. In fact, in a turning process, a rise in feed rate raises the tool-chip-workpiece contact surface and the frictional heat, which augments temperature [26] and residual stresses [22, 27]. In contrast, an increment in feed rate increases MRR, which depletes the heat with the sliding chip from the cutting zone, and thus, can diminish temperature and residual stresses [1, 19]. As a result, in a metal cutting operation, the level of residual stresses is dependent considerably on the contest between the two mechanisms [23]. For the interval of feed rate under study, the first mechanism dominated, in which ASRS rose with feed rate. Likewise, Capello [28] and Leppert and Peng [29] found that axial residual stresses rose with feed rate in turning of steels. For HSRS, the two mechanisms had different contributions to the generation of residual stresses in the two intervals of feed rate, leading to different variations of HSRS with flow rate.

Figures 7(a) and (b) portray that R_a and R_t were highly dependent on feed rate and rose with it for all the flow rates. Furthermore, the roughness values were slightly affected by the MQL flow rates. Consequently, the lowest values of R_a and R_t were achieved at the smallest value of feed rate for all the flow rates. This can be attributed to the fact that smaller feed rates generate less distinct feed marks at the machined surface and lower machining forces, resulting in smaller values of surface roughness parameters [1, 30].

3.3. Interaction between MQL flow rate and depth of cut

The impact of MQL flow rate and depth of cut on surface integrity was analyzed for Test Nos. 1, 5, and 6, whose cutting speed and feed rate were selected as 650 m/min and 0.19 mm/rev, respectively. Table 5 displays the plots of the variation of chip shape with flow rate and depth of cut. As seen in this table, long washer-type helical chips were produced at the depth of cut of 0.66 mm for all the MQL flow rates, short washer-type helical chips formed at the depth of cut of 1.5 mm for all the flow rates, and snarled tubular chips were produced at the depth of cut of 2.34 mm for all the flow rates. As a result, it is observed that chip shape changed with depth of cut, but remained unaffected with flow rate. Similar results were reported by [13] for turning of brass.

Figure 8(a) illustrates that the largest σ_a equal to 120 MPa was achieved at the depth of cuts of 1.5 in MQL3 mode, while the lowest σ_a, equal to 54 MPa, was obtained at the depth of cut of 0.66 mm for MQL1 mode. As a result, MQL turning at the flow rate of 3.5 ml/min and the depth of cut of 0.66mm is proposed to capture low values of σ_a.

Figure 8(b) displays that the largest σ_h, equal to 160 MPa, was obtained at the highest depth of cut equal to 2.34 mm in MQL2 mode, while the smallest σ_h equal to 77 MPa was achieved at the depth of cut of 0.66 for MQL2 mode. Therefore, MQL turning at the flow rate of 10 ml/min and the depth of cut of 0.66 mm is suggested to achieve low values of σ_h.

In a turning process, an increment in depth of cut augments the tool-chip contact area and the frictional heat in the cutting zone, which raises temperature and residual stresses [23]. Arunachalam et al. [31] reported that an increase in the depth of cut increased the tensile character of residual stresses. In contrast, increasing depth of cut raises the heat evacuation due to augmenting MRR, and as a result, can decrease temperature [32–34] and residual stresses [1, 28]. As earlier stated, the value of residual stresses changes significantly based on this contest between these two mechanisms.

Figure 9(a) illustrates the largest value of R_a, equal to 1.528 μm, was observed at the depth of cut of 2.34 mm in MQL1 mode, whereas the lowest value of R_a, equal to 1.188 μm, was obtained at the depth of cut of 0.66 mm for MQL2 mode. Consequently, MQL turning at the depth of cut 0.66 mm with the flow rate of 10 ml/min is proposed to obtain small values of R_a.

Figure 9(b) shows that the highest value of R_t, equal to 6.578 μm, was obtained at the depth of cut of 2.34 mm in MQL1 mode, while the smallest value of R_t, equal to 5.008 μm, was seen at the depth of cut of 1.5 mm for MQL3 mode. Thus, MQL turning at depth of cut 1.5 mm with the flow rate of 15 ml/min is recommended to reach small values of R_t. Similar to the previous results of roughness parameters, the interaction effects between depth of cut and flow rate are obviously seen.

4. Conclusions

In the present research study, a comparative experimental analysis was carried out to study the influences of various turning parameters including cutting speed, feed rate, and depth of cut and various MQL flow rates consisting of 3.5, 10, and 15 ml/min on chip shape, axial surface residual stress, hoop surface residual stress, average arithmetic surface roughness, and height peak from the valley in turning of AA6061-T6. The following conclusion are drawn:

- Chip shape changed with cutting conditions such as cutting speed, feed rate, and depth of cut, but remained almost unaffected with MQL flow rate. In other words, flow rate did not affect chip shape.
- The lowest value of cutting speed equal to 145 m/min provided the smallest residual stresses for all the flow rates.
- The smallest magnitude of feed rate equal to 0.07 mm/rev resulted in the lowest residual stresses for all the three flow rates.
- The lowest depth of cut 0.66 mm led generally to the smallest residual stresses for all the flow rates.
- There were high interaction effects between cutting speed and flow rate.
- The smallest surface roughness parameters were obtained at the lowest feed rate (0.07 mm/rev) for all the flow rates.
- High interaction effects existed between depth of cut and flow rate such that no clear trend can be observed for the variation of surface roughness parameters with depth of cut.
- Turning with MQL1 and MQL2 equal to 3.5 and 10 ml/min, respectively, are proposed in order to obtain the best overall surface integrity characteristics. These lower values of MQL flow rate are suitable for machining costs, ecology and environment, and machine operators' health.

In summary, the proper value of the flow rate of MQL turning should be selected depending on the used turning parameters and the required goal of surface integrity. Considering that the major part of the previous research concentrated on the comparative study of the effect of turning environments including dry, MQL, wet, and cryogenic on chip shape and surface integrity and only a few research works were conducted to analyze the influence of the value of MQL flow rate, the results of the present work can be beneficial for researchers and industrialists who are active and/or interested in this filed.

Declarations

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

Not applicable.

Availability of Data and Material

Not applicable.

Code Availability

Not applicable.

Ethics Approval

Not applicable.

Consent to Participate

Not applicable.

Consent for Publication

All authors agree to publish the manuscript.

Declaration of Interests

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

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Tables

Table 1 Turning tests and parameters

Test No.	Cutting speed $V(m/\min)$	Feed rate $f(mm/rev)$	Depth of cut $D(mm)$
1	650	0.19	1.5
2	650	0.07	1.5
3	145	0.19	1.5
4	650	0.31	1.5
5	650	0.19	2.34
6	650	0.19	0.66
7	1155	0.19	1.5

Table 2 MQL flow rate

Flow rate (ml/min)	Designation
3.5	MQL1
10	MQL2
15	MQL3

Tables 3 to 5 are available in the Supplementary Files section

Figures

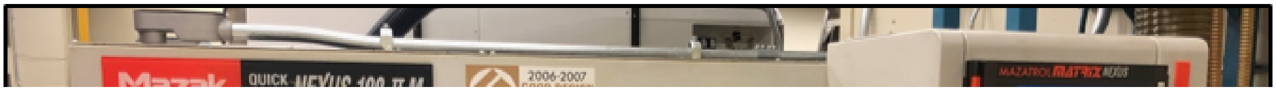
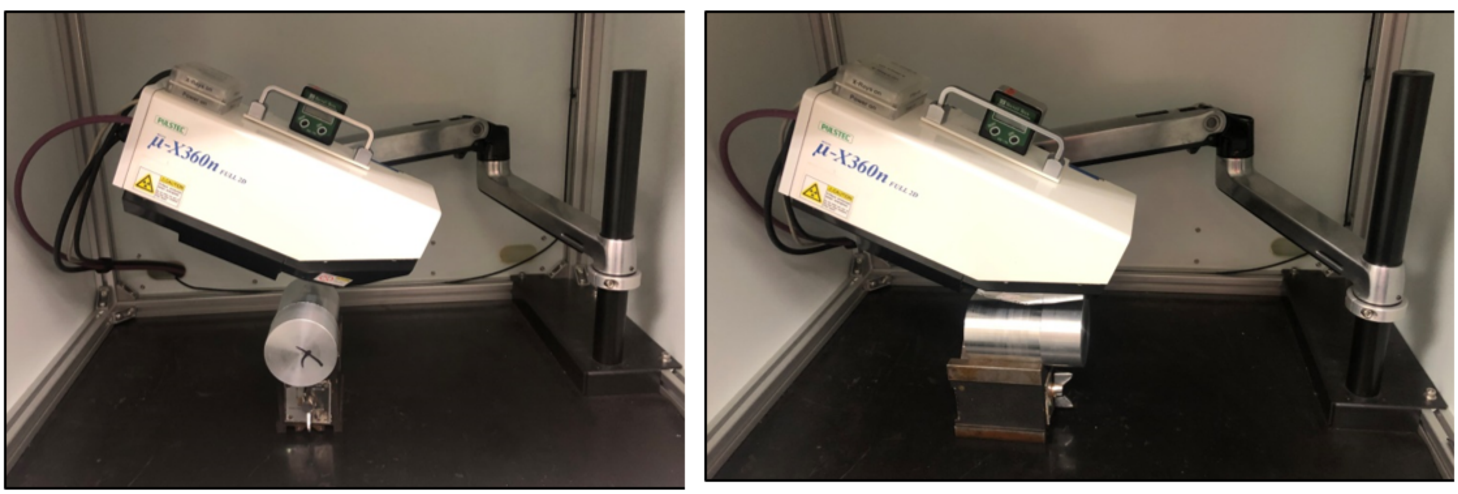


Figure 1

The experimental set-up of the turning process: (a) CNC machine, (b) MQL mode and (c) Tecnolub MQL device.

Figure 2

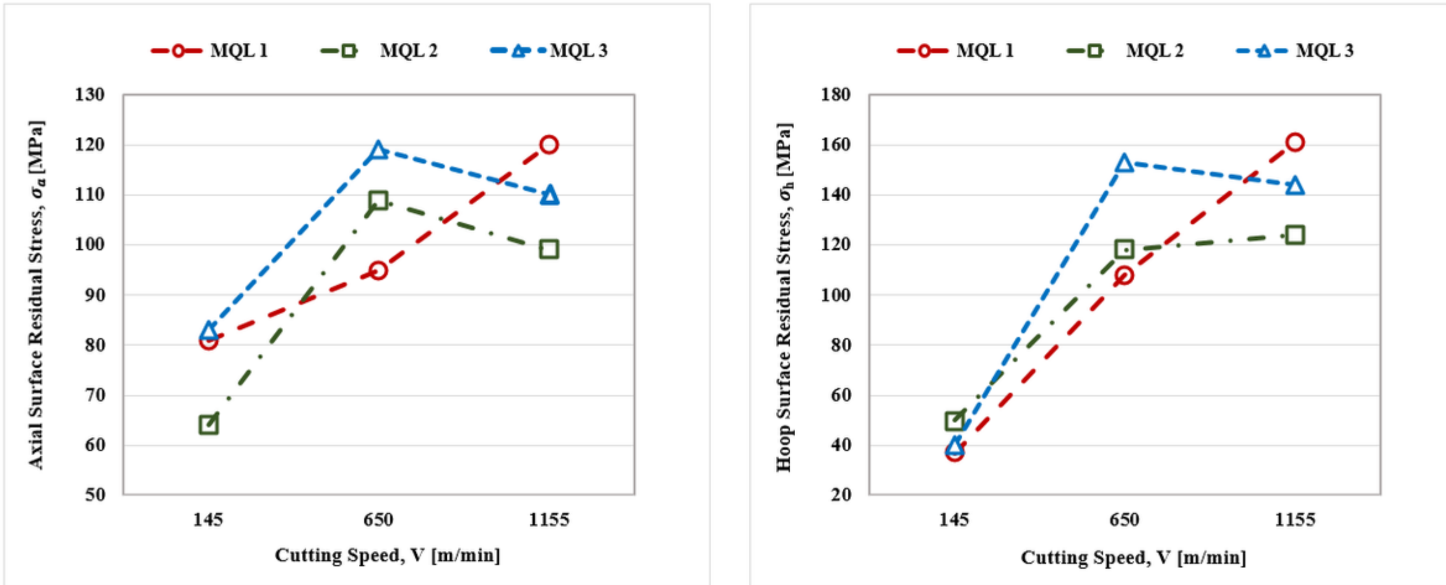
Surface roughness measurements using Mitutoyo SJ-410 profilometer.



(a) (b)

Figure 3

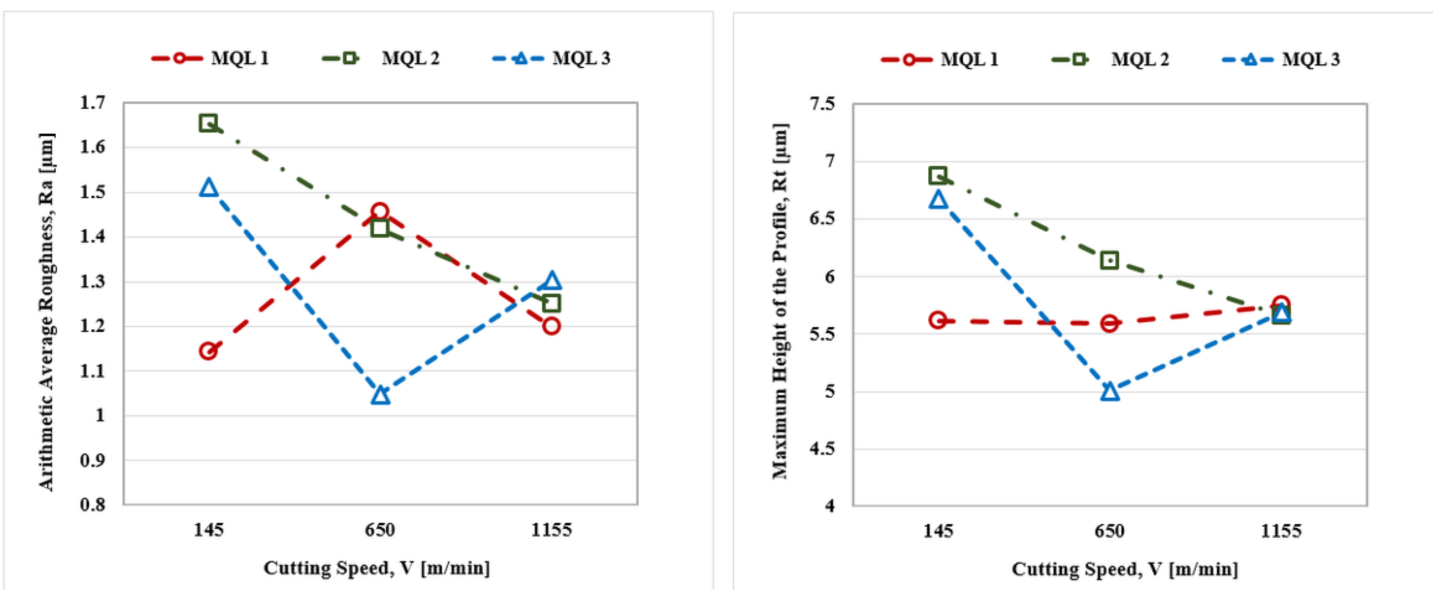
Residual stress measurements using Pulstec μ-X360n XRD machine: (a) Hoop and (b) Axial directions.



(a) (b)

Figure 4

Influence of MQL flow rate and cutting speed on (a) axial and (b) hoop surface residual stresses.



(a) (b)

Figure 5

Effect of MQL flow rate and cutting speed on (a) arithmetic average surface roughness and (b) maximum height of the profile.

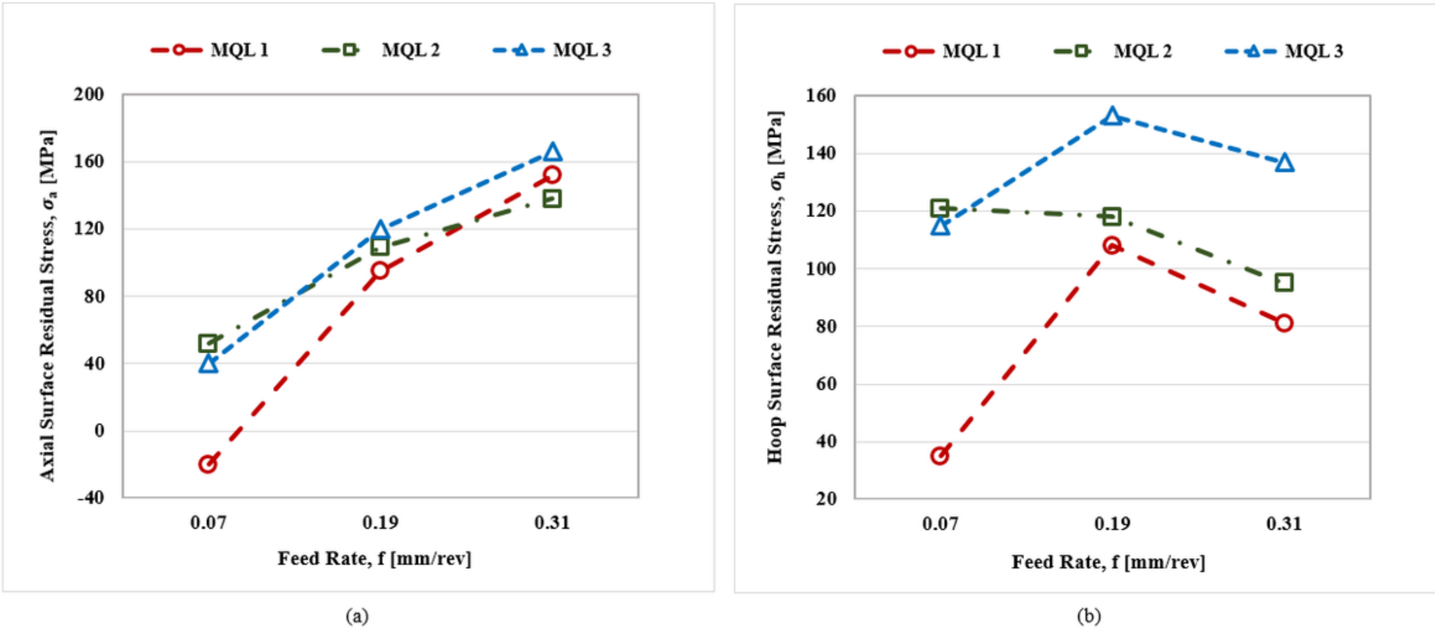


Figure 6

Impact of MQL flow rate and feed rate on (a) axial and (b) hoop surface residual stresses.

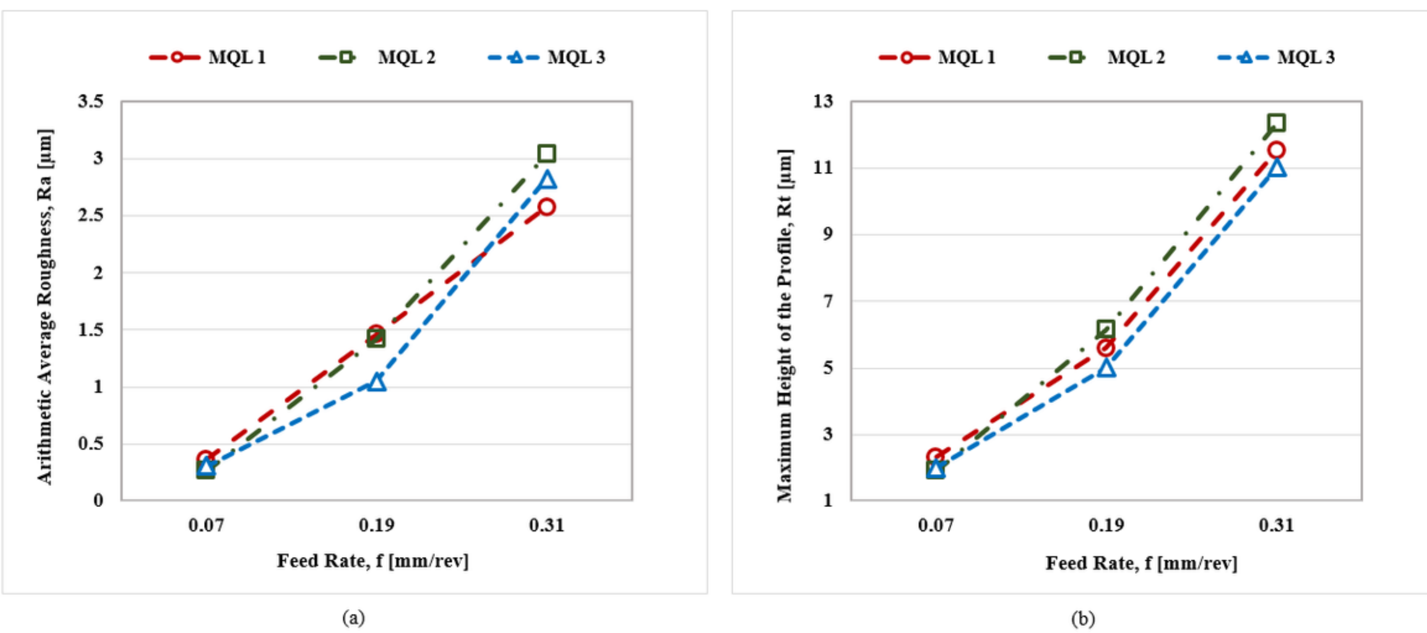


Figure 7

Effect of MQL flow rate and feed rate on (a) arithmetic average surface roughness and (b) maximum height of the profile.

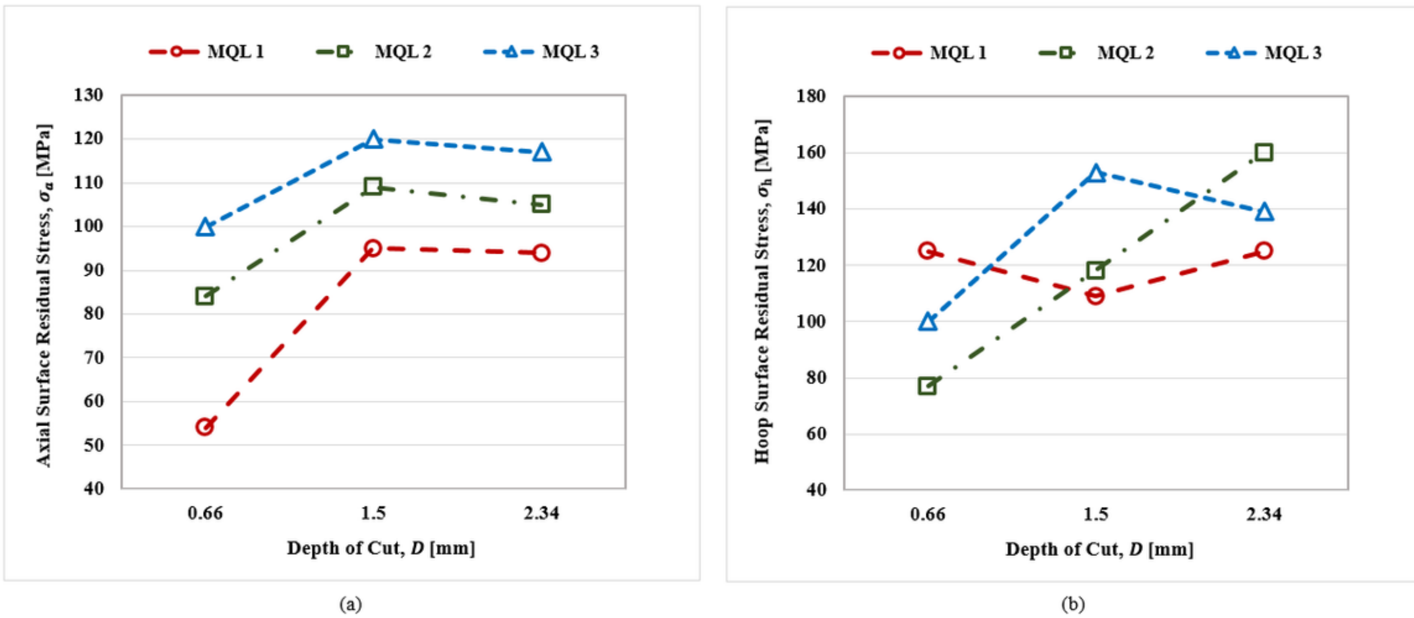


Figure 8

Influence of MQL flow rate and depth of cut on (a) axial and (b) hoop surface residual stresses.

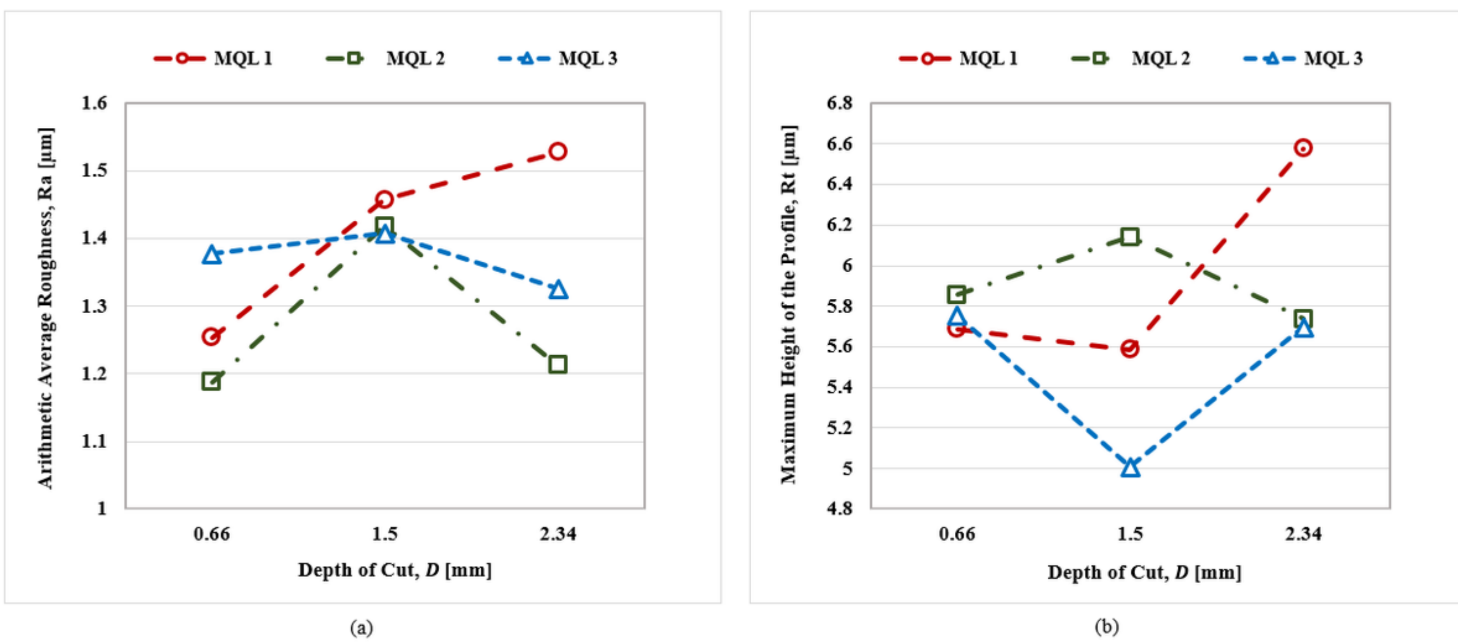


Figure 9

Impact of MQL flow rate and depth of cut on (a) arithmetic average surface roughness and (b) maximum height of the profile.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table3to5.docx