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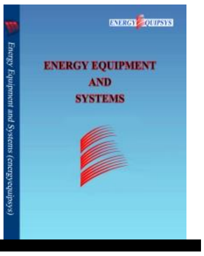

Experimental investigation of the effects of dressing and coolant-lubricant conditions on grinding of Nickel-based superalloy-Inconel 738

Authors

Mohammadjafar Hadad[a][*]
Javad Makarian[a]

[a] School of Mechanical Engineering, College of Engineering, University of Tehran, P.O. Box 11155/4563, Tehran, Iran

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ABSTRACT

In grinding operation, wheel topography influences the workpiece surface quality, grinding forces, abrasive grain wear and wheel loading. The difficulties associated with grinding nickel-base superalloys are mainly attributed to the high strength and low thermal diffusivity of these materials. Their high strength leads to high removal energy. The application of green machining techniques for sustainable manufacturing becomes more and more attractive nowadays to reduce the consumption of energy and cutting tools and cut fluids and consequently decrease the production costs and environmental effects. In this study, the effect of dressing parameters and wheel topography on Minimum Quantity Lubrication-MQL grinding performance of Nickel-base superalloy-Inconel 738 is investigated. In other words, to generate different grinding wheel topographies, depth of dressing and dressing speed has been changed during dressing and conditioning of vitrified Al_2O_3 *wheels using a single point diamond dresser. After dressing grinding wheels, machining tests have been conducted to study the influence of the wheel topography and coolant-lubricant types on the performance of grinding operation (workpiece surface quality and wheel loading). The tests have been performed in the presence of fluid as well as MQL with compressed air. The results show that applying MQL technique with the optimized dressing conditions improves the grinding performance of Inconel 738. Minimum quantity lubrication implemented in the grinding process is one of the realistic alternatives that can rise the abrasive processes on a sustainable level.*

Keywords: Sustainable Grinding, MQL, Surface Quality, Dressing, Inconel 738

1. Introduction

Sustainable manufacturing considers environmental, economic, and social aspects [1]. Generally, in different machining processes, offensive pollutants and by-products are generated to be treated properly to protect the environment [2, 3].

A cutting fluid is often used in machining to enhance the tool life and/or improve surface integrity [4]. The fluids that are used to lubricate in machining contain environmentally harmful or potentially damaging chemical constituents [5].

It must be noted that during the grinding operation, without using sufficient coolant-lubricant, thermal damage and dimensional inaccuracy on the workpiece surface will be generated and the methods of minimum

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[*] Corresponding author: Mohammadjafar Hadad
School of Mechanical Engineering, College of Engineering, University of Tehran, P.O. Box 11155/4563, Tehran, Iran
Email: mjhadad@ut.ac.ir

grinding fluids or dry grinding have not yet been fully successful in industrial applications [6, 7]. So in dry grinding, as therefore is no cutting fluid to transfer the heat from the contact zone, problems frequently occur in terms of thermal damage on the workpiece surface, increasing the grinding energy and grinding forces, wear of grinding wheel, low material removal rate (regarding relatively low depths of cut) as well as poor surface integrity compared to conventional flood grinding [8-10].

One attractive alternative for dry grinding is environmentally friendly-MQL grinding. This process uses a minimum quantity of lubricant and is referred to as near dry grinding. In minimum quantity lubrication (MQL) grinding, an air-oil mixture called an aerosol is fed onto the machining zone. In MQL process, aerosols are oil droplets dispersed in a jet of air, oil droplets carried by the air fly directly to the tool working zone, providing the needed cooling and lubricating actions [11-13]. A number of studies have shown that compared to dry grinding; MQL technique substantially enhances cutting performance in terms of increasing wheel life and improving the quality of the ground parts [14, 15].

Nickel-base superalloys are crucial materials of strategic products like power plants and aircraft engines because they have excellent mechanical properties in high temperatures. Amongst the various types of nickel-base superalloys, Inconel 738 is the newest commonly used. The turbine disks are produced via wrought processes, while blades and vanes are fabricated by investment casting [16]. To produce precision components from these materials with tight tolerances, grinding is a common and cost-effective method. In practice, conventional wheels (Al_2O_3) are applied in creep feed grinding of nickel-base superalloys. Due to the high wear rate of the abrasive grains, as well as the premature chip loading, continuous dressing technology is employed in grinding nickel-based superalloys. The continuous dressing maintains the geometrical accuracy of the ground profile, sharpens the abrasive grains in the grinding wheel, prevents the chip loading in the chip pocket, and remarkably reduces the specific grinding energy. Since grinding is the last stage in the manufacturing chain of these precision and costly products, surface and subsurface damages bring about high loss [16].

Specific distributions of abrasive grains constitute the grinding wheel surface topography. The grinding wheel topography is one of the most important input variables of the grinding process [17]. It is influenced by the wear during grinding process. In addition, active mechanisms of the dressing process are grit breakage or splintering, bonding breakage, grit break-out of the bonding, or grit deformation [18, 19].

Difficulties associated with grinding Inconel alloys necessitate investigating the influencing factors on the grinding of these alloys. The grinding of nickel-base superalloys has been investigated in recent years from different viewpoints [20]. But literature review shows the lack of study on the effects of grinding wheel surface topography on grinding performance in minimum quantity lubrication-MQL grinding of Inconel 738-Ni base superalloy [21, 22].

In order to improve MQL performance during the grinding of Inconel 738, in this study, the effects of dressing parameters and wheel topography on MQL grinding performance are investigated. In other words, to generate different grinding wheel topographies, depth of dressing and dressing speed has been changed during dressing and conditioning of vitrified Al_2O_3 wheels using a single point diamond dresser. After the dressing of grinding wheels, machining tests have been conducted to study the influence of the wheel topography and coolant-lubricant types on the performance of the grinding process. Performance indicators included: workpiece surface quality and wheel loading.

2. Experimental setup

Surface grinding experiments were conducted on PROMPT-SG-5010AH using a vitrified bond Al_2O_3 wheel. The workpiece was Inconel 738 with 160 mm length in grinding direction and 16 mm in width. A single point diamond dressing tool was used with access angle $\alpha_d=10^\circ$ (Fig.1). The experimental setup is summarized in Table 1. The wheel was dressed three times (three passes) before each experiment with different dressing conditions, as shown in Table1. The equipment utilized to control the minimum quantity of lubricant (MQL) was a homemade system in which creates the air envelope that served as the mixing chamber based on the Venturi effect. The surface roughness measurements were performed after the third pass. The workpiece roughness was measured by MarSurf PS1 Surface Roughness Tester (mobile roughness measurement) with a cut-off length of 0.8mm (according to DIN EN ISO 3274:1998). At the end of each test, R_z across the grinding direction was measured at five different points of the ground surface. The surface morphology and chip loading were observed using a digital microscope (DigiMicro manufactured by DNT Company), which possesses a maximum magnification of 200 times.

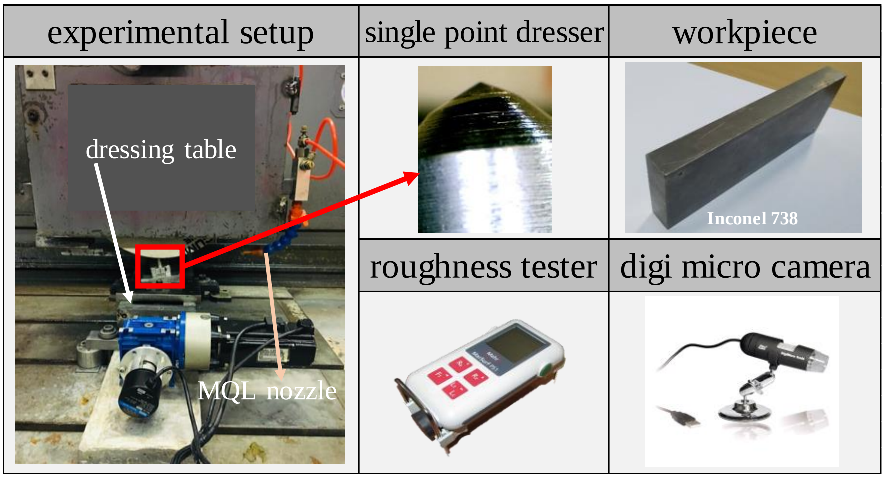

Fig.1. Experimental setup

Table 1: Grinding conditions

Grinding mode	Plunge surface grinding, down cut
Grinding wheel	Al_2O_3: WA60K9V (d_s=300 mm)
Grinding machine	PROMPT-SG-5010AH
Wheel speed (V_c)	V_c=30 m/s
Feed rate (V_{ft})	V_{ft}=4.5, 15 m/min
Depth of cut (a_e)	a_e=10 µm
Coolant-lubricant environments	Fluid (Wet), Minimum Quantity Lubrication (MQL)
Conventional fluid grinding (Wet)	Water-miscible coolant lubricant at 5% concentration
Conventional fluid flow rate	4.5 lit/hr
MQL oil	Vegetable oil
Viscosity of MQL oil (at 20°C)	84 cP
MQL oil flow rate	125 ml/hr
MQL carrier gas	Compressed air
Gas pressure in MQL	5 bar
Workpiece material	Nickel-base superalloy-Inconel 738; (160mm×50mm×16mm)
Dresser	Single point diamond
Depth of each dressing pass (a_d)	a_d=5, 10 µm
Number of dressing passes (N_{dp}), Total depth of dressing (a_{dt})	N_{dp}=3, a_{dt}=15, 30 µm
Dressing feed (v_d)	v_d=50-85-213-426-600 mm/min
Access angle (α_d)	α_d=10°

3. Results and discussion

3.1. Surface roughness and morphology

Figure 2 compares the average surface roughness (*R_z)* across the grinding direction for different wheel topographies, workpiece feed rates and coolant-lubricant types. The finest wheel topography can be achieved with a depth of dressing 5 µm and dressing feed 50 mm/min, while the coarsest wheel has been generated applying dressing depth and feed of 10 µm and 600 mm/min, respectively. Due to the larger chip thickness, in case of coarsely dressed wheels and high workpiece feed rate, induce higher roughness rather than fine dressed and low workpiece feed one. This clearly demonstrates that MQL system was able to penetrate into the region of contact between the grinding wheel and the workpiece more effectively than fluid cooling. It is clear that the coolant-lubricant in the grinding process influences the chip formation process by building up a lubricant film, thus lowering the friction forces and cooling the contact zone. As the lubrication effect increases, there is a corresponding increase inelastic-plastic deformation under the cutting edge of the abrasive grain, resulting in a decrease in workpiece roughness. By reducing friction forces, friction heat and, therefore, the total process heat are reduced [1, 5].

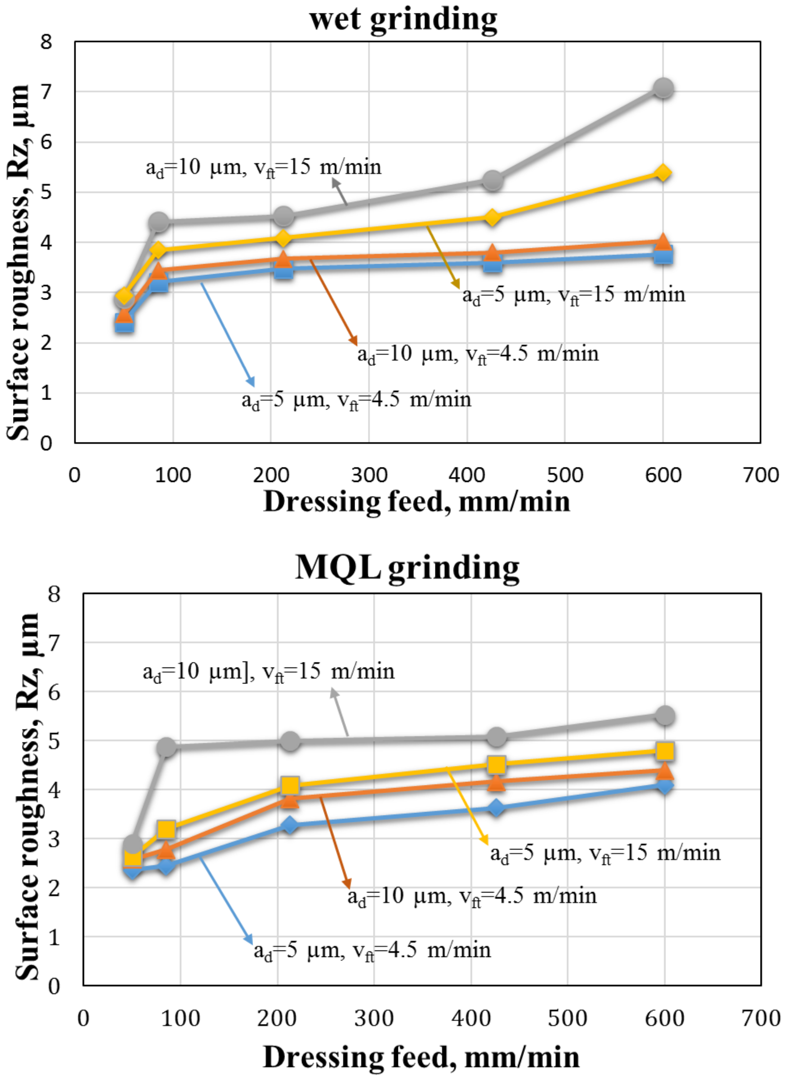

Fig. 2: Workpiece surface roughness vs. dressing speed for different depths of dressing, workpiece feed rates and coolant-lubricant conditions

During the dressing of conventional wheels with a single-point diamond tool (Fig.3), the dresser follows a path that would appear to be like a thread (fractured grooves) on the wheel and abrasive grains [1]. However, measurements of the size distribution of particles removed from the wheel by dressing would seem to contradict this concept of thread cutting by dressing [1, 22]. Generation of the theoretical profile in Fig.3 would require a ductile flow-type cutting mechanism between the dressing tool and the wheel, but the abrasive particles removed by dressing appear to be produced mainly by brittle fracture [1, 11]. Examples of size distributions for particles removed by single-point dressing are shown in Fig.4 for different values of depth of dressing using vitreous bonded Al_2O_3 wheel. Since each nominal grit size includes a range of abrasive particle sizes, the grit dimension corresponding to a particular grit number might be characterized by an average value [1]. Therefore, in Fig.4, also included for comparison is the calculated average grain diameter of the original 60 grit monocrystalline aluminum oxide used in manufacturing the grinding wheel using $d_g = 15.2m^{-1}$ [1].

It is apparent that the particles removed by dressing are somewhat finer than the original grain material and that a lower dressing depth also gives somewhat finer dressing particles. [1, 22] On the other hand, virtually the entire material dressed off the wheel consists of particles that are much bigger than the dressing depth. Therefore, wheel material is mostly removed by a brittle fracture to a depth

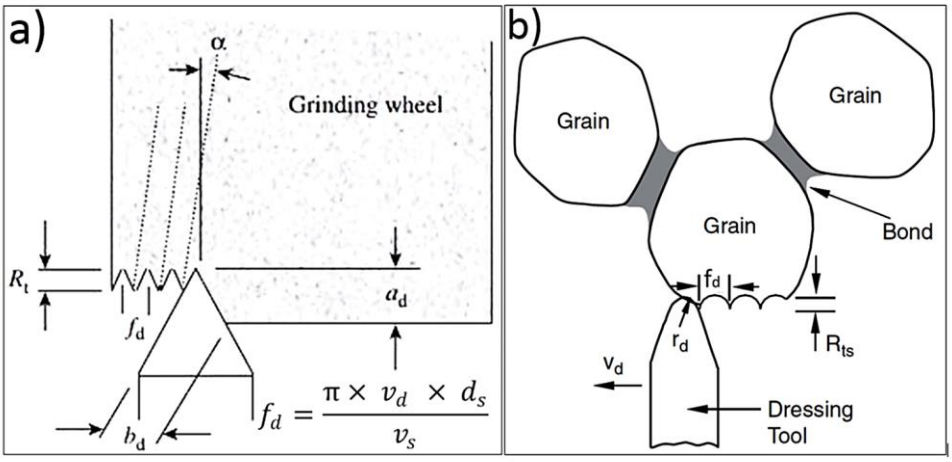

Fig. 3: Kinematics during dressing; cutting path of a single-point diamond dressing tool through: a) the grinding wheel, b) an abrasive grain [1]

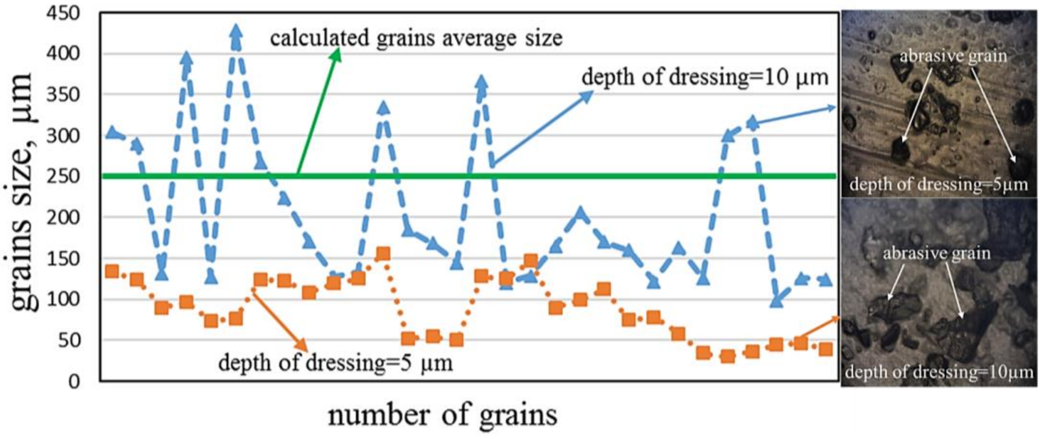

Fig.4: Grain size distribution of particles removed by single-point dressing measured using Image J software (the average diameter of the original grain is included for comparison); vd=426 mm/min (magnification ×500)

below that of the nominal path of the dressing tool. Because the dressing particles are generally much bigger than the depth of dressing but smaller than the original grains, it has been postulated that their removal from the wheel involves a two-step process of grain fracture followed by bond fracture, as schematically illustrated in Fig.5.

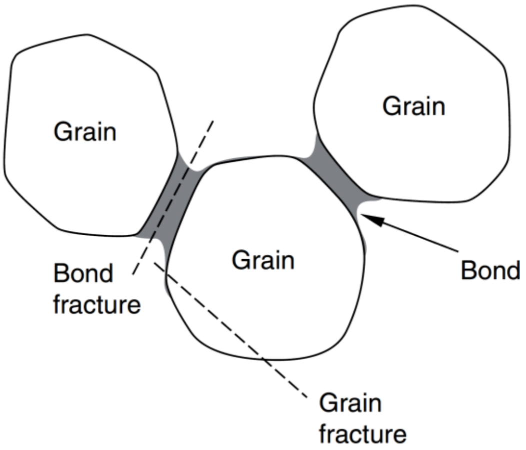

Fig.5: Illustration of grain fracture and bond fracture [1]

While bond fracture is mainly responsible for determining how many potentially active grains remain at the wheel surface, the morphology of these grains is largely controlled by grain fracture on a much finer scale and even by plastic deformation [11]. Although conventional ceramic grain materials are brittle, they can still flow plastically during dressing. In this case, the dressing lead and dressing depth were rather small (fine dressing). For coarser dressing with a much bigger dressing lead and dressing depth, there is much less deformation, and the grains appear more fractured [22]. In general, both grain fracture and plastic deformation play important roles. With finer dressing, localized plastic flow results in flattening and smoothing of some grain tips not fractured away. A similar effect is obtained by the addition of spark-out passes without incrementing the dressing depth [11]. Coarser dressing causes more grain fracture and a sharper wheel. In other words, coarser wheel dressing generally results in reduced grinding forces and rougher workpiece finishes, whereas finer dressing leads to bigger forces and smoother finishes [1]. The directed changing of the grinding wheel topography is a beneficial factor of the dressing process. Moreover, the dressing process (especially dressing feed) has a significant effect on the MQL oil mist performance in the grinding process that must be considered to optimize MQL grinding.

3.2. Wheel loading

Figures 6 and 7 show the wheel morphology after grinding for different grinding parameters and applied wheel dressing conditions as well as different coolant-lubricant types. The obvious differences in the morphology of surfaces ground with different wheel topography and coolant-lubricant types suggest a considerable influence of the MQL grinding on the chip-formation mechanisms. With regard to the surfaces of the ground specimens, it can be observed that there are hardly any side flows on surfaces ground with applying cutting oils in minimum quantity lubrication technique. While a better surface finish can be produced by resorting to finer dressing conditions, this will cause the wheel to be duller, thereby raising the grinding power and specific energy and increasing grinding temperature as well as the risk of thermal damage [11, 22].

In addition, a digital image processing technique has been used to determine the loading areas over the surface of grinding wheels using the toolbox of PYTHON and Adobe Illustrator software. The optical characteristics of the metal chips, the abrasive grains and wheel bond are considered. The wheel loading density experiments applied image processing are shown in Fig.8. It can be demonstrated from Figs. 6-8 that the least chips are loaded in wet grinding due to a large amount of cutting fluid and eventually enough fluid for chip removal. In addition, while grinding with grinding fluid (wet grinding), the temperature contributed to the workpiece is lower (because of higher convection heat transfer coefficient of fluid compare to MQL oil mist) than grinding with MQL technique. Thus, the chips (with lower temperature) tend much less to be loaded on the wheel.

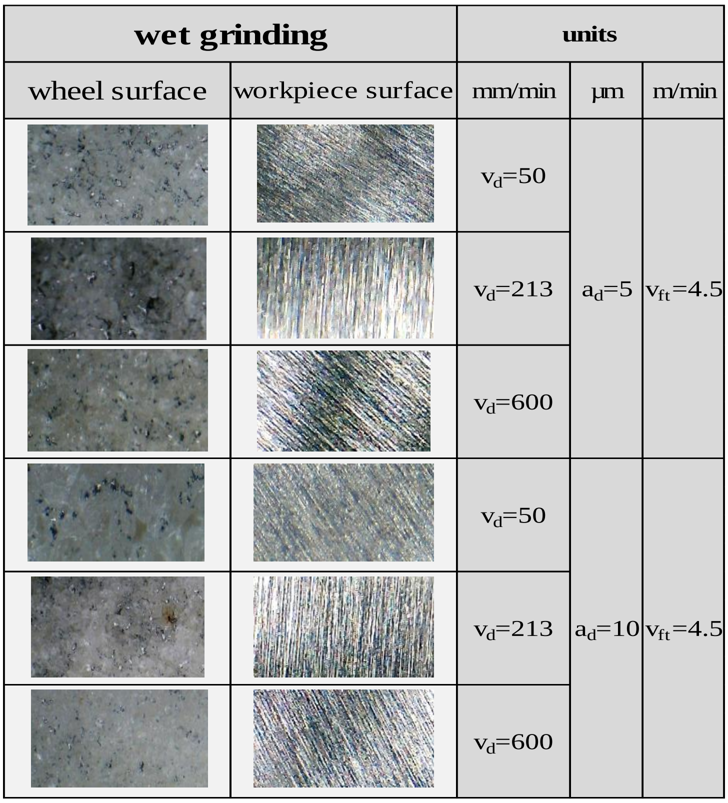

Fig. 6: Abrasive grain loading after wet grinding processes and surface morphology of ground workpieces (magnification ×200)

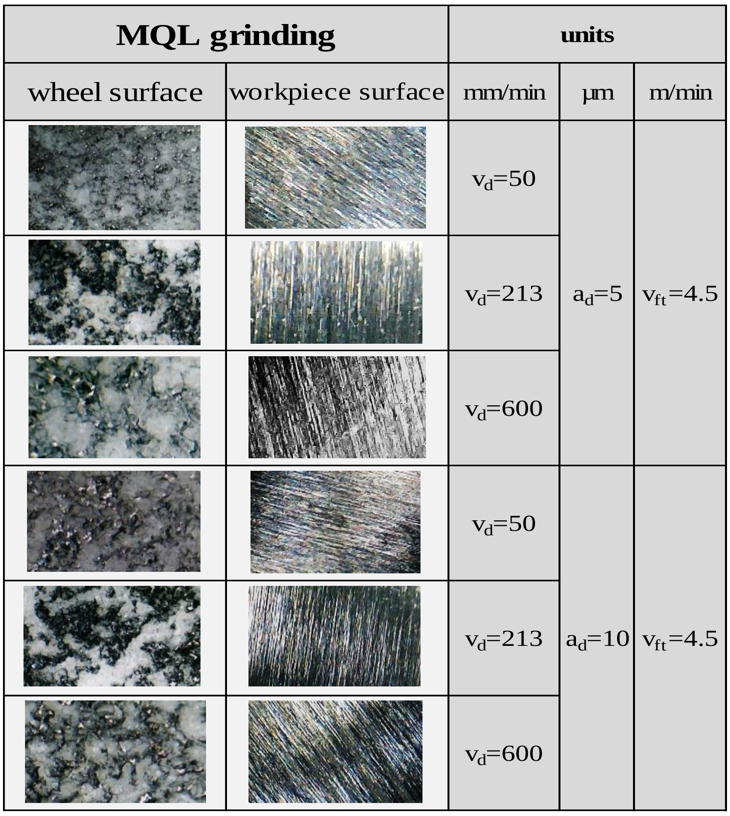

Fig.7: Abrasive grain loading after MQL grinding processes and surface morphology of ground workpieces (magnification ×200)

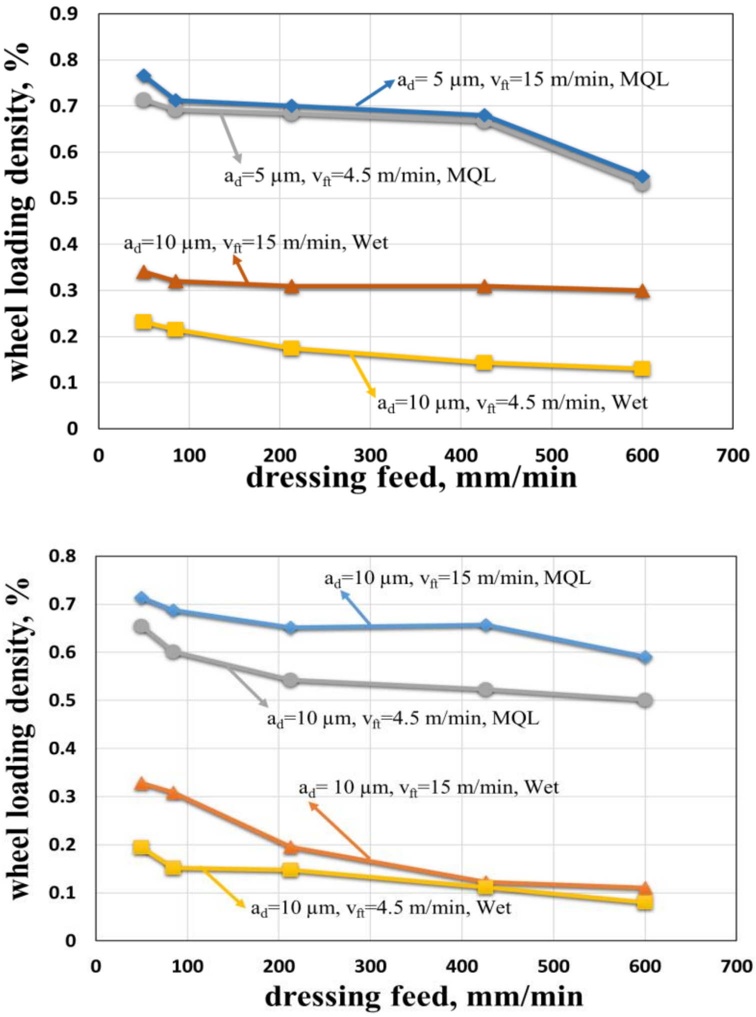

Fig.8: Wheel loading against dressing feed for different depths of dressing, workpiece feed rates and coolant-lubricant conditions

Chips produced under fluid conditions are mainly long, thin and lamellar, indicating the mechanism of chip formation to be predominantly by low temperature (Fig.9). The minimum quantity lubrication technique also provided almost all types of chips indicating the mechanism of chip formation to be by higher temperature than fluid grinding. Under grinding with fine-dressed wheels the chips are welded to each other due to higher grinding forces and temperatures (Fig.10). Also, the coarse-dressed wheel is less prone to chip loading in comparison with the fine-dressed one due to more gaps between the grains.

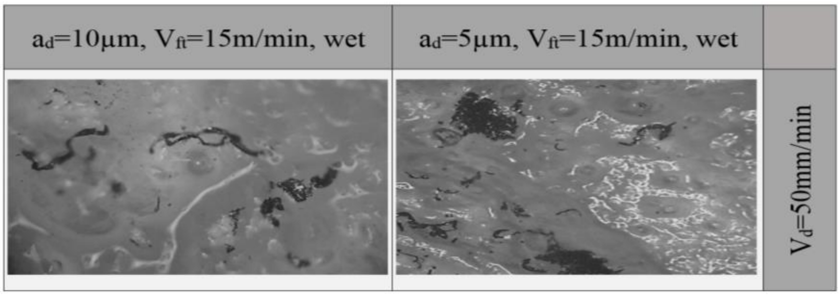

Fig.9: The chips obtained from wet grinding (magnification ×500)

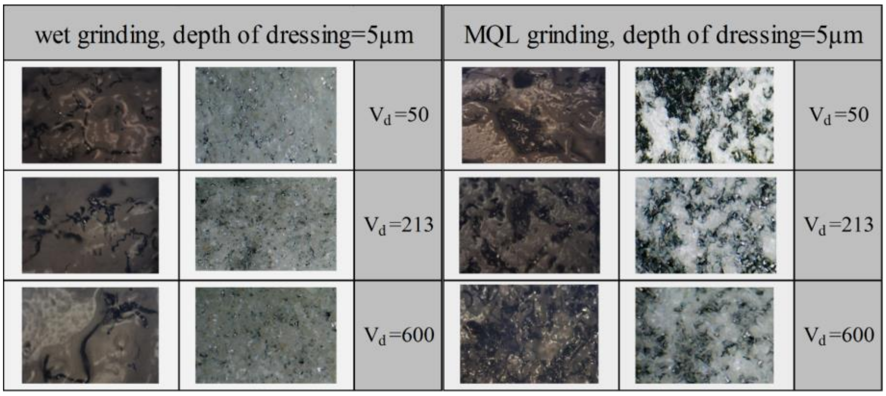

Fig.10: The chips (left sides with magnification ×500) and wheel loading (right sides with magnification ×200) obtained from wet and MQL grinding processes; vft=15 m/min

4. Conclusion

The main results obtained in this study are summarized as follows:

1. The grinding wheel surface topography has an important influence on the grinding process, and it can be managed by appropriate selection of depth of dressing and dressing speed.
2. Although conventional ceramic grain materials are brittle, they can still flow plastically during dressing. In this case, the dressing speed and depth of dressing were rather small (fine dressing). For coarser dressing with a much bigger dressing speed and depth of dressing, there is much less deformation and the grains appear more fractured.
3. In general, both grain fracture and plastic deformation play important roles. With finer dressing, localizes plastic flow results in flattening and smoothing of some grain tips not fractured away.
4. Coarser dressing causes more grain fracture and a sharper wheel, so it generally results in reduced grinding forces and rougher workpiece finishes, whereas finer dressing leads to bigger forces and smoother finishes.
5. Of the two single-point dressing parameters, the dressing speed is found to have a much bigger relative influence than the depth of dressing.
6. According to the obtained results in this study, MQL grinding with optimized dressing conditions improves the technical and economic aspects of grinding difficult to cut materials (lower energy consumption, higher tool life, lower waste of material, eliminating of cutting fluid application), and it also reduces the problems associated with the environment and operator health.

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