Machining evaluation of a hybrid MQL-CO2 grinding technology

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A B S T R A C T

Although there are already successful industrial experiences in other machining industries with the elimination of coolants, this is not so in the grinding industry due to the large amounts of generated heat that must be evacuated from the contact zone. In this work, a new approach to the elimination of fluids in grinding is presented. The technology is based on the use of a hybrid Minimum Quantity of Lubricant (MQL)-low temperature CO2 system that reduces lubrication consumption. Abrasive grits are protected by the layer of frozen oil, resulting in a significant improvement in grinding wheel life and surface quality of the machined component. Although the cooling action is reduced with respect to the conventional coolant, no thermal damage was observed on the workpiece.

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1. Introduction

New approaches to traditional problems in manufacturing to meet demands of consumers must contribute to a more sustainable production at global level. The new paradigm of sustainable production must include social, environmental and economic efficiency criteria (Pusavec et al., 2010a,b). It is scientifically accepted that production must contribute to sustainable development since it is the main enabler thereof (Jovane et al., 2008; Pusavec et al., 2010a,b). In this context, the increasing pressure imposed by laws and regulations likewise efforts at political levels to support the development of sustainable technologies within the EU, and also on a global scale, it has become a must-consider input for both machine manufacturers and users (Jegatheesan et al., 2009).

High added value sectors such as aeronautics, energy generation, high-speed railways, etc. are customers of high-performance machining processes. Customers from these sectors demand the manufacturing of parts in hard materials with very tight tolerances and superior surface finish. Demands come not only from precision. Fatigue life of the component is also a critical criterion in many cases. In this context, the grinding process is an excellent alternative to processes such as turning or milling. Grinding can produce very precise products with enhanced fatigue behaviour in difficult-to-machine materials.

Coolants and lubricants are usually employed in machining operations, including turning, milling, drilling and of course, grinding. However, the increased concern for environment and sustainability are pushing industry towards a new paradigm where eco-efficiency appears as the new keyword: special attention is not only focused on energy consumption and waste disposal (see ISO 14000), but also the costs generated by non-sustainable industrial practices must be questioned. No doubt, coolants and lubricants improve machining performance in many cases, however, a new point of view arises when considering the costs and risks associated with their use. In Fig. 1 the distribution of costs related to the use of cooling fluids in machining in the automotive industry is shown. In this example, it can be noted coolant costs are significantly higher than tooling costs.

Technologies for reducing the consumption of coolants and lubricants are available in conventional machining processes, involving the use of Minimum Quantity of Lubricant (MQL) or even dry machining. A large number of research works, together with industrial practice can be found in the fields of drilling, turning, or even different milling applications (Fratila, 2009). However, this is not the case of the grinding processes. In grinding, very high temperatures are reached. To avoid thermal damage, it is essential that large amounts of the heat generated be evacuated, otherwise there may be thermal damage of the workpiece, accelerated grinding wheel wear and thermally induced deformations, resulting in poor quality of the ground components.

By way of example to illustrate the current situation of grinding operations; in the grinding of turbine blades for the aerospace
industry a coolant flow of 750 l/min is required to grind with a wheel of 200 mm width. The cooling fluid must be clean and in good conditions, therefore filtering systems are compulsory nowadays. Those systems are expensive and may occupy considerable workshop space, as much as 120% of the machine space. Fig. 2 shows a Danobat FG-600-S together with the grinding fluid filtering system.

In this paper the existing alternatives to the use of conventional flooding systems are presented, together with their main advantages and limitations. Then, a proposal for a new hybrid MQL-CO2 grinding technology is described, and applied to surface grinding. Finally, the machining performance of the new technology is evaluated.

2. Sustainable grinding technologies

From the previous section it is clear that the use of MQL or dry cutting grinding techniques is not as extended as in the case of other metal removal processes. This fact explains that industrial and academic research efforts are currently being directed towards the development of grinding techniques enabling elimination, or at least, minimization of grinding fluid use while maintaining process efficiency. Grinding machine manufacturers are specially concerned with this topic, since the entire process cost (grinding wheel wear, waste disposal, etc.), including the cost and space occupied by the machine can be drastically reduced. In the following paragraphs, interesting research experiences in the field of grinding fluid minimization are presented.

Dry grinding still presents important limitations to be applied in industrial practice. Total elimination of the cutting fluid results in higher temperatures during the process, affecting surface integrity and geometrical precision of the ground part in addition to increasing grinding wheel wear and clogging (Klocke and Eisenblätter, 1997; Malkin and Guo, 2008; Marinescu et al., 2007; Ebbrell et al., 2000). However, in recent years special attention has been paid to this technology because of its potential benefits and the possibilities for direct measurement of process variables it offers. Thus, Tawakoli and Westkaemper (2007) researched the capabilities of dry grinding and showed that under special conditions heat generation can be largely reduced. They also analysed the possibility of aiding soft steel grinding with ultrasonic vibrations (Tawakoli and Azarhoushang, 2008). Klocke and Bücker (1996) presented results on external cylindrical dry grinding of 100Cr6V. Brinksmeier et al. (1997) reported research work on surface grinding of 16MnCr5 and 42CrMo4. More recently, Aurich et al. (2008) presented a novel approach to the problem based on the development of a superabrasive electroplated grinding wheel with a defined grain pattern for dry surface grinding. Since complete
elimination of grinding fluids is still limited by important problems, an eye must be kept on the development of alternative coolants with minimum environmental impact, like those reported by Herrmann et al. (2007).

A promising alternative to dry grinding can be found in MQL techniques and cryogenic cooling. In the case of MQL grinding, droplets of an air and oil mix are supplied to the working area (Klocke et al., 2000). Oil consumption and therefore lubricant-associated costs are drastically reduced. Literature works report that under certain conditions oil droplets reach the abrasive grains improving lubrication in the contact zone resulting in a prolongation of grinding wheel life and a better surface quality of the workpiece. da Silva et al. (2007) focused their attention on the evaluation of grinding wheel life and a better surface quality of the workpiece. da Silva et al. (2007) focused their attention on the surface integrity of surface ground ABNT 4340 steel parts. Tawakoli et al. (2009) studied the optimal application of the MQL system taking into account the workpiece material hardness. Reductions in grinding power and improvements in wheel wear in MQL-internal cylindrical grinding have also been reported by Hafnbræd and Malkin (2001).

Together with the reduction of lubricant, research experiences have opened the way to the application of cryogenic conditions to the grinding process. Paul and Chattopadhyay (1996) reported that cryogenic grinding using a jet of liquid nitrogen could reduce heat transfer into the workpiece specially at high speed and with ductile part materials. Results by Ben Friedj et al. (2006) seem to confirm this fact, since improvements in surface integrity in terms of better surface roughness, higher level of work hardening, lower level of tensile residual stresses and better resistance to corrosion were noticed in the cryogenic grinding of AISI 304 austenitic stainless steel. However, a recent work by Nguyen et al. (2007) on the use of liquid nitrogen for grind-hardening observes that the penetration of cold gas into the contact zone is very limited due to a very high evaporation rate, which is also increased by the turbulent airflow produced by wheel rotational speed. As a consequence, the effect of heat dissipation is only present in the proximity of the contact zone. Although heat dissipation due to cryogenic temperatures may not be as relevant, cryo-temperatures may favour material removal by shearing and limit the ground surface damage specially in ductile materials.

A real industrial application can somehow be useful to evaluate the economic impact of using conventional grinding fluids on the overall costs of the grinding operation. Engine valve finishing is a very common application of grinding for the automotive sector. Of course, one can find other industrial case-studies with higher impact (for instance, the grinding of turbine blades), but also with lower impact (cylindrical grinding of inner parts). Therefore, the selected process can be taken as representative of an average situation affecting SMEs facing strong cost and quality competition.

The example refers to valve stem grinding. The preliminary tests were performed on a grinding machine ESTARTA 327 MDA that uses a filtering equipment MONET with a capacity of 501/min and an average filtration mesh of 0.02 mm. In this example, the expected reduction in the space occupied by the filtration system is as high as 30%. Grinding was carried out under the conditions listed below:

- Valve Material: XS3CrMnNi219
- Grinding wheel: NORTON SG-120 PVX
- Regulating Wheel: MANHATTAN 80 ARL
- Plunge speed \((v_p)\): 25 mm/min
- Radius to be machined: 0.5 mm
- Coolant type: emulsion at 5%
- Coolant flow: 50 l/min

A total of 20 workpieces were machined in the study. The power consumed in the grinding process was 6.6 kW for the first workpiece, increasing to 8.6 kW for the last one due to wheel wear. The power consumed by the cooling pump and cooling equipment was 3.3 kW per workpiece. Therefore, in this case as much as 38.37% of energy consumption can be attributed to the use of conventional grinding fluids, with the corresponding impact of the operation on the total cost and environment.

In view of the above comments, it can be concluded that potential economic and environmental benefits could be obtained from the reduction/elimination of conventional fluids in grinding operations. In order to do so, a new approach to the problem of refrigeration and lubrication in the grinding process is presented in this paper. The objective is to significantly reduce the consumption/flow of oil-based cooling lubricants while maintaining process performance in surface grinding. As a result, coolant-related costs and space required for the filtering system can be drastically reduced. A combined MQL-low temperature CO\(_2\) system is proposed as an efficient alternative to traditional cooling/lubrication systems in grinding. Recent work by Pusavec et al. (2010a,b) suggests that since the cryogenic nitrogen costs are dramatically higher per same amount than conventional emulsion, the use of this alternative may lead to much higher costs in comparison to conventional emulsion usage. Even so, factors such as space occupied by the filtering system, cost of the filtering system itself, energy consumption in the pump (see the example above) and grinding wheel consumption must also be considered. This means that with the new process (which is still under extensive research) a window of applications in which technical and economical advantages may be gained is possible. Current research work of our group has set the objective of achieving 25% reduction in cost associated with the grinding process of each workpiece, due to respective reductions in energetic cost, lubricant and coolant cost, cutting fluid recycling cost, required floor space and grinding wheel consumption.

The proposal of the new system is original in that the cooling action is not directed towards the contact zone, but to the abrasive grains themselves. The objective is to protect abrasive grains from wear, rather than cooling the contact zone. At the same time, to reduce the risk of too a high heat flow into the workpiece due to efficient refrigeration, heat production within the contact zone is minimised by using the MQL oil system. This is due to a reduction of friction. Literature by Malkin and Guo (2008) and other authors shows that lower temperatures are related to compressive residual stresses on the workpiece surface/sub-surface. The system and experimental procedure are described in Section 3. Results of comparison of performance for a surface grinding application between a conventional flood cooling with soluble oil system and the new system in terms of grinding wheel wear, surface finish, grinding forces and force ratio are presented and discussed in Section 4. The cooling action of the new system is expected to be poor. Therefore, the possibility of thermal damage on the ground part is discussed in Section 5. Finally conclusions are drawn, confirming the excellent performance of the new approach.

### 3. Experimental procedure

The combined MQL-low temperature CO\(_2\) system was installed in a Danobat surface grinding machine, together with the conventional flooding system to carry out the comparison tests. The objective of the MQL-CO\(_2\) system is to fix the oil droplets on the surface of the abrasive grains. In other words, to create a durable tribofilm around the grits that improves sliding and lubrication under extreme pressure conditions. The oil used for such purpose is Biocut 3000, with a biodegradability index over 90% in the test of Zahn-Wellens and melting temperature \(-253\) K. As shown in Fig. 3, first the MQL is applied directly onto the grinding wheel surface,
and immediately afterwards, a CO₂ jet at 238 K is responsible for freezing the oil on the abrasive grains.

The MQL system is a LubriLean Basic with oil consumption of 0.06 l/min, using two coaxial nozzles that spray the oil in aerosol form with droplets between 15 and 35 μm diameter. At the same time, the CO₂ jet is controlled by a Hoke 2315 F4Y regulating valve, and applied to the grinding wheel surface using a 2 mm diameter circular cross section nozzle. A photograph of the surface of the wheel at 200× (see Fig. 4) shows that the layer of frozen oil has been effectively achieved.

During the set-up tests it was observed that the frozen oil layer thickness is a parameter that must be controlled, since too thick a layer is responsible for the occurrence of a sudden increase in the normal force at the entrance of the wheel in the workpiece. Grinding forces were measured under industrial conditions using a Kistler 9257B force measuring device (piezoelectric technology). Fig. 5 (left) shows a peak followed by a reduction in the normal grinding force. Grinding parameters for this test are listed in Table 1. Together with this reduction, an increase in the tangential component is observed. This effect is attributed to a minimization of the abrasive action at the beginning of the operation due to the excessive presence of frozen oil in the contact. Sliding between grinding wheel and workpiece occurs until the thickness of the frozen oil layer is low enough to permit the abrasive action of the grits (moment when the normal component decreases and the tangential increases) but at the same time, oil is still present to reduce friction in the interaction grit-part. This latter statement is confirmed by the results presented in Section 4.

To control layer thickness, additional tests were carried out varying the flow of CO₂ on the grinding wheel surface from a maximum value of 430 l/min down to a minimum of 40 l/min. The minimum value is the one which ensures that the frozen layer is effectively built on the wheel surface. Through testing it was found that stable operation without increase of the normal component at the entrance was obtained for the minimum value of CO₂ flow (this is, 40 l/min), as shown in Fig. 5 (up-right).

Together with the new MQL-CO₂ system, a conventional flooding system using a water-based emulsion (Rhenus TY100 at a concentration of 5% in water) was installed, so comparison
between the new proposal and the conventional system can be directly carried out. The fluid is delivered by a high pressure pump (20 bar) at 40 l/min, and uses a filtering deposit of 300 l of capacity.

4. Analysis of the process performance

Surface grinding experiments in an industrial environment were carried out, aiming at performance comparison of the new system with the traditional water-based emulsion in terms of grinding wheel wear, grinding forces, surface roughness and temperatures in the workpiece. The workpiece material in the industrial tests was AISI D2 tool steel which is commonly used for the manufacture of metal forming tools. An alumina grinding wheel of 400 mm diameter with specification CBL46I6V489 was used in all the grinding experiments. Grinding wheel speed was 35 m/s. In these experiments the depth of cut was varied from 0.015 mm to 0.03 mm and the workpiece speed was varied from 1 m/min to 30 m/min.

Grinding wheel life is commonly evaluated in terms of the so-called grinding ratio \( G \), which is the ratio between the volume of part material removed (ground) and the volume of grinding wheel lost (worn). Radial wear of the wheel complements the grinding ratio to evaluate wheel wear. Tests were carried out with different grinding condition severities, i.e., varying the part material removal rate \( Q_w \), measured in mm\(^3\)/s while keeping the geometric contact length \( l_g \), measured in mm) constant. For a given grinding wheel speed, a higher contact length involves a longer duration of the contact grit—workpiece. In other words, if contact length is kept constant, variations in grinding wheel wear can only be attributed to different friction conditions between wheel and workpiece.

Fig. 6 shows the evolution of radial wear as a function of volume of part material ground for different values of the material removal rate. A first look at the results reveals an impressive increase in grinding wheel life in the case of the new ecological system with respect to the conventional flooding alternative. Not only is radial wear lower in every single case for the new system, but also, it is even lower in the case of the MQL-CO₂ system when using the most aggressive grinding parameters \( Q_w = 100 \text{ mm}^3/\text{s} \) than in the case of the conventional system using the less efficient (from a productive point of view) grinding variables \( Q_w = 6.7 \text{ mm}^3/\text{s} \).

Results in terms of grinding ratio are also favorable to the new system. As expected, \( G \) decreases with an increase in the severity of the operation (when the volume of part material removed per second increases, more intense grinding wheel wear is expected). However, it can be noticed that the grinding ratio in the case of the MQL-CO₂ system with the most aggressive conditions \( G = 4.5 \) is still higher than that of the conventional flooding system \( G = 4.22 \) with the less aggressive conditions. Therefore, all the results of grinding wheel wear confirm the hypothesis that the abrasive grits are effectively protected by the layer of frozen oil.

The surface finish of the parts ground using both systems was also researched. It is well known that when using oil instead of water emulsions in conventional flooding systems the surface quality of the parts is clearly better since friction conditions between grinding wheel and workpiece are improved. In the case of the MQL-CO₂ system, it has been shown that frozen oil protects the integrity of the abrasive grits, and therefore it may be expected that oil is also present in the interface between grit and workpiece material.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Parameters of the test which results are shown in Fig. 5.</th>
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<tbody>
<tr>
<td>( a_e ) [mm]</td>
<td>0.02</td>
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<tr>
<td>( v_w ) [m/min]</td>
<td>15</td>
</tr>
<tr>
<td>( v_s ) [m/s]</td>
<td>35</td>
</tr>
<tr>
<td>( b_s ) [mm]</td>
<td>10</td>
</tr>
<tr>
<td>( \text{CO}_2 ) flow [l/min]</td>
<td>40–430</td>
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material removal rate is increased from 50 mm$^3$/s up to 100 mm$^3$/s. With this approach increasing workpiece speed can be noticed. In terms of average cutting speed from 20 m/min (left) to 30 m/min (right). With this approach the speed from 20 m/min (left) to 30 m/min (right).

In Fig. 6, the grinding wheel wear vs total volume of part material removed with the conventional and new ecological systems. Up: $Q_w = 6.7$ mm$^3$/s ($a_v = 0.04$ mm; $V_w = 1$ m/min; $v_s = 35$ m/s); center: $Q_w = 50$ mm$^3$/s ($a_v = 0.015$ mm; $V_w = 20$ m/min; $v_s = 35$ m/s); down: $Q_w = 100$ mm$^3$/s ($a_v = 0.02$ mm; $V_w = 30$ m/min; $v_s = 35$ m/s). Data related to grinding ratio $G$ in all the tests have also been included.

Surface finish was measured using a Mitutoyo SJ-301 roughness measuring instrument, and both $R_a$ and $R_z$ parameters were quantified (see Fig. 7). Results confirm that surface quality when using the new MQL-CO$_2$ system is slightly better than that obtained when using the conventional emulsion. The tests were carried out with a similar depth of cut ($0.015$–$0.02$ mm) but varying the workpiece speed from 20 m/min (left) to 30 m/min (right). With this approach the contact length is kept constant in both cases, although the material removal rate is increased from 50 mm$^3$/s up to 100 mm$^3$/s.

The general trend of an increase in surface roughness when increasing workpiece speed can be noticed. In terms of average roughness $R_a$, there does not seem to be a large difference between both systems. However, the definition of $R_a$ involves some filtering of the surface peaks and valleys. When taking a look at $R_z$, the difference becomes more apparent between the new and conventional cooling methods. Again, the results confirm that the oil effectively reaches the contact zone. Both $R_a$ and $R_z$ show lower values at the beginning of the tests, the trend again being more marked in the case of $R_z$. Probably, as the experiment progresses the temperature on the contact zone increases slightly and part of the frozen oil is lost. In other words, the amount of oil present at the beginning of the tests is higher resulting in an improved surface finish, and although frozen oil is partially lost, there is still enough lubricating action to protect the grits and produce better surface quality. A similar trend is observed in the case of the conventional cooling system, although the effect is less noticeable. The decrease in surface roughness at the end of the tests can be attributed to the appearance of wear flats on the surface of the abrasive grits as the test progresses, which is accompanied by a loss of cutting action and an increase in sliding between grinding wheel and workpiece.

Finally the evolution of grinding forces and force ratio during the tests with the new system was studied. During the grinding tests force signals are acquired and collected using a NI USB-6259 signal acquisition card and a LabView software. The force ratio $F$ is a commonly used variable in grinding. It provides a measure of the lubrication conditions between wheel and workpiece, and it is obtained as the ratio $F_1/F_2$.

Fig. 8 shows that the level of the grinding forces is similar in both cases. Since power consumption is directly related to the tangential force $F_t$, it can be stated that the new system does not introduce new power requirements in the machine spindle. However, the normal force $F_n$ tends to be higher in the new system, and as a result, the force ratio is 28% lower when using the MQL-CO$_2$ lubricating technology. Again, this is confirmation of the fact that oil is present and friction conditions are improved in the grit–workpiece interface.

In view of the above results it can be observed that the new system is competitive in terms of process performance, since it ensures the presence of lubricating oil in the interface wheel–workpiece, resulting in longer wheel life (reduced wear and increased grinding ratio), better surface finish and similar power consumption than in the case of the conventional flooding system. All these advantages are obtained with minimum oil consumption, which was the primary requirement of the development. However, the cooling action of the MQL-CO$_2$ technology has yet to be analysed. It has been shown that the lubricating action is optimal, however oil-based systems are traditionally poorer than water-based fluids in the cooling of the ground surface. Unacceptable thermal damage may occur on the workpiece as a consequence. In the next Section, an analysis of the extent of thermal damage produced on the component when applying the MQL-CO$_2$ technology is presented.

5. Thermal analysis of the process

The quality of a ground component is not only related to its surface finish or its dimensional accuracy, but also to its surface integrity. It must be considered that, should the heat produced during grinding not be effectively removed from the ground part, surface integrity may be negatively affected in the form of metallurgical transformations, oxidation, etc. leading to the appearance of tensile residual stresses and reduced fatigue life. Therefore, measures directed towards the reduction and effective evacuation of the heat generated during grinding are very commonly taken. No doubt, the delivery of efficient cooling fluids at very high pressures and flowrates is the most popular technique in industry.
In the new MQL-CO₂ system proposed here the cooling action of the water-based emulsion is not available. As a consequence it could be expected that, thermal damage of the ground component may be so high as to invalidate the new technology. In this Section an analysis of the thermal damage resulting from the application of the MQL-CO₂ system is presented. To do so, sub-surface temperatures are measured in the workpiece during grinding. Metallurgical analysis of the work material is also presented, so that in the case of thermal damage appearing its extent can be determined.

Measuring temperatures during the grinding process is a difficult task. A look at previously published work gives different solutions to the problem. A complete revision of the different experimental techniques available for temperature measurement in grinding can be found in the works of Davies et al. (2007) and Batako et al. 2005. The first experimental measurement of grinding zone temperature using thermocouples was introduced by Peklenik (1958). Workpiece—wheel thermocouples have been used, but the high impedance of the grinding wheel introduces important distortions in the measurement. Infra-red thermography is also commonly used. Infra-red thermography shows important limitations such as the difficulties in estimating good values of material emissivity (dependent on aspects such as surface roughness, temperature itself, etc.) and the fact the grinding tests must be carried out without fluid, which is far from actual industrial conditions.

The alternative is the use of contact thermocouples, which provide a simple robust economical method for temperature measurement. In this work commercial K-type thermocouples of low diameter (0.5 mm) were used. Thanks to their low diameter, thermal inertia is very low which enables a high sampling frequency as well as minimising the effect of temperature averaging. One of the most important problems when using thermocouples is the uncertainty in the positioning with respect to the ground surface. The distance between the contact workpiece—thermocouple and surface of the workpiece must be accurately known. Also, the sensor must be firmly held to the workpiece, otherwise contact may get lost and therefore, no temperature would be registered.

The problems that arise when trying to correctly place thermocouples inside a very hard material, such as tool steel with hardness of approx. 64HRC, are therefore evident. In this work commercial K-type thermocouples of low diameter (0.5 mm) were used. Thanks to their low diameter, thermal inertia is very low which enables a high sampling frequency as well as minimising the effect of temperature averaging. One of the most important problems when using thermocouples is the uncertainty in the positioning with respect to the ground surface. The distance between the contact workpiece—thermocouple and surface of the workpiece must be accurately known. Also, the sensor must be firmly held to the workpiece, otherwise contact may get lost and therefore, no temperature would be registered.

The problems that arise when trying to correctly place thermocouples inside a very hard material, such as tool steel with hardness of approx. 64HRC, are therefore evident. In this work a new method for thermocouple location is presented. The workpiece is first cut into 2 halves using wire electrical discharge machining (WEDM), and then precision beds are machined on each of the parts using sinking electrical discharge machining. At this stage thermocouples can be placed on the locations, and then the two halves are glued together using an industrial product. Using this method the uncertainty in the contact location is kept below 5 μm which is a very good value. It can also be ensured that the sensor does not lose contact with the workpiece. Fig. 9 shows one of the halves of the workpiece, and a detail of the contact workpiece—thermocouple.
Again, grinding tests with different parameters were carried out to compare the temperatures reached inside the workpiece during the process using the new MQL-CO₂ and the conventional water-based coolant. Aggressive grinding conditions enabling the possibility of thermal damage were set for the tests, involving the use of low workpiece speeds. In the grinding charts the limitation of grinding burn is related to low workpiece speed. If no thermal damage is observed when using \( v_w = 2 \) m/min, it can be expected that when using higher values of \( v_w \) the part will be also free of burn. The geometrical contact length, that defines the theoretical area of contact through which the heat is dissipated towards the workpiece was kept constant, so that the results from different tests can be properly compared.

Taking into account the dispersion accepted in the measurements provided by thermocouples, it can be seen that the surface temperature in the case of the water-based fluid is within the 673–723 K range, whereas in the case of the new system the maximum workpiece surface temperature ranges from 723 to 773 K. At a depth of 100 mm below the surface temperature decreases to 503–603 K in the first case, and 543–643 K with the new technology. These results show that even though the water-cooling action is not available in the case of the MQL-CO₂ system, surface and sub-surface workpiece temperatures are only slightly higher than those measured in the case of the conventional flooding system.

It has been largely advocated by Malkin and Guo (2007) that conventional cooling is largely inefficient in shallow-cut grinding, characterized by small contact lengths. This is probably the primary reason for the similarity in thermal properties of conventional and MQL-CO₂ cooling lubrication. A further effect can be observed. Normal forces are higher in the MQL-CO₂ system (see Section 3, Fig. 8). Consequently, deformations in the contact wheel–workpiece will also be higher, leading to an increase in the actual contact length with respect to the conventional cooling system. A longer contact length means a larger contact surface, and therefore, for the same amount of power consumption the heat density towards the component is lower.

Numerical simulation of the heat flow into the workpiece illustrates the above-explained fact. Fig. 11 represents the temperatures (obtained by numerical simulation) reached at a given point

![Fig. 9. Left: one half (cut by WEDM) of the workpiece for the grinding tests. Locations for thermocouples at different depths from the surface can be observed. Right: detail of the contact that can be achieved with a repeatability of 5 \( \mu \)m.](image)

![Fig. 10. Temperatures inside the workpiece as a function of depth from the ground surface. Left: water-based conventional cooling. Right: new MQL-CO₂ system. Tests carried out with workpiece speed \( v_w = 2 \) m/min, depth of cut \( a_w = 0.03 \) mm, grinding wheel tangential speed \( v_s = 35 \) m/s.](image)

![Fig. 11. Simulation of temperatures reached at a given point of the workpiece in two cases: results with a value of geometric contact length of \( l_g = 2.64 \) mm and a value of actual contact length of \( L_c = 3.86 \) mm (\( a_w = 0.03 \) mm, \( v_w = 2 \) m/min, \( v_s = 35 \) m/s).](image)
of the workpiece, as the grinding wheel is moved from left to right. In the two curves represented, the grinding parameters (type and diameter of wheel, workpiece material, depth of cut, wheel speed and workpiece speed, coolant delivery system) have been kept constant, although the actual contact length has been varied. The symbol \( l_c \) was used to make it clear the actual contact length is different (in fact, higher) from the geometric contact length \( l_g \), due to the deformations introduced by normal forces in the contact wheel–workpiece. Simulation shows that a higher contact length also results in lower temperatures in the ground component, confirming thus the benefits in the cooling action provided by an increase in \( F_n \) as that produced by the MQL-CO\(_2\) system.

Results for the temperatures in the workpiece have been given, nevertheless the possibility of thermal damage produced by those temperatures in the integrity of the component must be discussed. Based on the work from Marinescu et al. (2004), the grinding temperatures should be maintained below the softening temperature, above which the onset of tensile residual stresses tends to occur. For the work material used in the tests (AISI D2 tool steel) over 823 K only a minimal loss in hardness is observed (Dumitrescu et al., 2006). Therefore, after these considerations and in view of the results plotted in Fig. 10, the ground specimens should not be affected by the amount of heat generated.

Metallurgical analysis of the ground part confirms this hypothesis. Samples were polished and prepared for study in the microscope and for measurement of microhardness on a cross section with respect to the ground surface. Fig. 12 shows the structure of the tool steel at 200\(\times\) after having been ground using the MQL-CO\(_2\) technology (left) and after conventional grinding (right). Visual observation reveals a similar structure in the base material and sub-surface of the sample. Table 2 collects the values obtained for the microhardness at different depths from the ground surface. It can be seen that, with respect to the unaffected material, a slight increase in the hardness can be noticed. From the data given by the steel manufacturer, a slight increase in hardness with respect to the base material occurs until a temperature of 790 K is reached, temperature above which a dramatic reduction in hardness is observed. Therefore, from the results of microhardness gathered in Table 2 it can be stated that the MQL-CO\(_2\) technology does not induce thermal damage in the material.

### 6. Conclusions

From the work carried out the following conclusions can be drawn:

- A new grinding technology has been presented. The system involves the use of two nozzles: first, oil is supplied as MQL, and then a flow of CO\(_2\) at 238 K is in charge of fixing the frozen oil on the surface of the abrasive grits, protecting them from wear and improving sliding conditions, resulting in a better surface quality of the component.
- It is of primary importance to control the thickness of the frozen oil layer. If too thick a frozen layer is generated, an impact at the entrance of the grinding wheel in the operation may occur, increasing grinding forces and leading to problems in the process. Supply parameters have been optimized, and it has been found that the problem can be suppressed by setting the flow of CO\(_2\) at 40 l/min.
- The performance of the new system was evaluated in surface grinding on AISI D2 tool steel. Experiments show that grinding wheel wear with the MQL-CO\(_2\) system, even under the most aggressive conditions \((G = 4.5)\), is lower than with conventional coolant under the lightest grinding conditions \((G = 4.22)\).
- Sliding conditions are also improved as shown by surface finish and force ratio, which is 28% lower in the case of the MQL-CO\(_2\) system.
- Results show that even though the water-cooling action is not available in the case of the MQL-CO\(_2\) system, workpiece temperatures are only slightly higher than those in the conventional system. In both cases the temperatures are below that responsible for thermal damage of the material (833 K).
- The primary reason for the similarity in thermal properties of conventional and MQL-CO\(_2\) cooling lubrication is the fact (already explained by previous authors) that conventional cooling is largely inefficient in shallow-cut grinding, characterized by small contact lengths. Moreover, a high normal force \( F_n \) is related to high deformations in the contact wheel–workpiece, which in turn are responsible for an

### Table 2

<table>
<thead>
<tr>
<th>Distance to the surface [mm]</th>
<th>Hardness [HRC]</th>
<th>Distance to the surface [mm]</th>
<th>Hardness [HRC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>62.1</td>
<td>0.045</td>
<td>61.9</td>
</tr>
<tr>
<td>0.095</td>
<td>60.85</td>
<td>0.100</td>
<td>59.7</td>
</tr>
<tr>
<td>0.130</td>
<td>58.6</td>
<td>0.140</td>
<td>57.4</td>
</tr>
<tr>
<td>0.192</td>
<td>54.8</td>
<td>0.180</td>
<td>55.2</td>
</tr>
<tr>
<td>0.238</td>
<td>54.1</td>
<td>0.242</td>
<td>54.3</td>
</tr>
<tr>
<td>0.293</td>
<td>57.2</td>
<td>0.295</td>
<td>57.5</td>
</tr>
<tr>
<td>0.408</td>
<td>57</td>
<td>0.350</td>
<td>58</td>
</tr>
</tbody>
</table>
increase in the actual contact length. Finite Element simulation confirms that for the same conditions, a higher contact length produces lower temperatures.

- Finally, metallurgical analysis of the components ground with the new technology was carried out to confirm the absence of thermal damage. Microphotographs show a similar structure in the base material and in the sub-surface of the sample. The values obtained for the microhardness at different depths from the ground surface reveal a slight increase in the hardness from which it can be stated MQL-CO₂ technology does not induce thermal damage in the material.

- Further research work is currently being carried out with the objective of reducing operating costs associated with CO₂ consumption. Optimum nozzle design using CFD, use of a mix of CO₂ and other gases, as well as other alternatives are being analysed. Optimization of the application of the technology to cylindrical grinding and to other workpiece materials is also being studied.

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References


