Analysis of the Influence of Sparkout Time on Grinding Using Several Lubrication/Cooling Methods

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The plunge cylindrical grinding operation has been widely employed in the manufacturing process of components which require excellent surface quality achieved within small ranges of dimensional tolerance. The sparkout time has proved to be an important parameter in this operation, contributing to obtain surfaces with high geometric and dimensional precision. This parameter, which is defined as the period in which there is no wheel radial feed, allows the elimination of elastic deformations that build up as the grinding wheel is fed. Experimentation with sparkout time was applied in the plunge cylindrical grinding operation and included the Minimum Quantity Lubrication (MQL) technique, which has proved to be an environmentally correct alternative, combining a small amount of lubricating oil with an intense flow rate of compressed air. The conventional lubrication and cooling method and the method involving the nozzle proposed by Webster [10] were also used. The results showed that longer sparkout times led to a decrease in tangential forces, wheel diametrical wear and surface roughness values for the MQL method.

Keywords*: grinding, sparkout time, MQL*

Introduction

Today's global economy dictates the need for mechanical manufacturers to be increasingly competitive, impelling them to seek viable alternatives resulting in products with the best cost/benefit ratio in the market (Hafenbraedl and Malkin, 2001).

Within this context, the grinding process stands out for conferring good superficial, dimensional and geometric finish to the workpiece, which is difficult to achieve through other machining operations. However, improvements in the grinding process are crucial, since it is used in the final stages of production, when the workpiece already has a high added value (Irani et al., 2005). Therefore, it is highly relevant to monitor the entire process, accurately relating all the input parameters and output variables in order to produce analogous and convergent results.

However, optimization of the process is hindered by the difficulty of achieving the proper rigidity of the machine-workpiece-tool set. The lack of rigidity of the set is known to lead to the build up of elastic deformations during the working movement, causing the actual feed to lag behind the theoretical one, which in turn results in a dimensional error. It is therefore useful to establish a period when there is no wheel feed, called sparkout time, during which the deformations are gradually eliminated, removing material, eliminating the error and reaching the desired dimensions (Chen et al., 2002) (Hassui and Diniz, 2003) (Malkin, 1989) .

Hassui and Diniz (2003) carried out several plunge cylindrical grinding experiments on AISI 52100 quenched and tempered steel. They concluded that the decrease in the sparkout time makes the vibration at the end of sparkout to increase very much, but does not cause such damage in surface roughness. In this way, it is possible to have good workpiece quality even with high vibration level, much higher than the vibration obtained with a recently dressed wheel.

Although the grinding operation is quite satisfactory from a technological standpoint, reaching good standards of quality, it is still environmentally harmful due to the large amount of heat generated by the process, which makes necessary the use of high flow of cutting fluid in the region of the tool-workpiece interface. According to Hafenbraedl and Malkin (2001), the grinding process requires a large amount of energy per volume of removed material, and a considerable portion of this energy is converted into thermal energy, which may cause thermal and dimensional damage to the workpiece. Cutting fluids must therefore be applied to dissipate heat (Nathan et al., 1999) (Kopac and Krajnik, 2006). These oil-based fluids are harmful to the health of factory workers, leading to skin and respiratory problems.

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According to Irani et al. (2005), in the early 1990s, it was estimated that 130,000-250,000 tons per year of cutting fluid were used in Germany. After a certain amount of time, all this fluid must be replaced and disposed of in order to maintain a consistent production level. Because of the composition of grinding swarf (iron wheel material, oil, water, alloys), one can understand why there is a need to properly dispose of cutting fluids in the most ecologically friendly manner. The proper disposal of the oil, alloys and iron is the most critical because they pose the greatest environmental hazard (Brinksmeier and Eckebrecht, 1994).

It is in this context that MQL (Minimum Quantity of Lubricant) technique emerges as a viable alternative to conventional lubrication and cooling methods, combining an intense flow of compressed air with a small amount of oil to form a mist acting simultaneously as a coolant and a lubricant.

The MQL technique is already quite widely applied and has provided satisfactory results in machining processes with tools having a defined geometry. However, it has been little explored in grinding processes using tools with undefined geometries, in which there is a greater intensity of workpiece-tool interaction (Hafenbraedl and Malkin, 2001). Silva et al. (2006) applied the MQL technique to the cylindrical plunge grinding operation of ABNT 4340 quenched and tempered steel. They compared the performance of conventional aluminum oxide (Al_2O_3) grinding wheel and a superabrasives wheel of CBN. The authors have evaluated yet the conventional coolant method, characterized by high flow rate, becoming possible to compare the performance of each coolant method.

Silva et al. (2006) showed the effectiveness of the MQL technique in the external cylindrical grinding process by comparing with the conventional lubrication and cooling method (high flow rate and low pressure application). The surface roughness values and grinding wheel diametrical wear were significantly decreased with the use of MQL technique, as well as the decrease in the tangential cutting force and specific energy was observed, showing the good capacity of lubrication of the MQL technique.

The purpose of this investigation was to verify how and to what extent different spark out times influence the plunge cylindrical grinding operation using three lubrication and cooling methods, i.e., MQL, conventional and the nozzle proposed by Webster et al. (2005). This nozzle was projected to guarantee the desirable pressure and velocity of the coolant flow, reached by elimination of the turbulences inside the nozzle.

The output variables analyzed here were tangential cutting force, acoustic emission signals, roundness and grinding wheel diametral wear.

Methodology

Several different sparkout times (2s, 6s and 12s) were used in this study. The cutting fluid (a 3.5% concentration of emulsive oil) was applied using the nozzle proposed by Webster et al. (2005) with a rounded tip and a fluid exit diameter of 4 mm, as illustrated in Fig. 1. According to those authors, the rounded-shape nozzle with inner convex walls is capable of guaranteeing a better jet coherence by means of the fluid laminas approximation which has been formed during the flow process, minimizing the occurrence of pressure dip and turbulence during the way through and output of the cutting fluid. The fluid was also applied by the conventional method, using two 6.2 mm diameter nozzles under high flow rate and low pressure. The pressures and flow rate utilized to apply the cutting fluid at the workpiece-grinding wheel interface were 5 kgf/cm^2 and 22.6 l/min for Webster et al. (2005) model of lubrication and 4 kgf/cm^2 and 45 l/min for conventional cooling. These values were experimentally adopted aiming to reach the unity relationship between the grinding wheel tangential speed and the cutting fluid output jet speed.

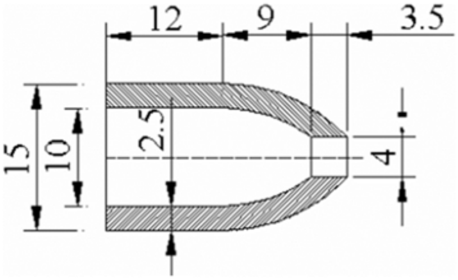

Figure 1. Nozzle based on Webster's model (dimensions in millimeters).

To apply the MQL technique, a nozzle was made based on the model developed by Silva et al. (2006), which is able to provide the appropriate mixture of compressed air (30m^3/h) and oil flow (60ml/h), resulting in the formation of a mist that is directed to the workpiece-tool interface. The dimensions in Fig. 2 are in millimeters.

The material of the workpieces utilized was the VC-131 steel, tempered and quenched with average hardness of 62 HRc. This steel has the following main elements: 2.1% C, 0.3% Mn, 11.5% Cr, 0.7% Mo, 0.2% V.

The tests were carried out using a conventional aluminum oxide (Al_2O_3) grinding wheel having the following characteristics: 355.6 x 25.4 x 127 mm - FE 38A60KV. A fliese type dresser was used for the dressing operations, keeping the dressing depth and the dresser transversal velocity constant, to prevent these operating conditions from affecting the output variables.

The experimental setup consisted of a CNC cylindrical grinding machine equipped with the accessories required to carry out the tests and for real time data acquisition of the tangential cutting force and acoustic emission signals during the execution of the grinding cycles. The tangential cutting force was calculated based on the induction motor voltage and electric current values, from which mechanical power was calculated.

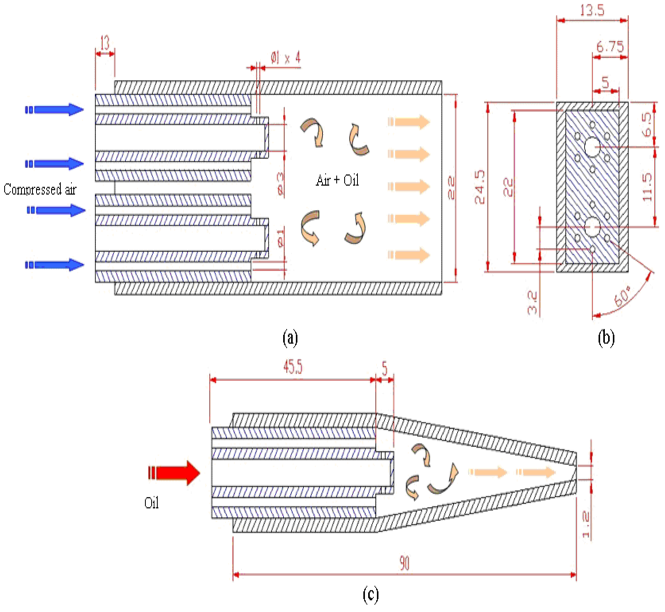

Figure 2. MQL nozzle. (a) Upper view, (b) lower view, (c) side view.

The workpiece surface roughness, and the roundness and diametral wear of the grinding wheel were measured after 10 grinding cycles, with each cycle comprising a 0.1mm advance of the grinding wheel toward the workpiece plus a corresponding sparkout time. Surface roughness (R_a) was measured with a Taylor Hobson Surtronic $^{3+}$ rugosimeter, using a 0.8 mm cut-off. Roundness was measured with a Taylor Hobson Talyrond 31 C roundness tester. The wear was evaluated by the method of impression of the worn grinding wheel profile on a body prepared for this purpose. This method consists of grinding the body to remove a fixed amount of material. When this was done, the irregularities between the worn and unworn regions of the grinding wheel were passed on the ground body, which was then measured using a TESA, model TT10 electronic displacement measurer with a precision of 1 micron (µm).

Forty-five tests were carried out in this study. Five experiments were done using each set of input variables (sparkout time and lubrication/cooling method).

Results and Discussion

Tangential Cutting Force

The tangential cutting force results for the ten grinding cycles carried out for each cooling/lubrication method are shown on Figure 3. Note that each point corresponds to an arithmetic mean during each grinding cycle, that is, the grinding cutting and spark-out period, from five repetitions of each test, all of which were conducted under identical grinding conditions.

An analysis of Fig. 3 indicates that the use of MQL method leads to higher intensity forces than those obtained through other lubrication and cooling methods. This can be explained, in part, by the lack of abundant fluid at the workpiece-tool interface, which would minimize the tribological effects and facilitate the removal of material. In the MQL technique, the tangential cutting force can be reduced by increasing the sparkout time, as evidenced starting from the second cycle, in which the lowest force was obtained with a 12-second sparkout time. The stable values of these forces lay within the range of 12.0 to 18.0 N. However, a comparison of the conventional method and the method using Webster's lubrication and cooling nozzle (Webster et al., 2005) revealed that the sparkout time did not affect directly the values of the tangential cutting force. Thus, it can be affirmed that a 2-second sparkout time is more profitable, since it leads to a reduction of manufacturing costs by reducing the duration of the operation.

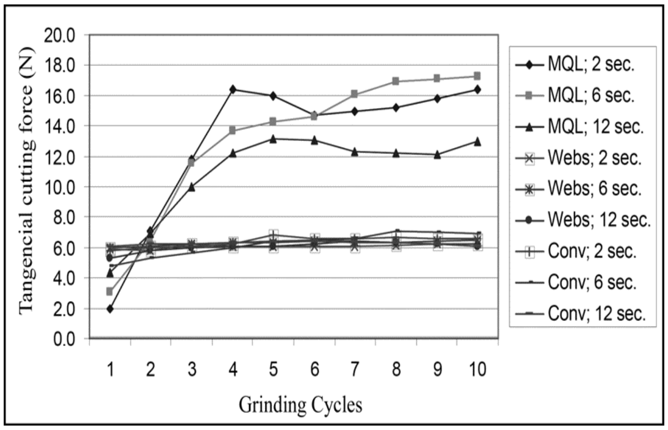

Figure 3. Influence of sparkout time and lubrication method on tangential cutting force.

Surface Roughness

It is important to point out that the surface roughness of a ground workpiece is affected principally by the size of the abrasive grain, the dressing conditions, the material removal rate, sparkout time and lubrication and cooling conditions.

Figure 4 shows the surface roughness values expressed in microns (µm) with varying lubrication conditions and sparkout times.

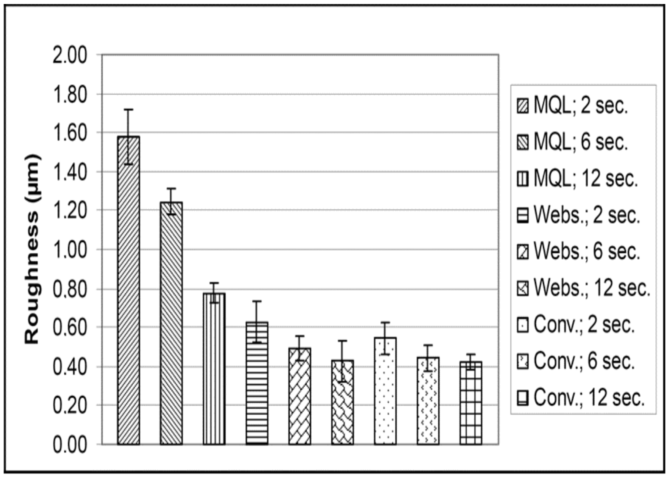

Figure 4. Influence of sparkout time and lubrication method on surface roughness.

As can be seen in Figure 4, the sparkout affects surface roughness values when using the MQL method. Longer sparkout times are therefore required when using this lubrication and cooling method in order to keep the surface roughness at acceptable values in the grinding process, defined according to Diniz et al (2000) between 0.2 and 1.6 mm.

There is greater difficulty of effective lubrication and cooling in the conventional lubrication method due to great dispersion of the fluid jet. As the cutting fluid speed is equal to the cutting speed in the Webster's method, there is an effective penetration of cutting fluid into the grinding zone, and therefore, guaranteeing the good surface quality of the workpiece with the use of a flow rate smaller than the conventional one. That is, the surface roughness values are similar for both methods of lubrication; however, the Webster's method presents the advantage of utilizing flow rates values significantly smaller. In the case of MQL, the effectiveness of the method is meaningful only with the use of greater sparkout times.

Roundness Deviations

The workpiece roundness was measured in order to verify their superficial integrity under the various lubrication and cooling conditions tested here, for it is the deviations of this feature that express the final error of the machined workpiece.

Figure 5 depict the roundness deviation values in microns (µm) varying lubrication conditions and sparkout times.

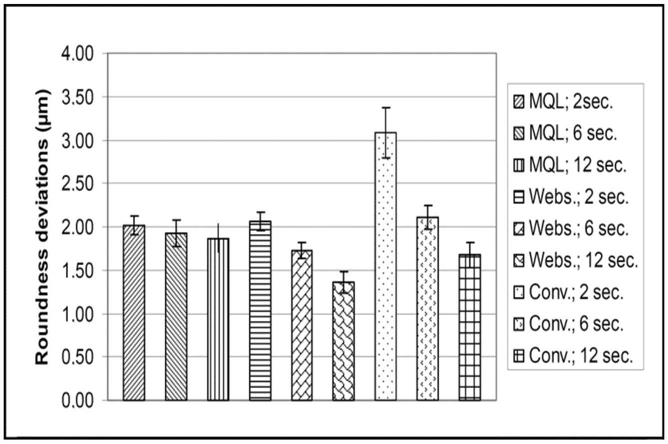

Figure 5 . Influence of sparkout time and lubrication method on roundness.

It indicates that longer sparkout times with the MQL method do not lead to lower roundness deviation values, which all lie within the same range. However, although these values are comparable, the deviation reduces with increased sparkout time. The roundness results obtained from Webster (2005) method indicate the uniform drop in deviation values as the sparkout time increases. Also, it can be noted for the roundness deviations in the conventional method of lubrication that greater sparkout times are responsible for providing better results.

Grinding Wheel Diametral Wear

The abrasive aluminum oxide (Al_2O_3) tool diametral wear values are illustrated in Fig. 6.

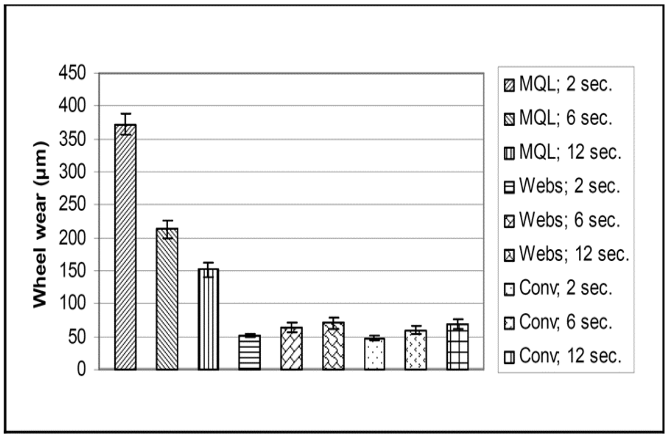

Figure 6. Influence of sparkout time and lubrication method on wheel wear.

Figure 6 shows that the wear of the grinding wheel when using MQL was significantly greater than the wear caused by the other lubrication and cooling conditions. It can also be noted, according to Fig. 6, for both Webster's and conventional methods of lubrication longer sparkout times led to higher grinding wheel wear as a result of the longer contact between the workpiece and the wheel, favoring the breakdown of grains and bonds. However, when the MQL method is employed, a longer sparkout time translates into a reduction of tool wear, due to good lubrication capacity of the cutting fluid applied through this technique.

Conclusions

Based on the results described herein and on the references consulted in this study, the following can be concluded with regard to the parameters investigated here:

- The use of the MQL technique resulted in growing tangential forces in the initial cycles, which stabilized after the 6th cycle. The stable values of these forces lay within the range of 12.0 to 18.0N.
- With the MQL method the use of longer sparkout times led to reduced tangential forces. However, it is not possible to observe a significant difference of tangential cutting force values in function of sparkout time for other methods of lubrication analyzed.
- With the conventional and Webster et al. (2005) lubrication and cooling methods, the tangential force remained stable throughout the grinding cycles at lower values than those obtained with the MQL technique.
- With regard to surface roughness, R_a, the MQL technique led to high values in comparison with the other two methods. Even so, these values decreased with increasing sparkout times.
- With the conventional and Webster et al. (2005) lubrication and cooling methods, the values of surface roughness showed no significant variation as a function of sparkout time.
- Roundness did not vary significantly in the three lubrication and cooling methods tested here with 2- and 6-second sparkout times. With 12 seconds, however, Webster et al. (2005) method showed the best results.
- With the MQL method, the wheel diametral wear dropped gradually as the sparkout time increased. With the other methods, this wear remained virtually constant for each sparkout time.

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References

Brinksmeier, E. and Eckebrecht, J., 1994, “Possibilities for the disposal of grinding swarf”, *CIRP Annals-Manufacturing Technology*, Vol. 43, pp. 593–597.

Chen, X., Rowe, W.B. and Cai, R., 2002, “Precision grinding using CBN wheels”, I*nternational Journal of Machine Tools & Manufacture*, Vol. 42, pp. 585–593.

Diniz, A.E., Marcondes, F.C., Coppini, N.L., 2000, “Material machining technology” (In Portuguese), Artiliber Ed., Campinas, SP, Brazil, 2nd. Edition.

Hafenbraedl, D. and Malkin, S., 2001, “Environmentally-conscious minimum quantity lubrification (MQL) for internal cylindrical grinding”, NANRI/ Society of Manufacturing Engineers, Vol. 28, pp. 149-154.

Hassui, A. and Diniz, A.E., 2003, “Correlating surface roughness and vibration on plunge cylindrical grinding of steel”, *International Journal of Machine Tools and Manufacture*, Vol. 43, pp. 855-862.

Irani, R.A., Bauer, R.J. and Warkentin, A., 2005, “A review of cutting fluid application in the grinding process”, *International Journal of Machine Tools & Manufacture*, Vol. 45, pp. 1696-1705.

Kopac, J. and Krajnik, P., 2006, “High-performance grinding-A review”, *Journal of Materials Processing Technology* , Vol. 175, pp. 278-284.

Malkin, S., 1989, “Grinding Mechanisms and Grinding Temperatures and Thermal Damage”, in Malkin, S. “Grinding Technology: theory and applications of machining with abrasives”, 1st. ed., Chichester, Ellis Horwood.

Nathan, R.D., Vijayaraghavan, L. and Krishnamurthy, R., 1999, “In-process monitoring of grinding burn in the cylindrical grinding of steel”, *Journal of Materials Processing Technology*, Vol. 91, pp. 37-42.

Silva, L.R., Bianchi, E.C., Fusse, R.Y., Catai, R.E., França, T.V. and Aguiar, P.R., 2006, “Analysis of surface integrity for minimum quantity lubricant - MQL in grinding”, *International Journal of Machine Tools and Manufacture*, Vol. 47, pp. 412-418.

Webster, J.A., Cui, C. and Mindek Jr., R.B., 1995, “Grinding fluid application system design”, *Annals of the CIRP*, Vol. 44, pp. 333-338.