A Review on Various Cooling System Employed in Grinding

Rajni B. Kinalkar, M.S. Harne

***Abstract*—Grinding is most commonly used as a finishing process to provide good surface, dimensional and geometrical quality. As thermal damage is one of the main limitations of grinding process. Cooling plays a crucial role in grinding to avoid thermal damage to the workpiece surface. Cooling and lubrication are especially important to ensure workpiece quality in grinding, because of high friction and intense heat generation involved in the process. This paper focused on Different approaches of cooling system as per the surface quality requirement for different types of material. Also it discusses the recent trends in cooling system.**

***Keywords*— Grinding, Cooling system, Cryo grinding, Slotted grinding wheel, MQL, Hybrid MQL.**

I. INTRODUCTION

Grinding process is widely used machining process in industry for surface smoothing and finishing. Grinding process involves a material removal by the contact between grinding wheels with a randomly structured topography with the workpiece. The quality of a machined surface is becoming more and more important in order to satisfy the increasing demands of sophisticated component performance, longevity, and reliability so that they can achieve their functions according to geometric, dimensional and surface considerations. An understanding of surface finish provides much advantage in avoiding failures; enhance component integrity and costs saving. Surface roughness is generally regarded as an important factor in terms of fatigue life performance. [1] Grinding operation is inherently associated with high specific energy requirement owing to shearing with adverse grit geometry and sliding of the grains, which leads to high temperature on the ground surface. Such high surface temperature usually results in thermal damage such as burning, oxidation, formation of untempered martensitic layer, induction of tensile residual stresses and cracks at the surface. The tensile residual stresses detrimentally reduce the static strength and fatigue life, enhance chemical corrosion, propagate cracks in brittle materials and lead to distortion while grinding and during service life of the product [2]. Traditionally coolant fluids have been used in grinding processes to reduce workpiece temperature and decrease the risk of thermal damage. In addition, thanks to their lubricant properties fluids serve to enhance process performances [3].

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***Correspondence Author(s)**
Rajni B. Kinalkar, ME Scholar, Department Mechanical Engineering, Government College of Engineering Aurangabad (MS), India
M.S. Harne, Asst. Professor, Department Mechanical Engineering, Government College of Engineering Aurangabad (MS), India

The researchers have tried to developed different strategies to control the high temperature at the grinding zone according to the application, economy, workpiece material, type of coolant, required tolerances, surface integrity etc.

II. GRINDING PROCESS

A. *Mechanics of Chip Formation During Grinding*

For grinding of a workpiece surface, ideal cutting can be obtained by many process combinations like ploughing due to lateral displacement, workpiece movement, grinding wheel movement, elasticity of the workpiece and vibration. Many parameters have effects on grinding process. Some of these parameters can be controlled while the others not [3] and [4]. Kinematic relation between grinding wheel and workpiece in grinding process is applied to each grain of the grinding wheel. Previous work in this area was based on mechanics of mean single grain. Some faces of grain during grinding can be illustrated the geometrical relation between a single grain and workpiece. Non-deformed chip shape, tool path length of the abrasive grain (lk), maximum nondeformed depth of cut (hm) and chip geometry are shown schematically in Fig. 1. Chip formation in grinding process can be divided into three successive stages: friction, ploughing and cutting. In up-cut grinding, grinding wheel grains rub on the workpiece surface rather than cutting due to the elastic deformation of the system. This is called friction stage. And then, plastic deformation takes place as the elastic limit is exceeded between the abrasive grain and workpiece. This is called ploughing stage. Workpiece material flows plastically through forward and sideward ahead of the abrasive grain and forms a groove. When the workpiece material can not resist the flow stress, chip is formed. The chip formation is called cutting stage. In this chip formation stage, energy is used most efficiently [4-6].

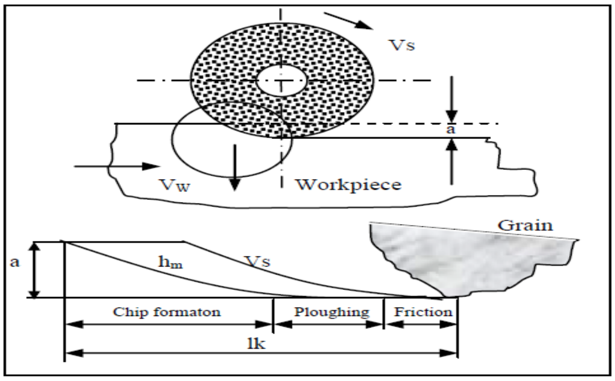

Fig. 1 Three Stages of Chip Formation in Grinding

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Grinding forces not only affect chip formation mechanics, grain wear and temperature distribution but also efficiency of the grinding operation. Therefore, grinding forces are among the most important factors affecting grinding quality.

Grinding is a complex machining process with lot of interactive parameters, which depend upon the grinding type and requirements of products. The surface quality produced in surface grinding is influenced by various parameters given as follows:

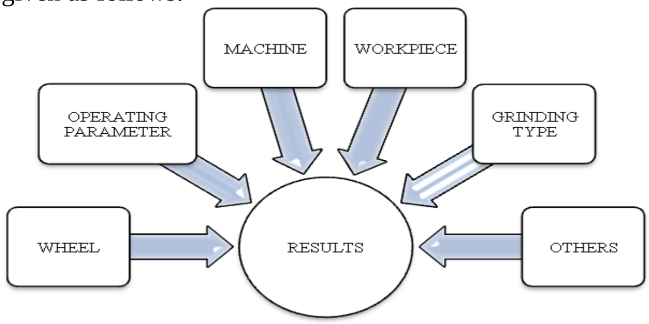

Fig. 2. Factors Affecting Grinding Results

(i) Wheel parameters: abrasives, grain size, grade, structure, binder, shape and dimension, wheel dressing etc.
(ii) Operating parameters: wheel speed, depth of cut, table speed, and dressing condition, etc.
(iii) Machine parameters: static and dynamic characteristics, spindle system, and table system, machine stiffness, holding system stiffness etc.
(iv) Work piece parameters: fracture mode, mechanical properties, and chemical composition, grindability, workpiece dimension etc.
(v) Grinding type: Surface grinding, cylindrical grinding etc.
(vi) Others: Coolant type, sparking out, environment etc.[7,8]

The grinding process requires a high energy expenditure per unit volume of material removed. Virtually all of this energy is dissipated as heat at the grinding zone where the wheel interacts with the workpiece. This leads to the generation of high temperatures which can cause various types of thermal damage to the workpiece, such as burning, metallurgical phase transformations, softening (tempering) of the surface layer with possible rehardening, unfavorable residual tensile stresses, cracks, and reduced fatigue strength [9,10]. Thermal damage is one of the main factors which affects workpiece quality and limits the production rates which can be achieved by grinding, so it is especially important to understand the underlying factors which affect the grinding temperatures.

B. Thermal Damage

Excessive grinding temperatures cause thermal damage to the workpiece. In this section, a few common types of thermal damage will be considered. By establishing a direct relationship between the heat transfer analysis of the previous section and some types of thermal damage, it becomes practically feasible to predict and control thermal damage by in-process monitoring of the grinding power.

1. Workpiece Burn

The most common type of thermal damage is workpiece burn. This phenomenon has been investigated mainly for grinding of plain carbon and alloy steels, although it is also a problem with other metallic materials [3,9]. Visible workpiece burn with steels is characterized by bluish temper colors on the workpiece, which are a consequence of oxide-layer formation [10,11]. Temper colors are usually removed by spark-out at the end of the grinding cycle, especially with cylindrical grinding, but this effect is cosmetic and the absence of temper colors on the ground surface does not necessarily mean that workpiece burn did not occur. From microhardness distributions in the subsurface of hardened steels, visible burn has been found to be accompanied by reaustenitization of the workpiece and rehardening due to the rapid cooling [10,12].

2. Tempering and Rehardening

Steels are usually ground in the hardened state. Transformations which may occur due to excessive grinding temperatures include tempering (softening) of the hard martensite phase, and also the formation of hard and brittle martensite (rehardening) if the temperature is high enough and persists long enough for reaustenitization to occur. Untempered martensite is formed by rapid cooling of the reaustenitized material mainly by heat conduction to the workpiece bulk after the grinding zone (heat source) passes [13,14]. Tempering commonly occurs near the workpiece surface during grinding of hardened steels, and it may be accompanied in severe cases by rehardening. The depth of the thermally affected layer may be reduced with faster workpiece velocities which results in shallower heat penetration and shorter heating times. The thermally affected layer produced during aggressive rough grinding may be subsequently removed by gentler finish grinding and spark-out at the end of the grinding cycle.

3. Residual Stresses

Grinding causes residual stresses in the vicinity of the finished surface, which can significantly affect the mechanical behavior of the material Residual stresses are induced by non-uniform plastic deformation near the workpiece surface [3,10,15-21]. Mechanical interactions of abrasive grains with the workpiece result in predominantly residual compressive stresses by localized plastic flow. Residual tensile stresses are caused mainly by thermally induced stresses and deformation associated with the grinding temperature and its gradient from the surface into the workpiece. Thermal expansion of hotter material closer to the surface is partially constrained by cooler subsurface material. This generates compressive thermal stresses near the surface which, if sufficiently big, cause plastic flow in compression. During subsequent cooling, after the grinding heat passes, cooling of the compressed material causes residual tensile stresses to develop. In order to ensure mechanical equilibrium, residual compressive stresses also arise deeper in the material, but these are much smaller in magnitude than the residual tensile stresses. The formation of thermally induced residual stresses is further complicated by any metallurgical transformations which may occur during the heating and cooling cycle, since these generally involve volumetric changes.

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C. Function of Cooling System

Functions of Cutting and Grinding Fluids Depending on the machining operation being performed, a cutting or grinding fluid has one or more of the following functions:

· Cooling the tool, workpiece, and chip

· Lubricating (reducing friction and minimizing erosion of tool)

· Controlling built-up edge on the tool

· Flushing away chips

· Protecting the workpiece tooling and machine from corrosion

The relative importance of each of these functions depends on the work material, the cutting or grinding tool, the machining conditions, and the finish required on the part. Grinding fluids perform several of the same functions as cutting fluids. Grinding fluids lubricate the grit/workpiece interface, thus reducing the generated heat and the power requirements for a given material removal rate.The primary difference between the functions of grinding and cutting fluids is that lubrication is more important in grinding than in cutting. In metal cutting, most of the heat generated during the cutting operation is carried away in the chip. Relatively less heat is generated in the workpiece and the tool. In the case of grinding, however, most of the heat is retained in the workpiece. Therefore, lubrication becomes more important for grinding fluids than for cutting fluids. Cutting Fluids. Two functions of cutting fluids include lubrication and cooling so that the frictional forces and temperature are reduced at the tool/workpiece interface. In high-speed cutting operations, the cooling provided by the cutting fluid is its most important function. At moderate cutting speeds both cooling and lubrication are important, but at low speeds, lubrication becomes the dominant function of a cutting fluid.

1. Cooling Effect

Cutting fluids reduce the temperature of the metal cutting operation by transferring heat away from the workpiece and the tool. Some of the factors involved in cooling are as follows:

· Cooling effects due to the application of the cutting fluid increase the shear strength of the material being cut, thus increasing the forces required for metal cutting. Generally, this effect is small for most metals

· The cooling effects of cutting fluids may be deleterious if the change in temperature caused in the cutting tool is abrupt and discontinuous. Abrupt changes in temperature may cause fracture and spalling of the tool; ceramic tooling is particularly sensitive in this regard

· The cooling from cutting fluids is generally related to their thermal properties. In general, cooling efficiency is less for an oil than for an emulsion and is greatest with a water solution. Frictional effects, however, may complicate this relationship because the lubricating properties influence the amount of heat generated

· Cooling efficiency can be reduced by the heat transfer characteristics of high-viscosity fluids. High cutting speeds can initially improve the cooling because the viscosity of the cutting fluid decreases with temperature, but beyond a certain temperature this beneficial effect on cooling is no longer present

· The effectiveness of cooling depends on the amount of surface wetting, fluid viscosity, chemical reactivity and molecular size, and the physical characteristics of fluid flow As Grinding operates at the high rotational speeds of the grinding wheels, the application of a fluid is extremely important to ensure fluid contact with the wheel and the workpiece. Furthermore, the relationship between the chemistry of the grinding wheel and that of the workpiece is also important. These interactions must be evaluated in choosing an appropriate cutting fluid for a specific grinding wheel material in a production situation. Generally, emulsions and waterbase solutions are the fluids of choice, with a wide array of esters, amides, sulfur compounds, and chlorine compounds successfully used in the fluid formulation. Oil-base solutions are chosen when lubrication of the wheel is the critical criterion. It is also important to use lubricants optimally. [22]. There are various author who give theoretical as well experimental Cooling System for optimal use to give required output. this paper is attempt to investigate the different cooling system's investigation and discussion have been made. Cooling system which have been used conventionally as well as new trends.

III. COOLANT AND LUBRICATION SYSTEM

A. Cryo- Grinding

S. Paul and A.B. Chattopadhay[23] have worked on study the effects of cryo-grinding by a liquid nitrogen jet particularly on the magnitude and nature of distribution of temperature and residual stresses at the ground surface of different steel specimens i.e. Mild steel, High Carbon Steel, Cold Die Steel, Hot die Steel and High Speed Steel[23]. For this they come up with experimental setup as shown in Fig.3

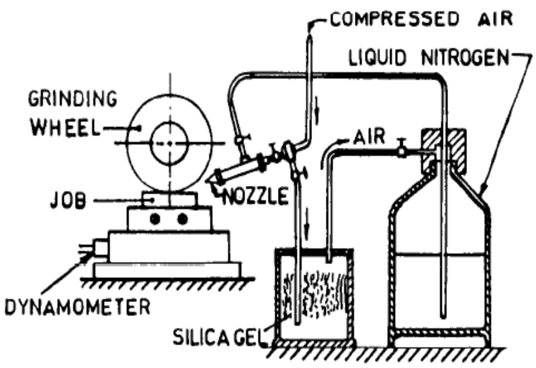

Fig. 3 Experimental Setup

The comparative study of cryo-cooling, dry cooling and flood cooling with soluble oil is done by the characteristics of chip formation and the mechanism of material removal in grinding under different conditions; the grinding chips were collected and studied under SEM. The grinding forces generated during cryo-cooling very reduced than the dry grinding and flood cooling with soluble oil. Cryo-cooling has been found to improve the surface quality by reducing the thermal damage to different degrees in different steels.

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The presence of sharp ridges and less plastic deformation also indicate that under cryo-cooling material removal takes place mostly by ideal shearing and ploughing and less by sliding and rubbing. Also the effect of cryo-cooling on residual stresses has been very pronounced in the case of HDS and HSS. As these steels possess high thermal stability and retain their mechanical properties at elevated temperatures, the reduced temperature generation. However Liquid nitrogen is relatively costlier than the conventional grinding fluids. Hence cryo-grinding for its economic viability should be employed for those critical components, which are severely and dynamically loaded in machines and failure of which leads to heavier consequential losses.

B. Grinding Wheel with Internal Coolant Supply

The internal coolant supply has been suggested as an ideal strategy. The coolant is delivered to the abrasive layer, directly into the contact zone where it is needed the most, thus providing advantages in particular at high contact lengths [24]. A variation of the internal cooling supply is the supply through gaps in the grinding wheel topography. These include engineered wheels with radial grooves in the grinding wheel body near the abrasive layer where the coolant is delivered into; the coolant is then transported through the radial grooves to the abrasive layer. Another simple form of this supply method are segmented grinding wheels, where the segments support an increased amount of coolant in the contact zone. The fig 2 below shows the Hydraulic design of a grinding wheel with an internal cooling lubricant supply [28]. The cooling channels inside the wheel are designed similar to those of centrifugal pumps. This ensures the coolant supply at high grinding wheel speeds. But it is found that the channels inside the grinding wheel with internal coolant supply diminish the formation of this lubrication gap. As a consequence of the comparably low amount of coolant delivered through each channel, in combination with the high circumferential speeds, air is sucked into the channels. This leads to the formation of an oil mist, resulting in a low pressure inside the channels.

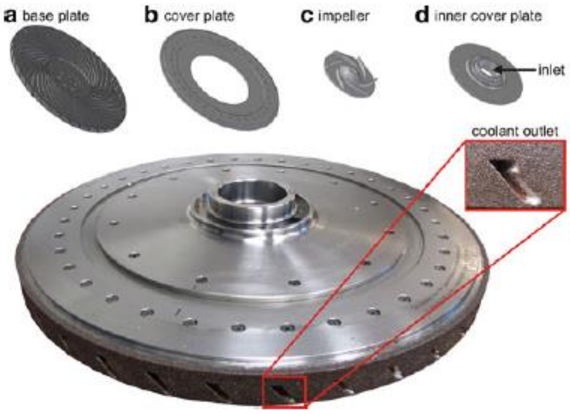

Fig 4. Grinding Wheel with Internal Cooling Lubricant Supply

The lower coolant pressures of the grinding wheel with internal coolant supply can result into film boiling at the outlets of the channels. An evaporation of the coolant results into a film between the workpiece and the outlets, hampering heat transfer and the ability of the coolant to enter the area between two outlets in the contact zone [24],[28]. To improve the cooling performance, two main requirements must be met:

- increasing the amount of coolant transported through the contact zone and simultaneously
- providing a high coolant pressure [24].

In 2013 Jan C. Aurich and Benjamin Kirsch[24] come with an idea of a slotted grinding wheel with optimized coolant supply where 70 slots were milled inside the wheel, shifted symmetrical alongside the centerline of the grinding wheel axis, slightly rotated by an inclination angle of 15º as shown in Fig. 5

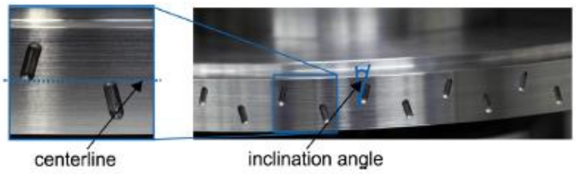

Fig. 5 Arrangement of the Slots

Also the performance of the slotted wheel was evaluated in comparison to the standard grinding wheel. The results of the internal/external dual mode using the grinding wheel with internal coolant supply will also be presented as reference. All wheels were operated using the same free jet nozzle (FJN) with identical parameters. It is found that the maximum pressure developed in the slotted wheel both tangential and normal forces were lower than those of the other setups (Refer Fig. 6) Also the Highly significant differences can be observed in the comparison of the alteration of the surface layers for the three setups. (Refer fig 6)

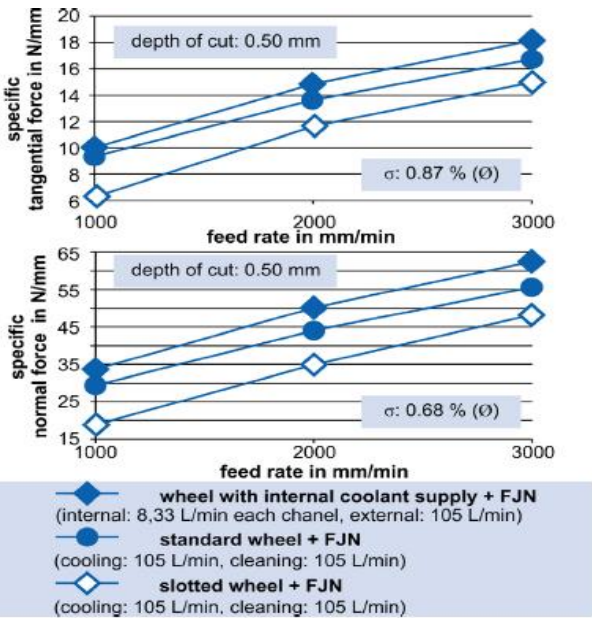

Fig 6 Specific Forces for the three Setups.

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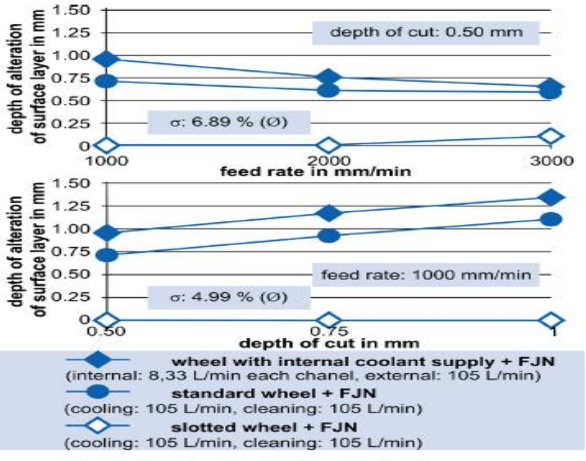

Fig. 7. Alteration of Surface Layer for the three Setups.

Therefore it can conclude that significant improvements of the cooling efficiency could be achieved by the use of the slotted wheel. This suitability can only be led back to a higher amount of coolant in the contact zone, not to a better bulk-cooling effect, as the same nozzle was used for all examined setups. The examined coolant pressures confirm that a higher contact zone flow rate due to the supply method itself (FJN) can be excluded. Hence, the superior cooling effect can only be explained by the additional coolant delivered through the slots of the wheel.

C. Minimum Quantity Lubrication (MQL)

New developments in grinding processes are also related to the concern for sustainable production. Nowadays, this is a matter of primary concern in the metal industry, and machining pro- cesses are not excluded from this new situation. Increased concern for the environment and sustainability are driving industry towards a new paradigm. Machine manufacturers and users bear the increasing pressure imposed by regulations on a global scale. Special attention is not only focused on energy consumption and waste disposal, but also on the costs generated by non-sustainable industrial practices, including social, environmental and economic efficiency cri- teria [27]. It is scientifically accepted that production must contribute to sustainable development as it is the main enabler thereof.

On the other hand, despite persistent attempts to completely eliminate cutting fluids, in many cases cooling is still essential to achieve a feasible tool service life and the required surface qualities of the machined part. This is particularly true when narrow tolerances and high dimensional precision and shape are required, or when uses machining critical materials that are difficult to cut. This makes MQL system an interesting alternative, because it combines the functionality of cooling with an extremely low consumption of fluids (usually < 100ml/h). These minimal amounts of oil are sufficient, in many cases, to reduce the tool's friction and preventing the adherence of material simultaneously [23]. Leonardo R. Silva et.al.[25] studied the new developed vegetable based cutting fluids (VBCFs) contain almost no harmful materials and are environmentally friendly, healthier for operators and having a higher rate of biodegradability (>95%). Here VBCF and Air mixture is used as lubricant in the grinding operation. The material used in these tests was the quenched and tempered ground AISI 4340 steel (0.4% C; 1.8% Ni; 0.8% Cr; 0.23% Mo; 0.68% Mn; 0.23% Si), with an average hardness value of 52 HRc, and external diameter and length of 36 and 42 mm. The tests were carried out using aluminum oxide (Al2O3) grinding wheels with the following characteristics: (355.6 × 50.8 × 127 – FE 38A60KV) manufactured by Norton.

(a) Original nozzle of the grinding machine. (b) Nozzle used in the MQL experimentation

Fig 8. Assembly of the Original Nozzle and the Nozzle used in Tests with MQL System.

For the assembly of the MQL system, a series of preliminary tests were carried out to determine the best lubricant and compressed air flow rate, as well as the best choice of the various types of lubricants using the MQL technology. A synthetic solution in 5% concentration was used in the flooded cooling condition. The maximum flow rate supplied by the pump and by the machine original nozzle was11 L/min. The equipment used to control the minimum quantity of lubricant (MQL) was the Accu-lube. The performance of the application of different cooling systems was evaluated based on analysis of the surface integrity (roughness, microstructure and microhardness).

a. Surface Roughness:

The analysis of of the results obtained with the conventional cutting fluid application system and with the MQL system indicates that the application of cutting fluid by MQL system led to satisfactory results when compared with conventional system. This phenomenon is associated with the more efficient penetration of the fluid into the cutting region.

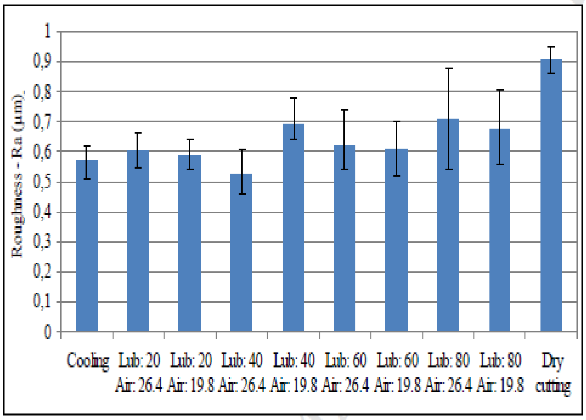

Fig.9. Roughness (Ra) After 5 Cycles of 1mm in Different Cooling Conditions with the Al2O3 Grinding Wheel (air: m/s; lubricant: mL/h) and Dry Cutting.

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In general, the MQL system led to lower roughness values, probably because of the more effective lubrication and the cooling of the abrasive grains at the workpiece-wheel interface.

b. Microstructure:

The microstructure of the samples was analyzed by Scanning Electron Microscopy (SEM) to verify possible damages caused on the surface of the material by means of thermal and mechanical requests to which they were submitted. Figure 7 shows the micrographs of the sample cross-sections; illustrating possible subsurface alterations that took place in the material when Al2O3 grinding wheel was used with conventional cooling, dry cutting, with the use of the MQL system and also part of the heat-treated sample. The superficial alterations produced by the various lubrication and cooling conditions were minimal, without significant differences between the conditions tested. Analyzing the microstructures, it can be noted that the quenched and tempered AISI 4340 steel shows martensite structure. The presence or not of this structure is a complex process, dependent on the heat treatments previously carried out and on the temperature heating and cooling time imposed by the cutting fluid.

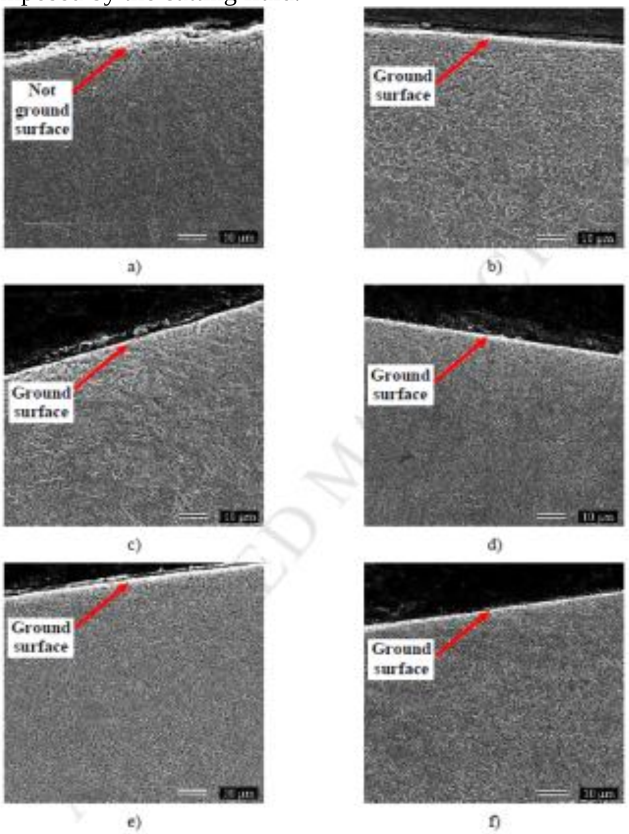

Figure 8. Subsurface Microstructures Obtained After 5 Cycles of 1mm in Different Cooling Conditions - 1,000x.

a) Heat treatment (not ground surface); b) dry cutting; c) conventional cooling; d) MQL system (lubricant: 40 mL/h; air: 26.4 m/s); e) MQL system (lubricant: 20 mL/h; air: 26.4 m/s) and f) MQL system (lubricant: 60 mL/h; air: 26.4 m/s).

c. Microhardness :

Fig.9 represents the variation in average microhardness as a function of cooling conditions. The results associated with dry cutting and heat treated material are also exhibited.

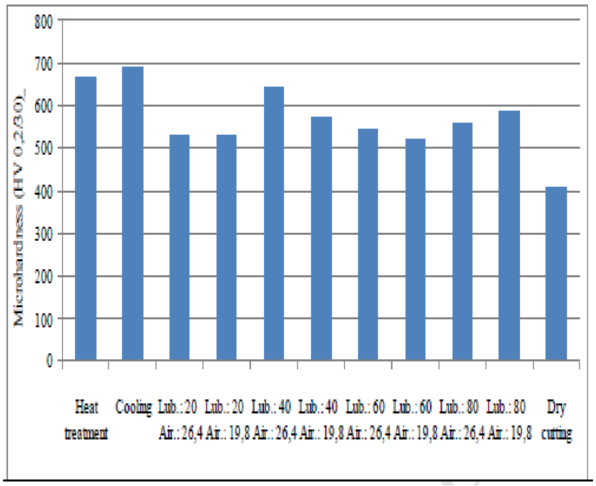

Figure 9. Variation of Microhardness at a Depth of 70 µm from the Surface in Different Cooling Conditions After 5 Cycles of 1 mm (lub.: ml/h and air.: m/s).

The results obtained in the microhardness measurement for different conditions of lubrication and cooling also showed no significant changes subsurface, except in dry cutting. These data confirm the observations made in analysis of microstructure, except in dry condition. The above points shows us The MQL system could be applied efficiently in the grinding process, providing environmentally friendly and technologically relevant gains in cutting conditions tested.

D. Hybrid MQL- CO_2 Cooling System

This system is also known as MCG system (Minimum Coolant Grinding). The system combines the application of lubricant in the form of micro-drops using the Minimum Quantity of Lubricant technology with the application of a CO2 flow at low temperature. The temperature of the gas is low enough to freeze the lubricant drops on the abrasive grits. The hypothesis behind is that only a thin film of oil is responsible for effective tribo-action, then the amount of oil can be greatly reduced if effective freezing is achieved [27]. Therefore, the aim is to create a durable tribofilm around the grits that improves sliding and lubrication under conditions of extreme pressure. The layer of frozen oil around each abrasive grain preserves them from excessive wear. Moreover, an ultra-efficient application of grind- ing oil results in friction reduction, leading to lower heat generation in the contact area [26]. R. Alberdi et.al. had worked on this system combining MQL and CO2 cooling. The schematics of the system is shoen in fig. 10.

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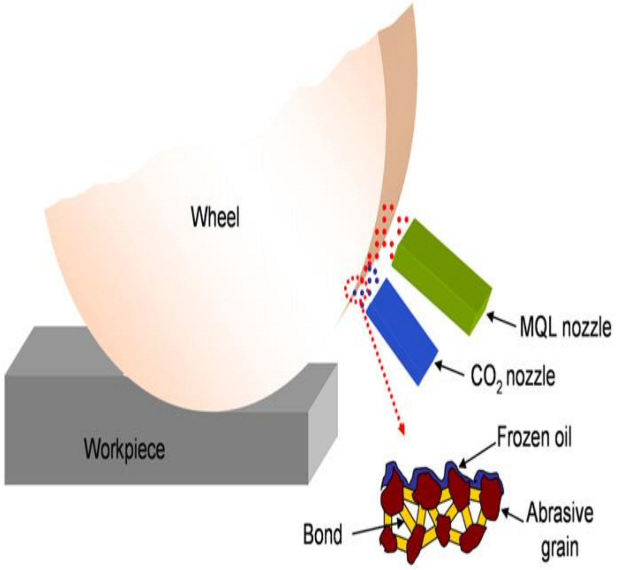
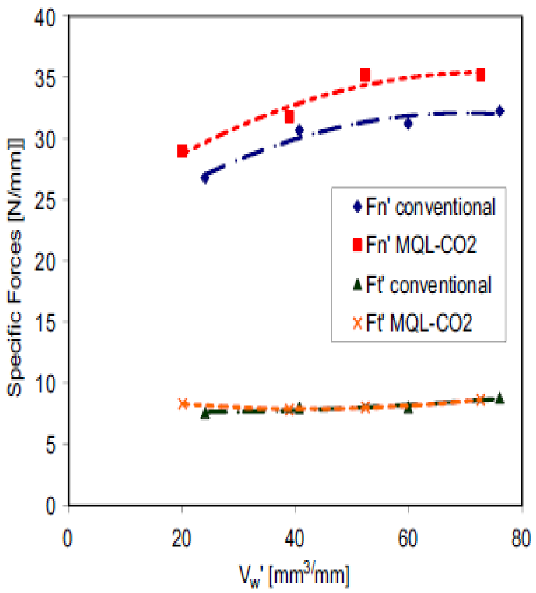


Fig. 10. Schematic of the System.

The lubricant is not directed to contact zone, but to the abrasive grits themselves in the form of oil droplets that are frozen bylow-temperatureCO_2. Therefore, the aim is to create a durable tribo film around the grits that improves sliding and lubrification under conditions of extreme pressure. The MQL is directly applied to the wheel surface, and immediately afterwards, a CO_2 jet at -35 ºC is responsible for freezing the oil on the abrasive grains. TheCO_2 jet is controlled by a Hoke 2315 F4Y regulating valve, and applied to the wheel surface using a 2mm diameter circular crosssection nozzle. The oil used for the MQL system is a Biocut 3000 Wellens and melting temperature -20 ºC. ThecombinedMQL-CO2 system was installed in a Danobat surface grinding machine, which is also equipped with a conventional flooding system, so that comparison tests between both technologies can be carried out. The results were discussed in terms of forces developed and surface quality of the workpiece, which is as below:



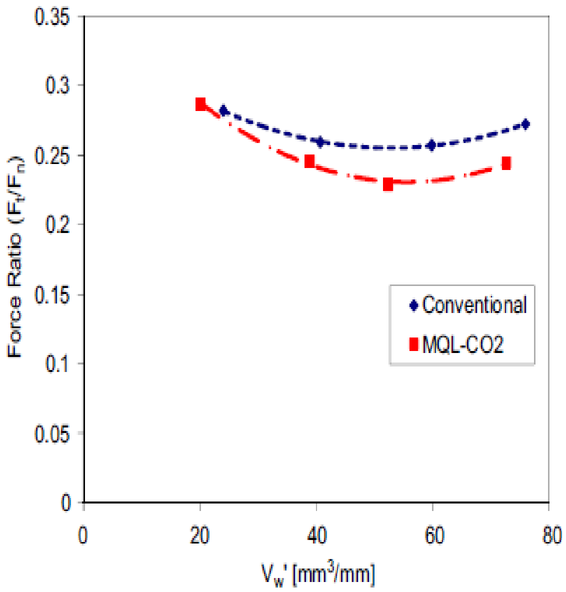


Fig. 11. Specific Normal (F’n) and Tangential(F’t) Grinding Forces (up) and Force Ratio (μ) (down) vs V’w During the Tests with the MQL-CO_2 and the Conventional Cooling Systems. Workpiece Speed Vw =30 m/min, Depth of cut =10 mm.

The above figure depicts that tangential force values are very similar for both systems. From the power view point, consumption in the spindle and the specific grinding energy, it can be deduced that the new technology is as efficient as conventional cooling under these conditions. However, an increase in the normal force of about 25% with respect to the normal force measured in the conventional system should be noticed. This is translated in to a reduction in the force ratio (average of 0.27 in the case of conventional flooding, 0.25 in the case of the MQL-CO_2 system). In other words, the MQL-CO_2 system exhibits improved friction conditions, thus confirming the effective presence of oil on the interface abrasive–workpiece.

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However ther is not a very conclusive big difference between results of conventional flood system and MQL-CO_2 system. In Ra there is no clear difference between both systems. But apparently the improvement becomes significant in terms of Rz

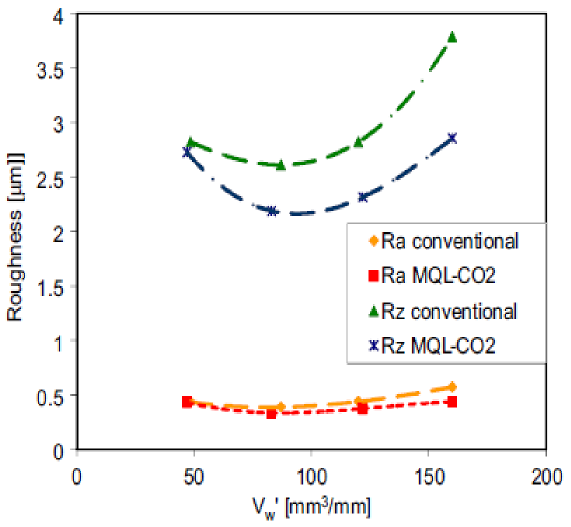

Fig. 12. Surface Roughness (Ra and Rz) with the Conventional and MQL-CO2 Systems. Workpiece Speed=20 m/min, Depth of cut=20 mm.

The above results clearly show that the MCL system is as good as conventional system in the performance. And when the economy of lubrication is considered it is more viable solution for reducing the use of lubricant and coolant.

IV. CONCLUSION

High heat evolved during grinding process causes the thermal deformation, residual stresses, micro crack etc. generated on ground surfaces which affects the productivity of the process. Therefore to overcome these defects the proper cooling and lubrication system has to adopt. Also optimally adopt the lubricating system as per the machining requirement but however coolants show adverse effect on environment also it very expensive. It is necessary to use different coolant reducing strategies like MQL.

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