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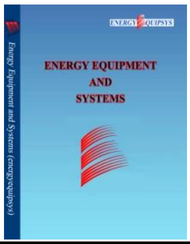

Experimental investigation of the effect of single point dressing parameters on grinding of Mo40 hardened steel using mounted point grinding tool

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ABSTRACT

Nowadays, steel hardening has received much attention from researchers due to its frequent use in industries, especially is widely used in energy equipment, aerospace, and petrochemical industries. Low capability in chip removal of hardened steel has always been a significant machining issue. Mounted point grinding is a machining method to improve surface finish and remove burrs on the workpiece walls and hard-to-reach areas. This process is usually used without preparing the grinding wheel before and during the grinding operation, which reduces the proper performance of the process. Environmental contamination, surface integrity, coolant-lubricant-related diseases that affect workers' health, and machining costs heavily depend on the appropriate dressing and proper coolant-lubricant usage. In this study, the effect of dressing conditions (depth of dressing and dressing feed) and the workpiece feed rate during the mounted point grinding of a Mo40 hardened steel in two traditional wet and Minimum Quantity Lubrication (MQL) environments has been investigated. Surface roughness and wheel loading are two significant outputs in every grinding operation. The experimental result of this study reveals an improvement in enhancing the surface roughness in a soft dressing condition. Moreover, this study aimed to achieve proper surface roughness by implementing MQL technique to significantly reduce total cutting fluid usage compared to traditional wet machining. This study observed a higher wheel loading in MQL technique than in the conventional wet grinding.

Keywords: Dressing; Wheel Loading; Surface Quality; Grinding; Environmentally Friendly Machining.

1. Introduction

Due to its unique nature and technical conditions, the grinding process is one of the primary and applied processes in the final operation on the workpiece and surface polishing. This process is used to polish the surfaces of many parts made with different processes such as milling, welding, metal forming, and other new methods of parts production [1]–[3]. Therefore, control of grinding conditions significantly affects the

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comprehensive properties of surfaces, such as surface roughness, burns, and metallurgical changes of workpiece surfaces [4]. One of the most critical problems that affect the mentioned characteristics is the coolant-lubricant environment that affects the grinding process. Due to the low volume of material removal in grinding compared to other machining methods such as turning and milling, a significant amount of heat generated in the grinding area are transferred inside the workpiece. Traditional cutting fluids are a combination of water and petroleum-based fluids kept at high temperatures. The incidence of skin and respiratory diseases when using these fluids and the increase in total costs lead to research in the field of Minimum Quantity Lubrication (MQL). The mixture of air and oil at the nozzle tip and its application to the grinding area reduces friction and improves surface roughness [5]–[8]. The MQL technique can reduce frictional heat generation and, to some extent, keep the part temperature lower than dry machining by cooling the tool-workpiece interface [9], [10]. Another feature of this technology is the dryness of the chips and workpiece after machining, making them easier to transport. MQL is most used in mass production processes in the machining of aluminum parts, which has led to reduced costs, optimized parts quality, and reduced environmental effects of manufactured parts. Since grinding is an abrasive process, it generates much energy at the tool-joint interface. The application of MQL in grinding has more problems than using other coolant-lubricant techniques, and therefore little research has been done in this field. Chelgani et al. [11] conducted a study to compare dry grinding and wet grinding. According to this study, it was found that the amount of energy required to grind a piece with the same machining parameters in the dry condition is between 15% to 50% more than the wet condition. The use of cutting fluid improves the surface quality and reduces the surface roughness compared to dry grinding. The results of reference [12] show that although the fluid consumption in the MQL method is lower than conventional wet cutting, the material removal rate is the same in both methods. The MQL method does not hurt the grinding speed. However, the workpiece surface temperature while using a traditional wet grinding is lower than MQL grinding. As a result, the grinding forces are lower. Silva et al. [13] also conducted their research based on the effect of MQL technique on the grinding process. They machined 4340 tempered steel with CBN and aluminum oxide grinding wheels and concluded that the MQL method was suitable for this operation and even reduced the grinding wheel's surface roughness and radial wear, and the grinding wheel remained sharp for a longer time. There was also no significant adverse effect on the use of this technique. In using two different grinding wheels in the presence of MQL, it was observed that Al_2O_3 grinding wheel leads to better topography on the workpiece surface. In contrast, CBN grinding wheel leaves more residual stress on the workpiece surface. Hadad et al. [14] investigated 100Cr6 hardened steel under different grinding conditions to investigate the effect of MQL on the roughness of the workpiece surface. This study found that the use of MQL reduces the number of forces applied to the workpiece compared to the dry grinding mode and prevents surface defects in the workpiece. It was also found that MQL could be an alternative to traditional cutting fluids by optimizing several grinding parameters.

In conventional grinding wheels with abrasive grains of alumina and silicon carbide, as in Fig. 1, in order to create the desired profile on the wheel surface, a dresser tool in the radial direction penetrates the grinding wheel, and then the desired profile is created on the grinding wheel by transverse movement. In each dressing pass, a layer to the depth of a_d is removed from the surface of the grinding wheel. The progress of the dresser in the transverse direction for each turn of the grinding wheel is called the pitch of dressing and is obtained from Eq.1 [4]:

$$f_d = \frac{d_s \times v_d \times \pi}{v_s} \qquad (1)$$

f_d represents the amount of dresser pitch movement per turn of the grinding wheel, v_d indicates the dressing feed rate, and v_s indicates the grinding wheel speed. Also, the angle of the dresser is generally in the range of 10 to 15 degrees. Equation 2 shows the effect of dressing depth and feed rate on the workpiece surface roughness [4].

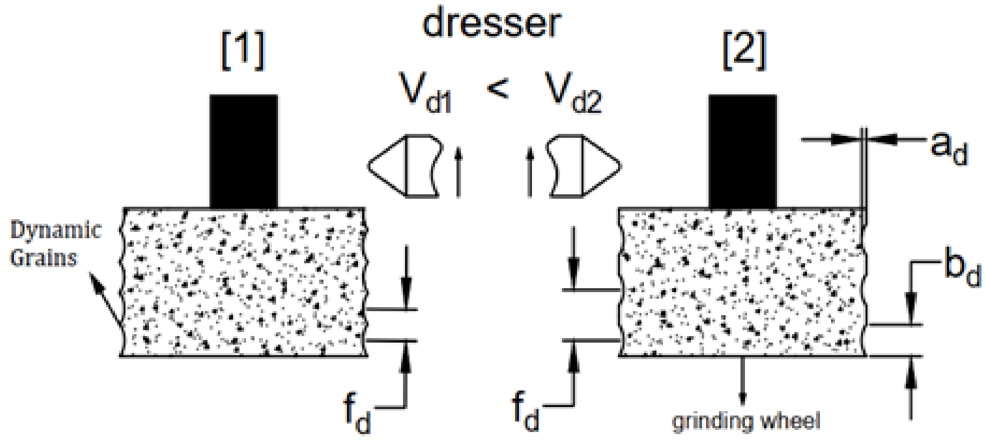

Fig. 1. Schematic diagram of the dressing process

$$R_a = R_1 S_d^{0.5} \quad a_d^{0.25} \left(Q'_w / v_c \right) \tag{2}$$

a_d is the depth of dressing, Q_w is the material removal rate v_c is the cutting speed. The effect of dressing feed rate on the overlap coefficient, which is one of the factors affecting the surface roughness of the workpiece after grinding, can be seen in Eq.3 [4].

$$U_d = \frac{b_d}{f_d} \tag{3}$$

Increasing the overlap coefficient leads to a soft topography on the grinding wheel surface and thus reduces the surface roughness of the workpiece. The mechanical dressing may be done manually or automatically. In the present study, the dressing feed rate and the overlap coefficient of the grinding wheel surface have been controlled using a control system. Huang et al. [15] found the effect of the amount of dressing depth and the feed rate on the normal force and sharpness of the dressing. Studies show that after dressing with an increasing overlap coefficient, a better surface finish with many cutting edges has been observed [16].

In other words, depending on the characteristics of the grinding wheel, there is an optimal rate for the overlap coefficient, an increase of which will not improve the surface characteristics and will only increase the dressing time. In another study presented by Kadivar et al. [17], the effects of dressing parameters on the micro-grinding of Ti-6Al-4V alloy were investigated. In this research, Ti-6Al-4V block-shaped workpiece has been ground with changes in dressing parameters. This paper indicates that the overlap ratio in dressing and the grinding speed during grinding have a significant effect on surface roughness and grinding forces. Increasing the overlap ratio can reduce the surface roughness and increase the grinding force by 70%.

During the grinding of some materials, the chips may be located in the space between the abrasive grains or welded on top of the abrasive grains. This event is called grinding wheel loading. This phenomenon leads to excessive wear and vibration in the grinding process. This phenomenon also increases the cutting force and temperature and reduces the grinding wheel life. These changes have many effects on the process. There are two general loading types: adhesive loading and filler loading.

In adhesive loading, the chips adhere to the surface of the abrasive grains and bond, and chip loading means that the chips fill the pores or voids in the grinding wheel surface. Some research studies have been done to explain and study the loading mechanism, according to which the leading cause of grinding wheel loading in grinding soft materials can be expressed as adhesion between active grains and chips. In addition to cleaning the grinding wheel surface during the grinding process using cutting fluid, another method of removing chips on the grinding wheel surface is the dressing process. Various methods such as mechanical dressing with fixed diamond tools, rotary dressing, electrochemical dressing, laser dressing, and electro-discharge dressing have been proposed. Single point dressers are a common method for dressing and removing chips on the grinding wheel surface. According to Malkin [4], due to the wear of the diamond of the dressing tool, the overlap ratio will change over time. Adjusting the tool progress properly to create a uniform topography in the grinding wheel is necessary.

According to Wegener [18] in the study of aluminum oxide dressing by diamond tools, an adequate amount of coolant is essential in the mechanical dressing process. The thermal stability of diamond decreases at 720°C. While aluminum oxide retains its properties up to 1160°C. Therefore, dressing at temperatures above 720 degrees leads to diamond wear by aluminum oxide. Also, this study shows that the effective behavior of grinding wheels is mainly determined by the surface topography, which itself is affected by the overlap ratio.

The extensive use of Mo40 steel in industry and inaccessible walls and areas, especially in the molding industry, is a reason to use the mounted point grinding process. Optimization of mounted point grinding technique and study of effective parameters of dressing conditions on the surface roughness of the workpiece are some of the topics considered in the present study, which have not been studied intensely in this field. The workpiece surface roughness and morphology that have been ground and the amount of loading of the grinding wheel surface are essential issues in this process. Accordingly, the dressing of mounted point grinding wheels is very important. The small diameter of this group of grinding wheels leads to more loading of the grinding wheel surface, and not paying attention to this variable leads to an increase in surface roughness and damage.

2. Experimental Setup

In order to investigate the effect of process parameters such as depth of dressing, dressing feed, cooling-lubricant environment, and workpiece feed rate during the grinding process, experiments have been performed on Mo40 steel. The conditions for conducting the present research experiments are presented in Table 1.

All experiments in the present study were performed on a three-axis CNC machine model R-MAN6B. Instead of a milling tool, a mounted point grinding wheel was installed on the machine, and for its dressing, a diamond dresser tool was used, clamped by a chuck in a specific position. Dressing feed and depth are applied by adjusting the CNC machine's linear motion by controlling the tool's movement in front of the dresser. All grinding experiments in Table 1 have been performed in MQL and wet environments (Fig. 2). During the dressing process, grinding fluid with a flow rate of three liters per minute was used for all experiments of the present study.

Table 1. The mounted point grinding conditions

Variables	Values	Units
Workpiece dimensions	30*200	mm
Dressing feed rate (V_d)	10-50-100	mm/min
Cutting fluid flow rate	3	l/min
Oil flow rate in MQL	200	mm/h
Air pressure in MQL	5	Bar
Depth of cut (a_p)	20	µm
Workpiece feed rate	60-200	mm/min
Cutting speed (V_s)	25	m/s
Grinding wheel	Al_2O_3	WA60K9V
Type of dresser	Single Point	---
Positioning angle of dresser	10	Degree
Depth of dressing (a_d)	20-30-40	µm
Number of dressing passes	3	---
Total depth of dressing (a_{dt})	60-90-120	µm

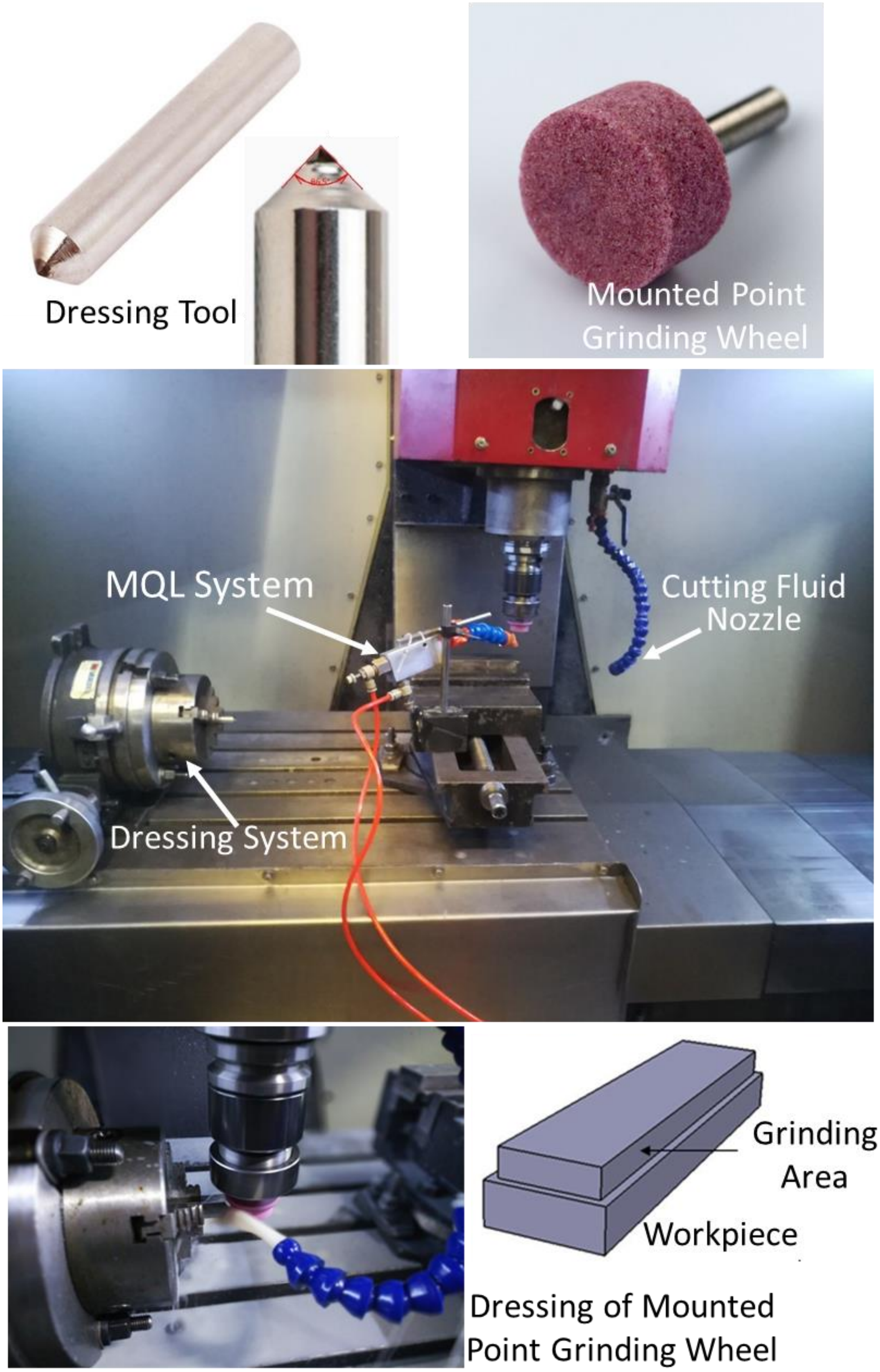

Fig. 2. Experimental setup

In the dressing operation, two parameters, the dressing depth and feed were investigated. Also, workpiece speed was considered a variable parameter to investigate its effect on surface roughness. A grinding operation has been performed during two passes to investigate the effect of dressing parameters on surface roughness. After each experiment, the surface roughness of the workpiece was measured perpendicular to the grinding direction at five different points using Mitutoyo SJ-210 surface roughness tester, and the average of these measurements is expressed as the roughness value. The ground surface morphology, grinding wheel topography before and after the grinding operation, and wheel loading have been studied and presented by Olympus optical microscope model BH2-UMA. Due to the application of this steel in the hardened conditions in the industry, in the present study, the parts were subjected to heat treatment and tempering after initial machining to reach a hardness of 50±2 HRC.

3. Results and Discussion

Figure 3 shows the effects of dressing depth and feed and workpiece feed rate on workpiece surface roughness during conventional wet grinding. With the increasing dressing depth and feed, the grinding wheel and workpiece surface topography have become rough due to the reduction in the overlap and the movement pitch of dressing, while with the rising of the workpiece feed rate, the chip thickness and length increase. In other words, as the workpiece moves rapidly, the penetration depth of each grain at the workpiece surface increases, resulting in thicker chips being removed from the workpiece surface, which increases the workpiece surface roughness (Eq.4) [4].

$$h = H\left[\frac{6}{rc_0}\left(\frac{v_w}{v_s}\right)\left(\frac{a}{d_c}\right)^{0.5}\right]^{\frac{1}{m+2}}$$

$$H = \left(m+1\right)^{0.5}\left[\frac{(m+1)(m+2)(m+3)}{6}\right]^{\frac{1}{m}} \tag{4}$$

The effect of dressing and grinding parameters in different coolant-lubricant environments is presented in Figs. 4 and 5. Under soft dressing conditions, the workpiece surface burns when grinding at a feed rate of 60 and 200 mm/min. By performing soft dressing, an increase in the number of active cutting edges on the grinding wheel surface occurs due to the fine breakage of the grains and their conversion into several fine edges. For this reason, during grinding, the number of active edges and the friction of the grains on the workpiece surface increased, and as a result, the temperature increased. Since the ability to heat remove and cooling of MQL is less than cutting fluid, the heat generated buming of the workpiece surface. However, by increasing the dressing depth or feed, burnings are prevented on the workpiece surface and subsurface.

With increasing depth of dressing, the rate of grain breakage is increased, which leads to a decrease in the number of active grains in the grinding zone and less grain overlap when the grains hit the workpiece surface, which increases surface roughness and prevents workpiece surface burn. Due to the shape of the cutting edge, the angle between the cutting edge contour and the workpiece surface is initially very small, and no chips will form as a result. Only the workpiece material will be compressed around and below the flat wear area of the grain.

When the cutting edge penetrates deep enough into the workpiece and the chip thickness (h_{cu}) reaches the grain cutting depth (T_{μ}), the actual chip formation begins. Because the deformation and chip formation processes are performed sequentially, to increase the chip removal efficiency, it is necessary to know how much of the h_{cu} chip thickness is generated as the chip and the amount of effective chip thickness (h_{cueff}) (Fig. 6). Chip formation and therefore h_{cueff} and T_{μ} are affected by the frictional conditions of the cutting edge. To better understand the effect of friction on the movement of abrasive grain in the workpiece, it is better to investigate the differences in chip formation in the lubrication mode with grinding oil.

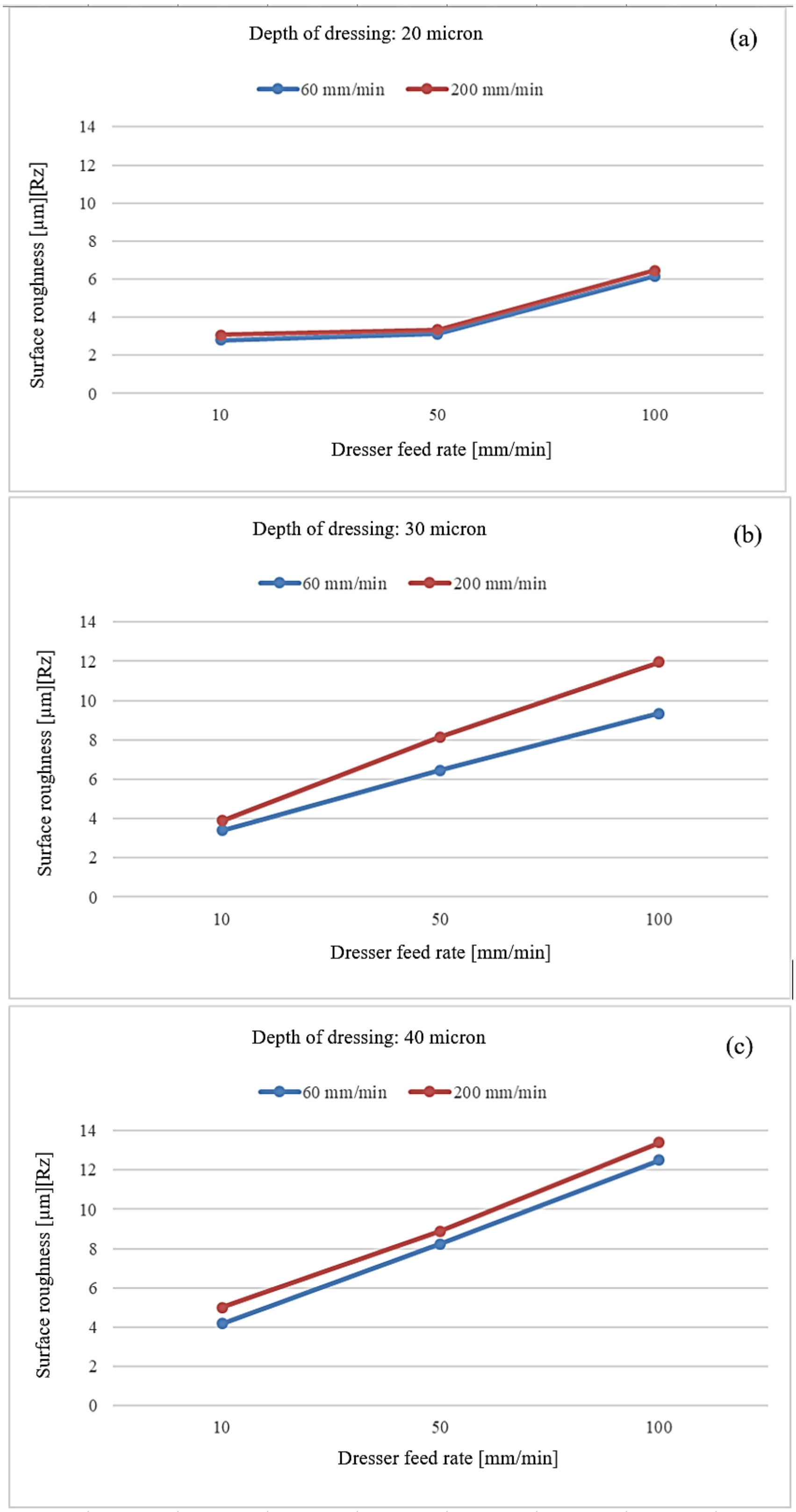

Fig. 3. Effect of dressing depth and feed, and workpiece feed rate during grinding on surface roughness in wet grinding at depth of cut: a) 20µm, b) 30µm, c) 40µm

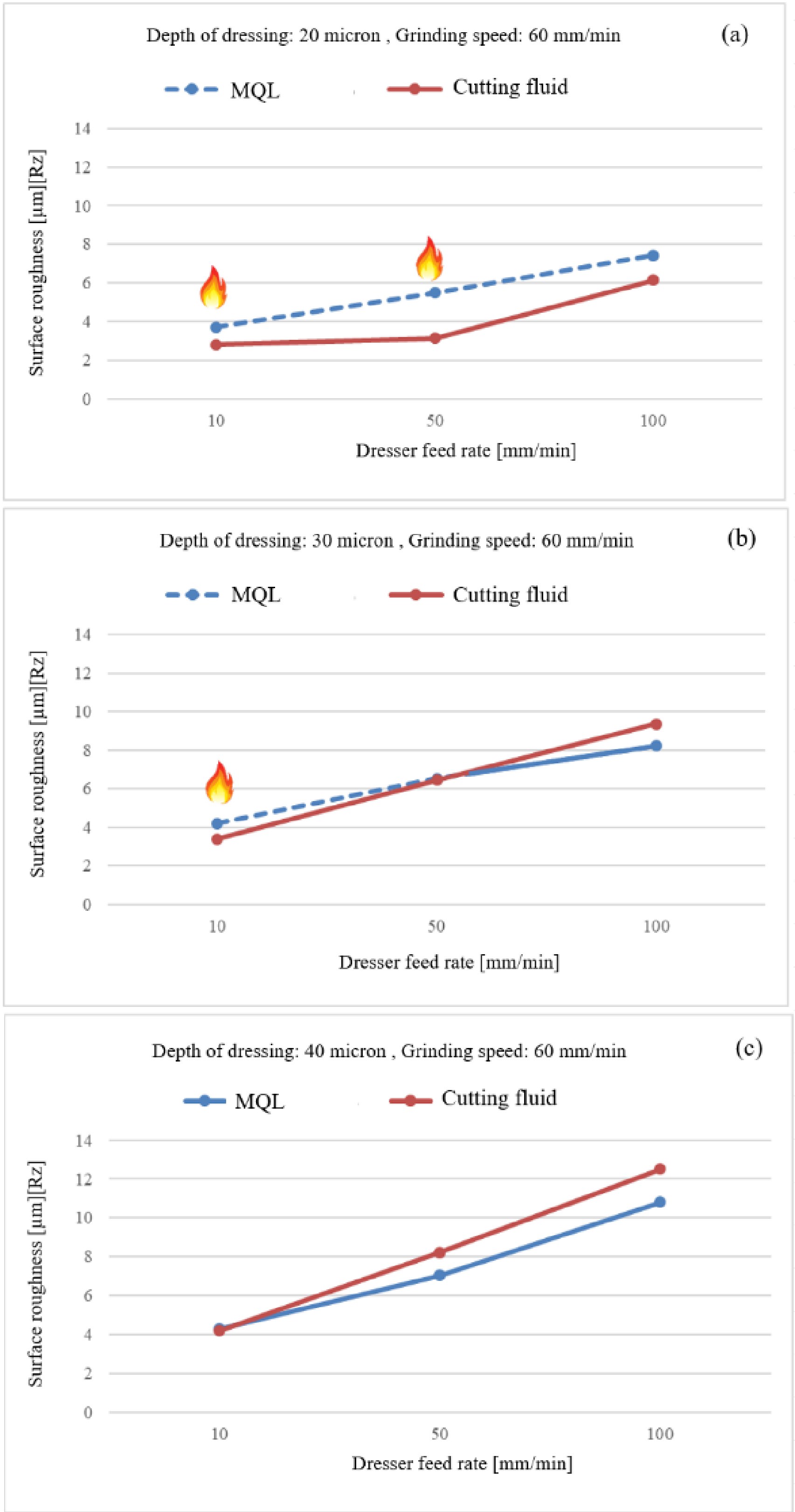

Fig. 4. The influence of lubricant on surface roughness in various dressing depth of cut: a) 20µm, b) 30µm, c) 40µm (workpiece feed rate: 60mm/min)

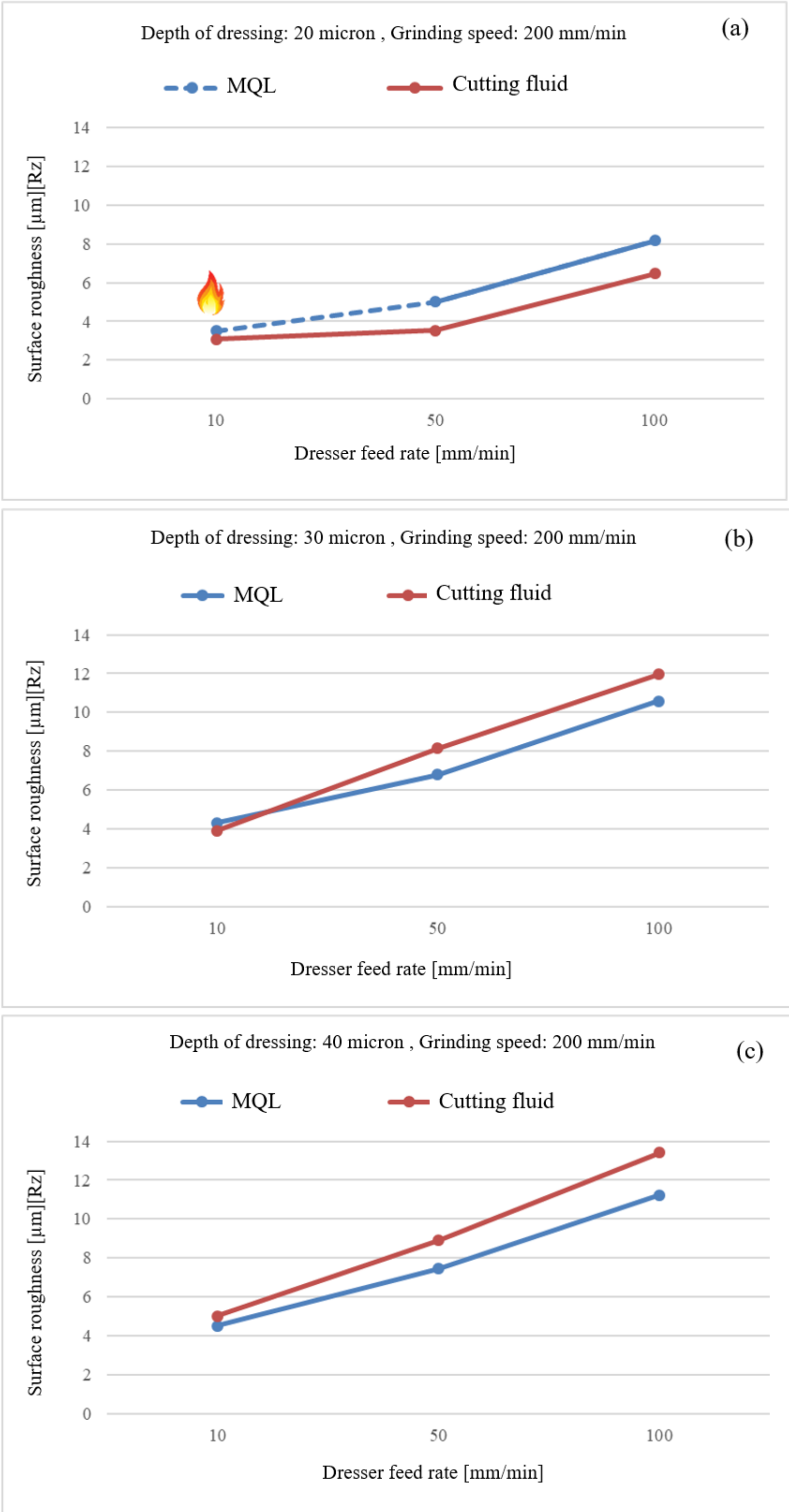

Fig. 5. The influence of lubricant on surface roughness in various dressing depth of cut: a) 20µm, b) 30µm, c) 40µm (workpiece feed rate: 200 mm/min)

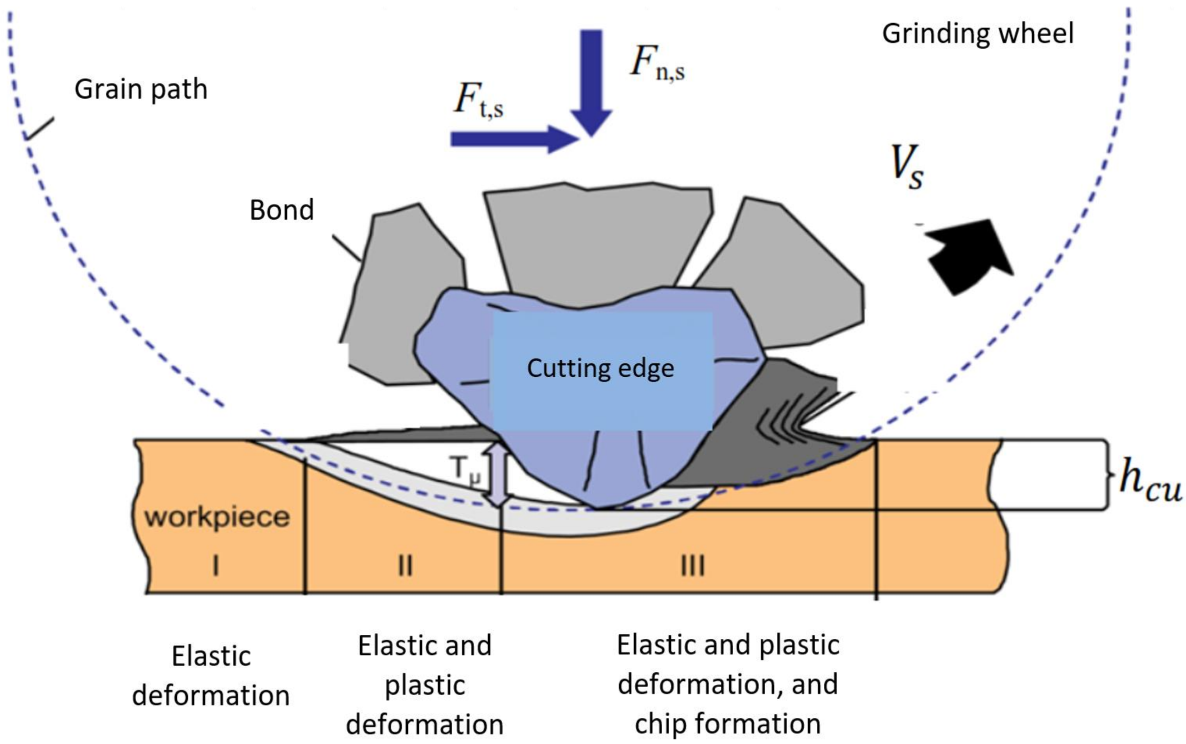

Fig. 6. Chip formation mechanism during grinding operation [19]

Figure 7 shows the effect of friction on grain cutting depth and chip formation efficiency. As lubrication increases, the cutting depth of the grain increases, and therefore the plastic deformation of the material becomes longer and longer. By increasing the lubrication capacity of cutting fluids, the cutting efficiency decreases. A thinner (smaller h_{cueff}) chip will be formed at a constant deformed chip thickness and low friction. Studies show that in addition to friction, other parameters such as the cutting edge radius ρ_s, the effective cutting speed angle η, the cutting speed V_c and the flow properties of the workpiece affect the h_{cueff} and T_μ values. Usually, the worn and flat cutting edges, with a small sharpness parameter and a small angle η, lead to a forward deformation of the material, a larger grain cutting depth, and therefore a smaller effective chip thickness. The grain cutting depth will increase as the workpiece material softens as the machining temperatures increase. As the softness of the workpiece material increases, the grain cutting depth decreases, as the straining hardness will have a more substantial effect in this case. The workpiece material in the flow below the cutting edge is also determined by friction. As the friction increases, the grain cutting depth decreases. On the other hand, during dry grinding, the cutting and plowing forces will be greater than the wet grinding process. Also, in dry grinding, frictional forces are more. It should be noted that the formation of lubricating film by a physical/chemical process can reduce the adhesion between the workpiece and the grain and thus the wear of the grains.

In general, grinding fluids create a lubricating film that affects the chip formation process, reducing frictional forces, and cooling the workpiece and tool surface. As lubrication increases, the elastic/plastic deformation of the workpiece below the cutting edge of the grain increases and reduces the workpiece surface roughness. As the frictional forces decrease, the frictional heat decreases. However, too much lubrication (high viscosity oil) increases the grinding forces, which reduces the cutting process efficiency and thus consumes more energy in the deformation processes [11].

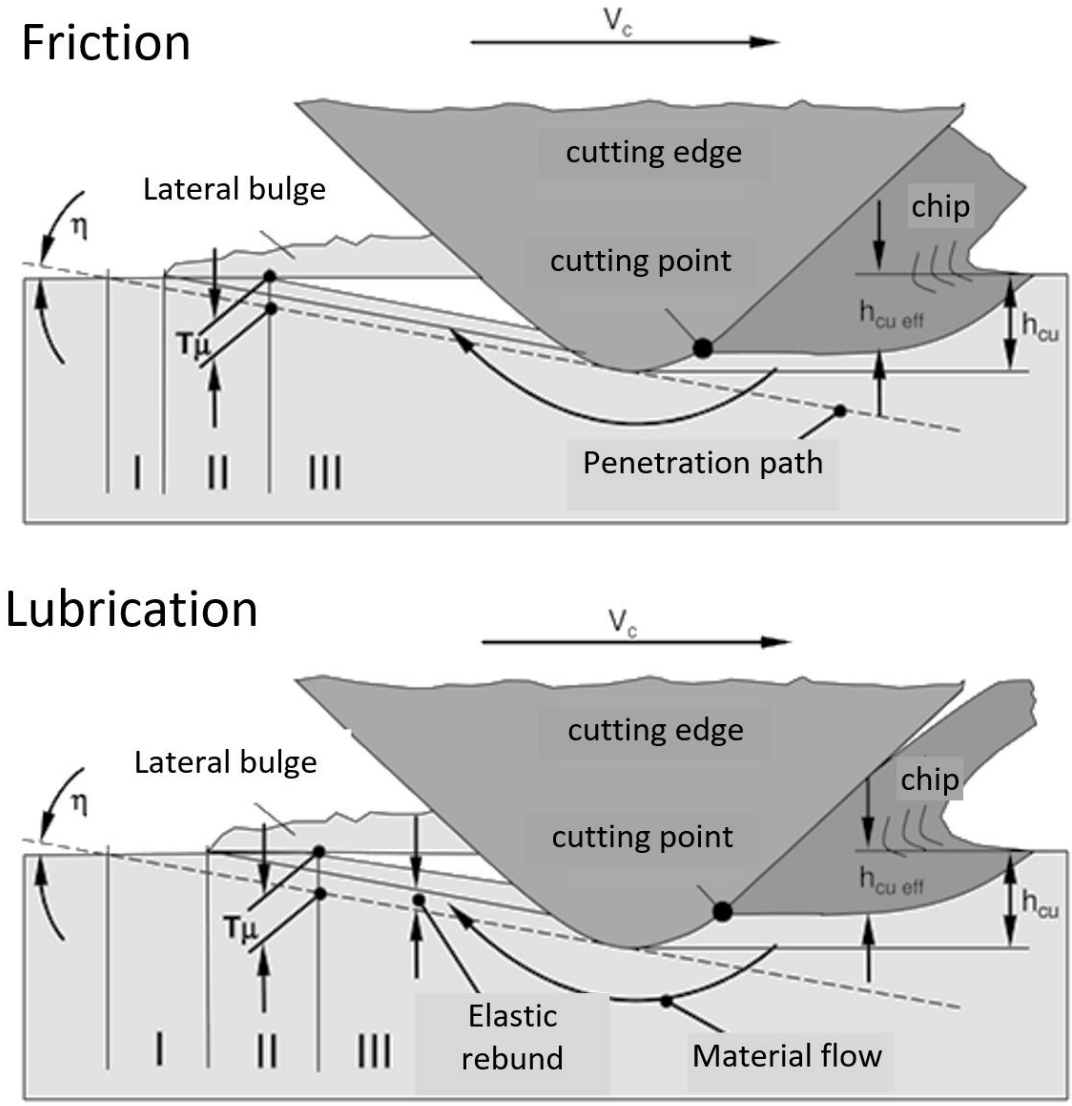

Fig. 7. The influence of friction on the depth of cut and machining efficiency [19]

On the other hand, it should be noted that with increasing viscosity, oil droplets adhere to the surface of the grinding wheel and workpiece and are less dispersed in the air. Figs. 4 and 5 show lower surface roughness values occur when using MQL (especially in rough grinding conditions). This phenomenon can be due to the flattening of the grain or the lack of sharpness of the grains. The blunt grains and the oil film between the wear flat area of the grains and the workpiece surface, result in smoothing the workpiece surface and increasing the deformation zone at the grinding zone. On the other hand, by keeping the deformed chip thickness constant, if the friction decreases, the effective chip thickness decreases and consequently reducing the surface roughness.

Wheel surface topography after dressing with different parameters is shown in Figs. 8 and 9. Figure 9 shows that in the case of soft dressing (at low dressing depth and feed) when the dresser hits the grains, the plastic deformation of the grains occurs, which results in smoother grain flat areas and minor grain breakage. During rough dressing, the dynamic behavior of the dressing process is different. In this case, brittle grain breakage is the predominant phenomenon, and deformation decreases, so the grinding wheel surface will be sharper and rougher after rough dressing.

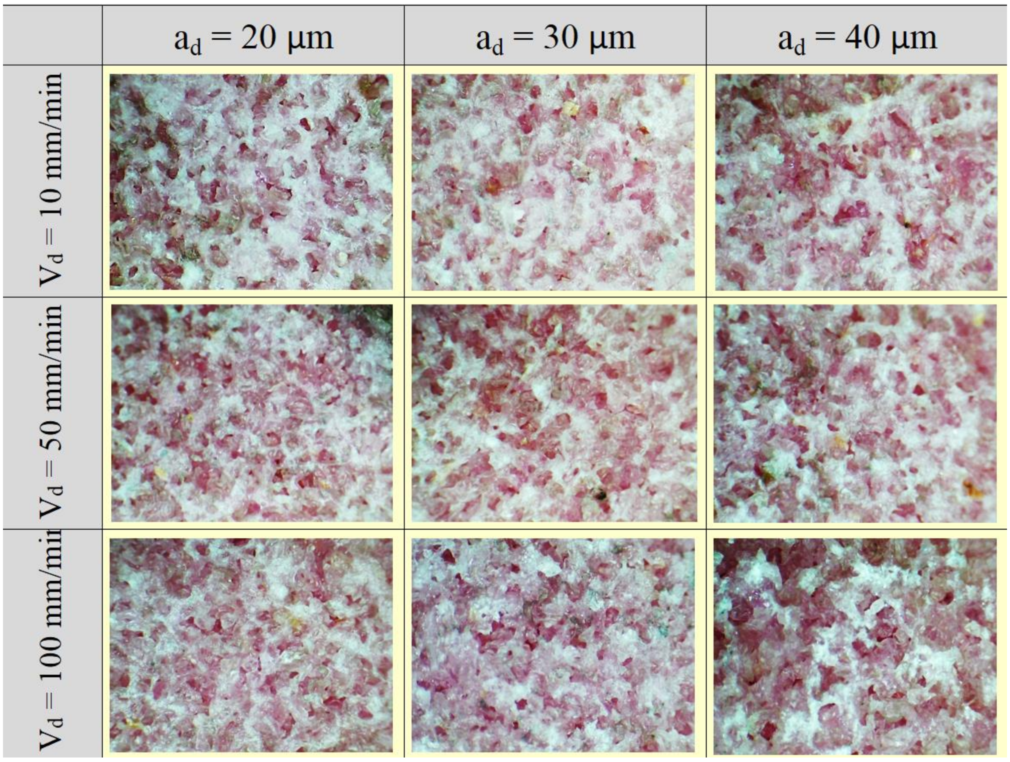

Fig. 8. Topographic image of the mounted point grinding wheel surface after dressing (with 200x magnification)

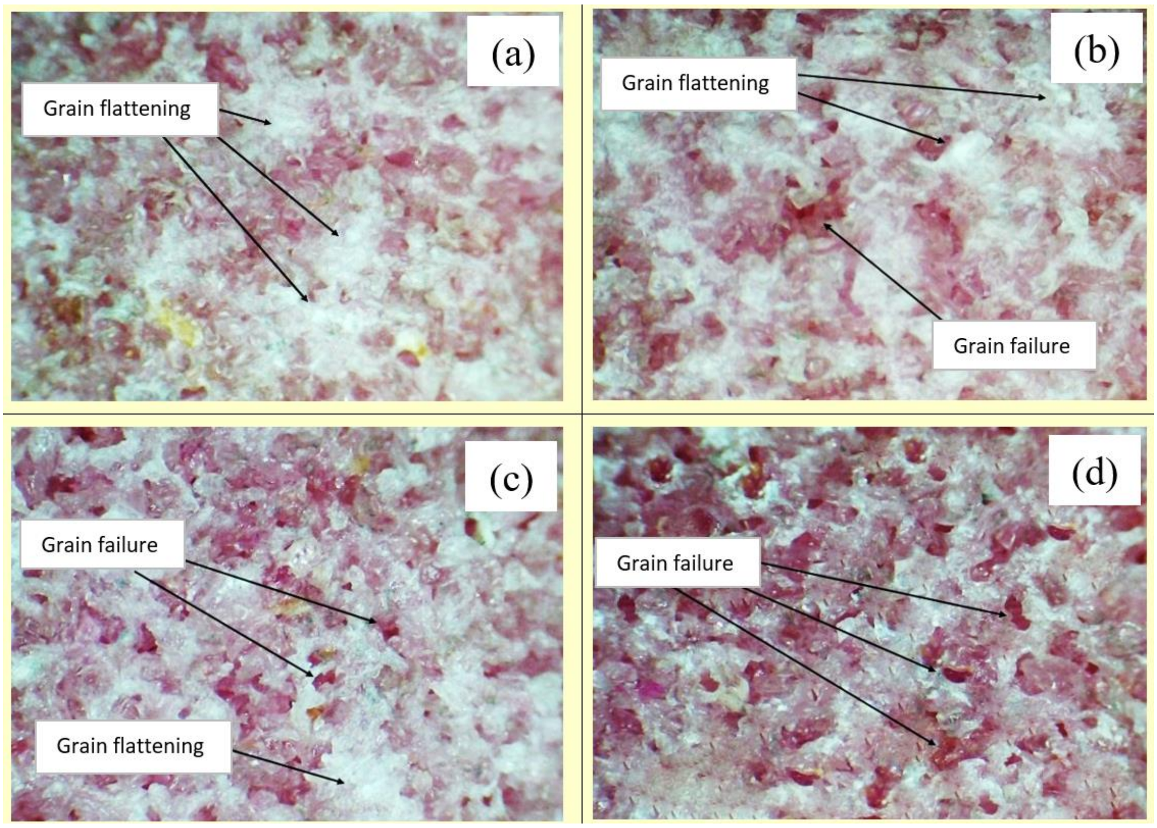

Fig. 9. The mounted point grinding wheel surface topography under different conditions: a) a_d=20μm, v_d=10mm/min, b) a_d=20μm, v_d=100mm/min, c) a_d=40μm, v_d=10mm/min, d) a_d=40μm, v_d=100mm/min

The chip removal process depends on the physical properties of the abrasive and the workpiece when the abrasive cutting edge engages the workpiece surface. Five main phenomena occur in the cutting edge motion path (Fig. 10): micro-sliding, micro-grooving, micro-ploughing, micro-cutting or micro-chipping, and micro-breaking. In micro-ploughing, continuous plastic or elastic deformation occurs around it without chipping. In actual processes, the simultaneous effect of several abrasive grains or repeated collisions of a single grain leads to various defects in the workpiece material at the edges around the grain path (lateral flow). Micro-cutting leads to the formation of chips. Micro- ploughing and micro-cutting generally occur during the machining of soft materials. The relationship between micro-ploughing and micro-cutting depends on common conditions such as grain and workpiece matching, grinding parameters, and cutting edge geometry. Micro-breaking occurs in the form of crack formation and propagation. As a result of this phenomenon, the volume of chips removed can be manifold the volume of the grain movement path. Micro-failures often occur during the machining of hard-brittle materials such as glass, ceramics, and silicon; Therefore, the mechanism of surface formation during grinding involves these primary processes. These processes most often depend on the workpiece material and lubrication conditions.

Figure 11 shows the morphology and quality of the workpiece surface after grinding with different dressing conditions and coolant-lubricant environments. According to Fig. 11, the best surface quality in the soft dressing process with a depth of 20μm and a feed rate of 10 mm/min was achieved by conventional wet grinding. Performing the process with similar parameters in the MQL method a grinding environment resulted in burnout of the workpiece surface, which can be due to less cooling in MQL technique than wet grinding and more grinding power and force by performing fine dressing in these conditions.

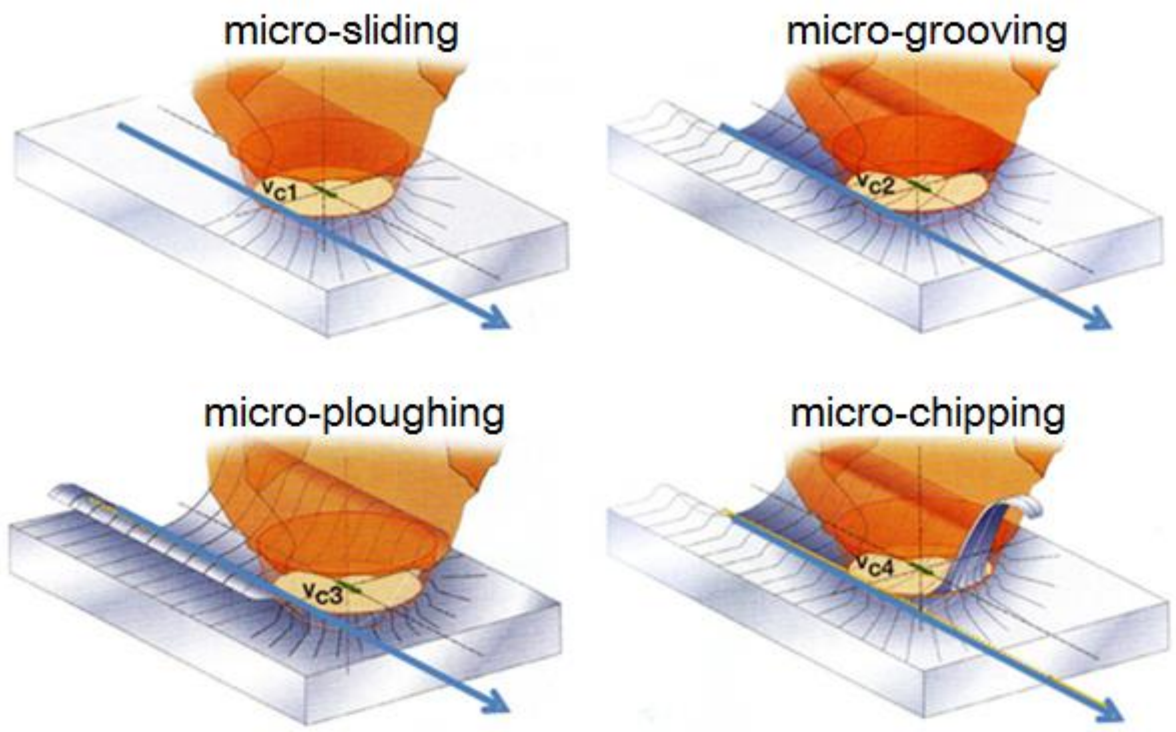

Fig. 10. Physical interaction between abrasive particles and the workpiece surface [19]

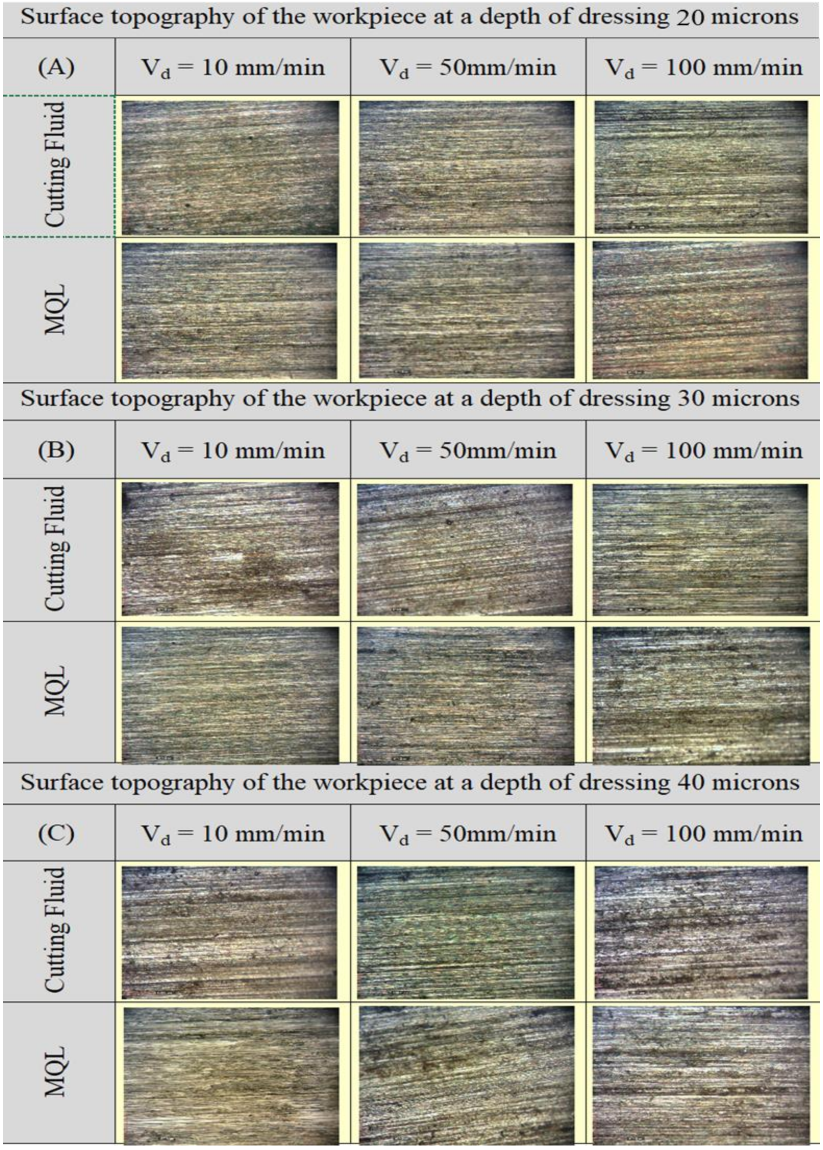

Fig. 11. Workpiece surface morphology in various depths of dressing conditions (workpiece speed during grilling=200 mm/min)

During grinding the separated chips may be adhered in the porous spaces between the abrasive grains or welded to the abrasive grains. This phenomenon is termed wheel loading. This event causes the grinding wheel grains to blunt, resulting in abrasion and vibration. It also increases the cutting force and temperature and reduces the wheel life. As discussed in the application of coolant-lubricant, it is crucial to find the conditions of the dressing and the best type of coolant-lubricant environment to increase the wheel life and reduce the number of dressing processes.

Figure 12 shows the chips adhered to the mounted point grinding wheel medium after the grinding process. However, by performing rough dressing (increasing dressing depth or feed) by reducing the number of active cutting edges, oil droplets penetration and their lubrication effect in the MQL technique is increased compared to cutting fluid, and consequently, the workpiece surface roughness is lower in MQL grinding in comparison to wet grinding. According to Fig. 4 and workpiece surface morphology, it can be concluded that increasing the dressing speed has more significant effect on the wheel surface topography. Therefore, MQL will be more effective in these conditions.

In general, six different phases can be defined in the formation of chips during grinding, as shown in Fig. 13. In the first phase, the abrasive grain first creates a groove by elastic and plastic deformation in the workpiece, which is pressed to the edges around the groove. The workpiece surface is assumed to be compressed in this phase, and no chips are formed. The formation of chips begins by continuing to move the grain in the workpiece material (phase 2). Depending on the space in front of the grain, chips are compressed and bent. At low depths and feed rates, the contact surface is completed in the third phase, creating fine-grained chips. At high depths and feed rates, the cutting edge penetrates more into the workpiece material, resulting in a distinct cutting zone with a length of 75% of the maximum grain length on the surface (phase 3). In this case, more heat flux and temperature are created in the contact area. Due to the small effective cooling/lubricating surface, the heat generated is not entirely dissipated and melts the deformed chip on top of the plastic. If the grain engagement ends in this phase, tadpole-shaped chips are formed (phase 4). If a collision occurs across the contact area, the entire workpiece will melt into the space between the grains after tending to form tadpole-shaped chips. Due to surface tension, the molten chip becomes spherical after leaving the contact surface (phases 5 and 6). The formation of spherical chips is commonly in grinding processes.

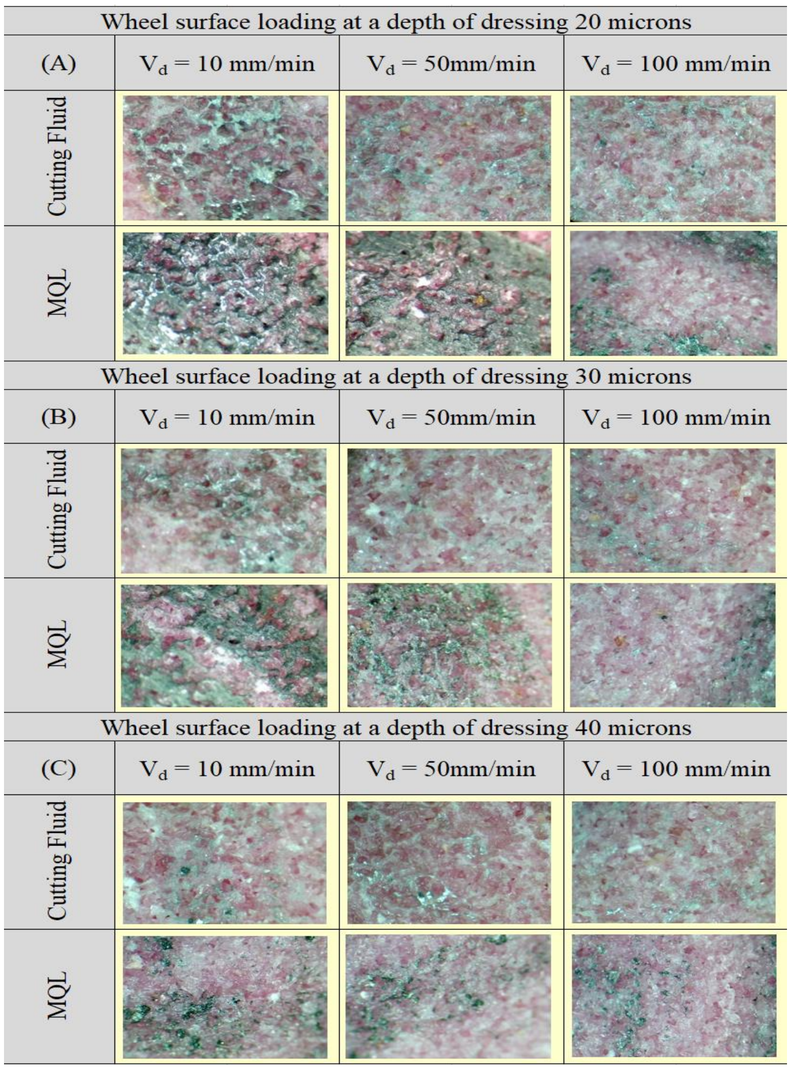

Fig. 12. Wheel loading under various dressing and coolant-lubricant conditions (workpiece speed during grilling=200 mm/min)

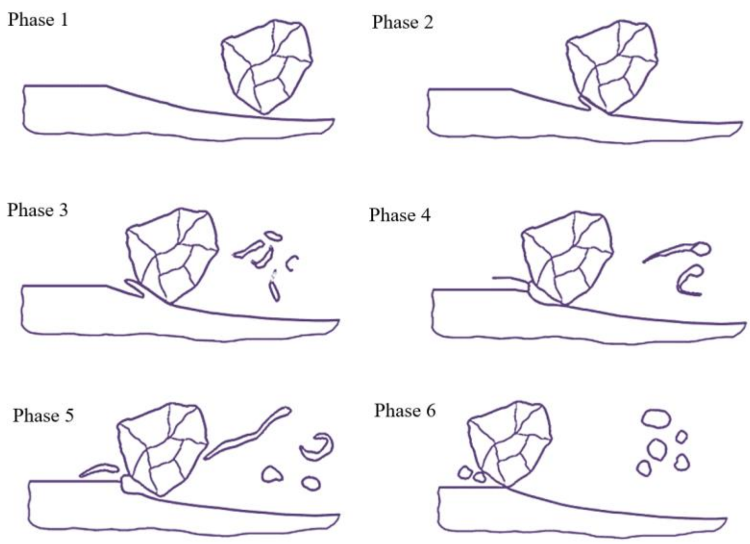

Fig. 13. Different phases of chip formation [19]

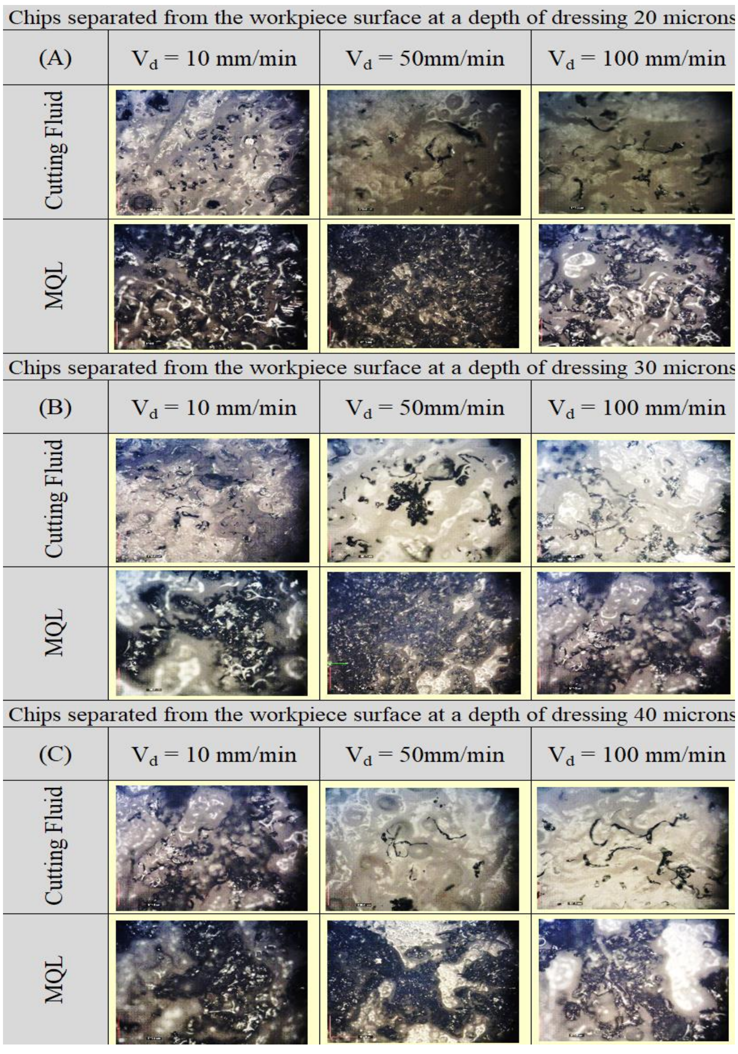

Fig. 14. Grinding chips from different machining conditions (workpiece speed during grilling=200 mm/min)

If wet grinding is used in the process, due to the high heat transfer coefficients of the cutting fluid, the chips separated from the workpiece are well removed from the grinding area and not adhered to the wheel surface. However, using MQL will increase wheel loading compared to wet grinding, due to the high viscosity of the MQL oil as well as high temperatures at the grinding zone due to low heat transfer by MQL. Chips removed from the workpiece surface under different grinding conditions are shown in Fig. 14. It can be shown that the chips removed from the surface are melted and adhered to each other when using MQL technique due to the high temperature in the grinding area. Melting of most chips is a factor for further loading the grinding wheel surface in MQL grinding.

5. Conclusion

The present study investigates the effects of dressing and coolant-lubricant environment on the surface quality of Mo40 steel in the mounted point grinding process. The most important results can be summarized as follows:

1. The grinding performance using mounted point grinding wheel is affected by the topography of the grinding wheel surface, and the process can be optimized by performing a proper dressing.
2. By performing soft dressing (with low dressing depths and feed rates), the number of active cutting edges in the grinding zone will increase, and as a result, the machining forces and the heat generated will increase. In this case, applying MQL method as the cutting fluid due to the low cooling ability will cause burns on the workpiece surface.
3. Reducing grinding heat and temperature using grinding wheels with rough topography (reducing active grains in the conflict zone) makes it possible to use the MQL technique with higher efficiency.
4. Increasing the workpiece feed rate during grinding operation increases the engagement of the grinding wheel with the workpiece, and as a result, more grains penetrate to the surface, which increases the workpiece surface roughness.
5. Increasing the dressing feed rate of reduces the overlap ratio and the number of active fine edges, and as a result, increases the workpiece surface roughness.
6. The loading of the grinding wheel surface in soft dressing conditions is much more than rough dressing due to the increase in the number of fine edges, the increase in heat generated at the grinding zone, and the decrease in the porosity of the grinding wheel surface.
7. due to the lack of fluid to remove chips and low cooling properties in MQL technique, therefore MQL grinding causes the chips to stick to the grinding wheel surface, and consequently grinding wheel surface load increases.

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