Comparing Different Plunge Cylindrical Grinding Cycles Based on Workpiece Roughness and Process Vibration

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Grinding is an important process used when tight dimensional accuracy and low workpiece surface roughness are demanded. Despite the fact that grinding is widely used in industry, it is not well understood. The elastic deformation, which occurs in the beginning of the cycles, makes it necessary a spark out in the end of the cycle. An alternative to this is the use of a three-phase cycle. The main objective of this work is to compare the plunge cylindrical conventional grinding cycle (with spark out) and a three-phase one in terms of workpiece surface roughness. In order to accomplish this goal, several plunge grinding of hardened AISI 4340 steel experiments were carried out using both kinds of cycles in different grinding conditions. The vibration signal of the system was acquired in order to better understand the differences between the two kinds of cycles. The main conclusion was that conventional cycle produces lower workpiece surface roughness than the three-phase one (both with the same cycle time). It happens because the elastic deformation is better released in the conventional cycle.
Keywords*: grinding, vibration, surface roughness*

Introduction

The knowledge about the relationship between input and output parameters in manufacturing processes has been exhaustively sought recently, aiming to fulfill the consumer's need for products with lower costs and better quality.

Grinding is a very important manufacturing process, mainly where tight dimensional accuracy and low workpiece surface roughness are demanded. The grinding process is, usually, the last machining operation of a surface and, therefore, has a high aggregated cost.

Despite the fact that grinding is widely used in industry, it is not as understood as the machining processes that use tools with defined geometry. Factors like the very high number of cutting edges with non-uniform geometry, depth of cut variation on each cutting edge, high cutting temperatures and cutting forces which produce plastic deformations make the understanding and optimization of this process difficult (Malkin, 1989).

One of the problems of a grinding process is the elastic deformation of the workpiece and wheel spindle that occurs in the beginning of the cycle; mainly in plunge cylindrical grinding operation. These deformations, as it will be explained later in this work, make it necessary the presence of a spark out time at the end of the grinding cycle (King and Hahn, 1986), what makes the cycle longer and, therefore, the process less productive. One alternative to spark out is the use of a three-phase cycle. The main objective of this work is to compare the plunge cylindrical conventional grinding cycle (with spark out) and the three-phase one in terms of workpiece surface roughness. In order to accomplish this goal, several grinding experiments were carried out using both kinds of cycles and different grinding conditions, in the plunge cylindrical grinding of hardened AISI 4340 steel. The vibration of the workpiece fixture was measured in order to compare the chip thickness in the two different kinds of cycles. The main purpose of this is to evaluate the amount of elastic recovery in each situation and conclude if it is better to recover all the elastic deformation at once at a higher rate (case of conventional cycle with spark out) or to do the elastic deformation and recovery divided in three smaller parts.

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Nomenclature

U_d = *dressing overlap ratio, dimensionless*
b_d = *dresser thickness at dressing depth, mm*
s_d = *dresser feed per wheel revolution, mm/rev*
f = *infeed, mm/rev*

Subscripts

d relative to dresser
1 relative to the roughing infeed
2 relative to the semi finishing infeed
3 relative to the internal finishing infeed
\+ relative to the upper level of the variable
\- relative to the lower level of the variable

Review of Literature

In a plunge cylindrical grinding operation, when the wheel touches the workpiece (moment T_1 in Fig. 1) and starts its radial movement with an infeed rate previously set (the infeed rate is represented by the slopes of the curves in the figure), the wheel spindle and the workpiece are elastically deformed, which makes the programmed infeed rate different from the actual one (period between T_1 and T_2 in Fig. 1) in the beginning of the cycle (Malkin, 1989). Therefore, there is a delay between the diameter that should be ground (theoretical workpiece diameter) and the diameter actually being ground. After some workpiece revolutions, the actual infeed rate becomes equal to the programmed one (period between T_2 and T_3 in Fig. 1, where the slopes of the two curves are the same), but the difference between the theoretical and actual diameter being ground is still present. Therefore, to reach the desired workpiece dimension and also to obtain good surface roughness and tight form tolerances, at the end of the cycle the wheel must stop its radial movement for a moment in order to remove the initial elastic deformation that starts being released and improve the workpiece surface roughness (Chen and Rowe, 1999). This period is called sparkout (period between T_3 and T_4 in Fig. 1). During this period, chips are still being removed, but their thickness decreases as elastic deformation is recovered (Malkin, 1989).

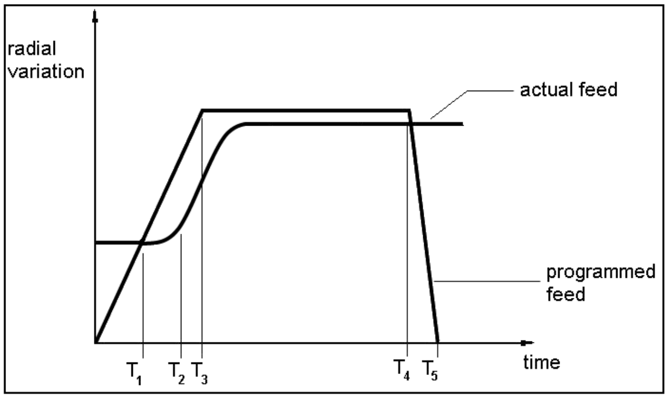

Figure 1. Difference between programmed and actual feed in a plunge cylindrical grinding operation.

Okamura, Nakajima and Uno (1975) measured cutting forces in the conventional cylindrical grinding cycle and showed that they increase during the initial period of the cycle (when elastic deformation occurs), stay constant when actual infeed rate is equal to the programmed one, and decrease during sparkout. Verkerk (1978) stated that the normal force is related to the metal removal rate, so when the feed rate is increased, the same happens to the normal force. Saini and Wager (1985) related the normal force directly with the cutting depth. Tönshoff et al. (1992) evaluated chatter vibration models of grinding process and showed that this characteristic is related to the forces and energy of the process. Hassui et al. (1998) measured acoustic emission and workpiece vibration also in the conventional grinding cycle and showed that they have similar behavior of cutting forces, i.e., when elastic deformation is occurring, these signals are increasing, due to the increase in the chip volume being removed. When actual infeed rate is equal to the programmed one, these signals become constant and during the sparkout, they decrease due to the reduction in chip volume. Therefore, all the signals (force, acoustic emission and vibration) are strongly dependent on the volume of chip being removed.

As already cited, three-phase plunge cylindrical grinding is one alternative to the conventional grinding cycle. The wheel radial movement in this kind of cycle is divided in three phases with decreasing infeed rates, as shown in Fig. 2. The elastic deformation occurring in the first phase of the cycle is supposed to be released in the next two phases. The material stock which is programmed to be removed in each phase is decreasing due to the decrease of the infeed rate, but the actual stock of the second and third phase is higher than the programmed one, due to the elastic recovery that happens during these phases.

Workpiece surface roughness is a very important quality parameter for ground surfaces. In grinding operations, factors like wheel grain size, dressing overlap ratio, cutting fluid, grinding conditions and so on determine the final roughness value. Hassui and Diniz (2003) carried out plunge cylindrical grinding experiments in AISI 52100 quenched and tempered steel with average hardness of 58 HR_C. These experiments had as input variables the workpiece velocity and the sparkout time, in two levels – the first level was the time necessary for the complete release of elastic deformation (complete sparkout) and the second level was half of this time. The authors concluded that workpiece velocity has little influence on surface roughness in the beginning of wheel life, but, as the wheel gets dull, its influence increases. They also concluded that the influence of sparkout time is stronger than the influence of workpiece velocity. The values of surface roughness using just half of the time necessary for complete sparkout, was up to 50% higher than those obtained when complete sparkout was used. This result occurred because when the wheel was retracted in the experiments using the cycle with half of the time necessary for complete sparkout, it was still removing some volume of chip. Therefore, in order to achieve low workpiece surface roughness it is important to have small amount (or even none) of chip being removed at the moment of wheel retraction. So, workpiece surface roughness, like vibration, acoustic emission and force, is also strongly dependent on the chip volume being removed.

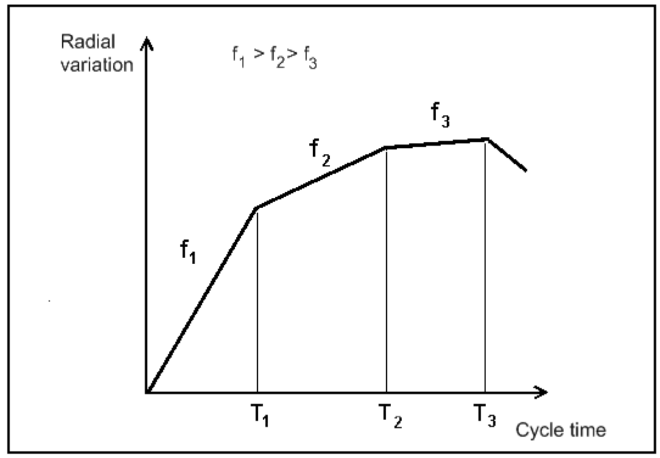

Figure 2. Grinding cycle with three phases.

Domala et al. (1995) studied the relationship between the surface properties of the wheel and the resulting ground workpiece. This study has identified three process disturbances that contribute to the ground texture; out of round wheel, and two vibration modes. Tönshoff et al. (1992) mentioned that roughness is related with wheel topography and engagement of wheel and workpiece that in its turn is related to grinding forces and energy, and these last two are related with chatter vibration.

Experimental Procedures

The machine tool used in the experiments was a CNC cylindrical grinder and the operation was the plunge cylindrical grinding. The wheel dressing was carried out with a single point diamond tool. The width of the dresser (b_d) was 0.7 mm measured at 0.03 mm from the dresser tip (value of the dressing depth of cut – a_d).

The dressing operation can be characterized by the dressing overlap ratio (U_d) (Oliveira, 1988) described by Eq. 1.

$$U_d = \frac{b_d}{S_d} \tag{1}$$

where S_d is the dresses feed per wheel revolution.

In this work the value of U_d was 5, which is a typical value for finish grinding.

The experiments were carried out using a FE38A80KVS wheel from Norton Abrasives. Cutting fluid applied was a solution of 4% of synthetic oil in water. The wheel speed was kept constant in all experiments (30 m/s).

The workpieces were made of AISI 4340 quenched and tempered steel with average hardness of 56 HR_C. Figure 3 shows a scheme of the workpiece used. The grinding was done on the surfaces of 40 mm diameter. They were fixed on the machine by a rotary tailstock in one side and by a fixed tailstock in the other side.

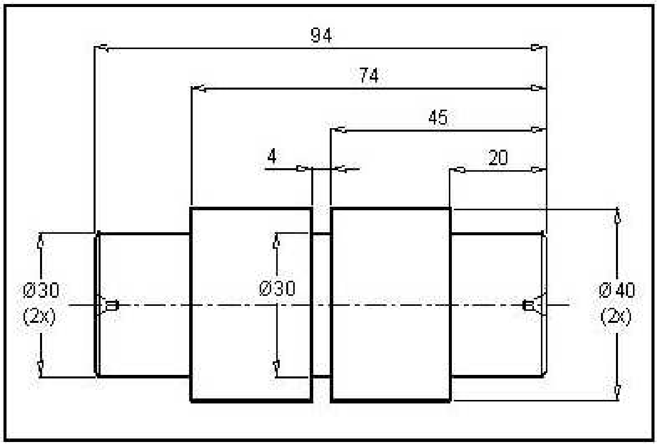

Figure 3. Workpieces used in the experiments (unities in mm).

Two kinds of grinding cycles were used: the so called conventional one containing a first phase with a constant wheel infeed velocity followed by the sparkout, and the three-phases cycle having three different decreasing infeed velocities, followed by just one workpiece rotation without wheel infeed.

Table 1 shows the values of the input variables with their respective levels for the three-phase cycle.

Table 1. Input variables for the three-phase cycle.

Variables	Lowest level (-)	Highest level (+)
Phase 1 infeed (mm/rev) f_1	0.007	0.009
Phase 2 infeed (mm/rev) f_2	0.0028	
Phase 3 infeed (mm/rev) f_3	0.0004	0.00055
Stock removed 1 (mm)	0.26	0.28
Stock removed 2 (mm)	0.013	0.033
Stock removed 3 (mm)	0.007	0.01

The conventional cycles were defined in such a way that they last the same time as the three-phase one does. Therefore, the infeed values of these cycles (the conventional cycle has just one phase with wheel infeed) were equal to the three-phase infeed 1 values, and the sparkout had the duration of the sum of the time of the phase 2 and 3 of three-phase cycles plus the time spent by one workpiece rotation ($T_{f2} + T_{f3} + T_{1rot}$).

The input variables for the conventional cycle experiments were f1 (infeed value) and sparkout time. The highest level of the second phase of the three-phase cycle time was used in the calculation of sparkout time. The time for one workpiece rotation was always 0.53 s. Table 2 shows the input variables used in each conventional cycle experiment. All the experiments were carried out at least twice.

From now on the sparkout time equal to 6.80 s will be called T_{spk+}, and equal to 5.88 s will be called T_{spk-}.

Table 2. Input variables of the conventional cycle experiments.

Experiment	f_1 (mm/rev)	T_{f3} (s)	Sparkout time (s) ($T_{f2} + T_{f3} + T_{1rot}$)
1	0.009	4.57	6.80
2	0.009	3.65	5.88
3	0.007	4.57	6.80
4	0.007	3.65	5.88

The acquisition of the vibration raw signal of the process was made through an accelerometer attached to the machine fixed tailstock. The sensor signal passed through a coupler connected with a filter and, after that, through an A/D board to be stored in a PC memory. The filter used was a low pass with a cutoff frequency of 1 kHz and the gain was set to 100 times. The sample rate was 10 kHz and Labview software was used for acquisition and signal processing.

The surface roughness was measured three times in each ground surface equally spaced through the perimeter. A portable rugosimeter Mitutoyo Surftest 211 with cutoff set in 0.8 mm was used for these measurements. The surface roughness measurement and vibration signal acquisitions were done on each workpiece ground.

Results and Discussion

Figure 4 shows a comparison of workpiece surface roughness (average of three measurements in each surface) obtained in the conventional and three-phase cycles. It is important to remember that the experiments represented by the two connected bars in Fig. 4 had the same cutting time. It can be seen in this figure that roughness obtained in the conventional cycles was around 28% lower than those obtained in the three-phase ones. This occurrence can be explained by the fact that the sparkout, in the conventional cycle, was more efficient to retrieve the elastic deformation of the workpiece-wheel spindle system, and also to dump vibration, than the lower infeed velocities of the three-phase cycle. As it was expected, roughness increased a little as cutting conditions became more aggressive for the three-phase cycle. On the other hand, it remained almost constant for the conventional cycles, no matter the infeed value and sparkout time used. This fact demonstrates that even the shortest sparkout time (5.88 s) was able to remove almost all the elastic deformation, regardless the value of the infeed.

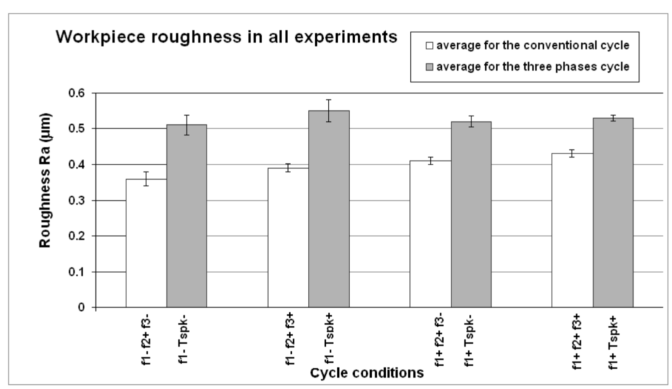

Figure 4. Workpiece roughness for both, conventional and three-phase cycle.

Figure 5 presents a comparison of vibration signals that occurred in phases 2 and 4, in two different situations: a) these phases after other previous phases (phase 2 after the previous phase 1, and phase 3 after the previous phases 1 and 2); b) these phases isolated of other phases, i.e., either f_2 or f_3 infeed rates were used since the beginning of the cycles without any previous phases. When used after other phases, the previous phases were used in their maximum values, i.e., when phase 2 was analyzed, the infeed rate of phase 1 was f_1^+, and when phase 3 was analyzed, the infeed rates of phases 1 and 2 were f_1^+ and f_2^+ respectively. At first, it can be seen in Fig. 5 how greater is the vibration value when the phases are anteceded by other phase(s) than when the phase is used in isolation. Secondly, this figure also shows that the vibration value is dependent on infeed rate value; the higher the second, the greatest the first. With these results it can be concluded that a large amount of elastic deformation had still to be recovered at the end of phase 2 and 3 in a three-phase cycle. The vibration level of the phases was roughly 4 times bigger when grinding was carried out with previous phases than when no previous phases were used.

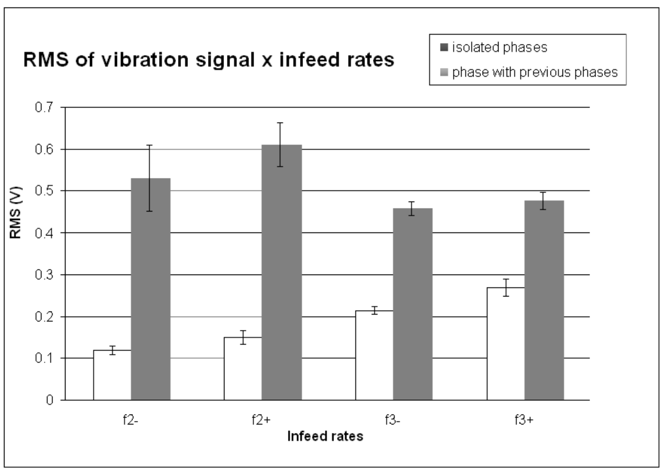

Figure 5. Vibration RMS for the phases with and without previous phases.

Figures 6 and 7 show the behavior of the RMS of the vibration signal for the experiments with f_1^+, f_2^+ and f_3^+, and f_1^-, f_2^- and f_3^- respectively (three-phase cycles).

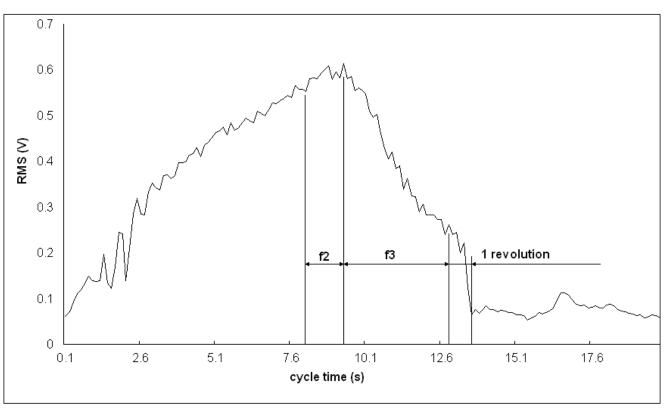

Figure 6. Vibrations signal behavior for three-phase cycle – infeed rates $f_1^+ f_2^+ f_3^+$.

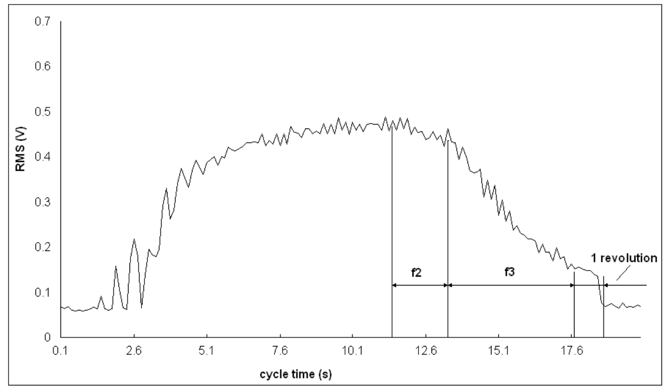

Figure 7. Vibration signal behavior for three-phase cycle – infeed rates f_1^- f_2^- f_3^- .

Before starting the discussions of Figures 6 and 7, it is important to point out that according to Hassui and Diniz (2003) vibration signal is strongly dependent on the volume of chip removed per minute (removal rate) for plunge cylindrical grinding operations. Actually, the normal grinding force and, consequently, vibration signal are dependent on the removal rate (Okamura, Nakajima and Uno, 1975). Therefore, the vibration signal grows as actual infeed rate increases, and decreases as this rate decreases.

Figure 6 (infeed rates of the three phases in their highest values) shows that during all the first (infeed rate f_1) and second (infeed rate f_2) phases the vibration signal are increasing due to the rise in the actual infeed rate. Therefore, it can be concluded that elastic deformation was occurring during all the first phase. During the second phase, the elastic deformation stopped and even started its recovery, but the actual infeed rate was greater than that observed in the first phase. This fact occurred due to the sum of the chip removed because the workpiece was going towards the wheel (due to elastic recovery), and the chip removed because the wheel was going towards the workpiece (due to f_2). Only when the third phase started and the programmed infeed rate was very low, the removal rate and, consequently, the vibration signal decreased. This occurrence is similar to what happens during sparkout time in a conventional grinding cycle. If phase 2 had been extended, the actual infeed would decrease up to f_2 and would stabilize. At this moment, the vibration signal would have the value shown on Fig. 5 (see the value for f_2^+ isolated), i.e., the value obtained when this infeed rate is used without any previous phase. It also can be seen in Fig. 6 that at the end of phase 3 there was some elastic deformation still to be recovered, since the vibration signal was still decreasing and was much higher than the value shown on Fig. 5 for f_3^+ isolated.

When the three infeed rates were in their minimum values, the behavior of the vibration x cycle time curve changed (Fig. 7). This figure shows that the vibration level, proportional to the cutting force and to the removal rate, reached its highest and constant level in the first phase of the cycle. According to Okamura, Nakajima and Uno (1975), this occurrence points out that the wheel left the initial phase with elastic deformation and reached the period with constant actual infeed rate. In phase 2, a little decrease of the vibration signal amplitude occurred, which indicates that the removal rate (and so the cutting force) is also decreasing. In other words, during phase 2 the elastic deformation recovery started but did not finish. It is possible to evaluate the quantity of elastic deformation remaining on the workpiece-wheel spindle system at the end of phase 2, comparing the vibration value at the end of the second phase (Fig. 7) to the value shown in Fig. 5 (see the value for isolated f_2^-). During phase 3 elastic recovery continued, but at its end, some elastic deformation was still present. One can be sure of this due to the fact that at this moment the vibration signal was not stabilized yet and its level was much higher than that shown in Fig 5 (see the vibration value for isolated f_3^-). However, the difference between the vibration values at the end of phase 3 for the experiment with f_1^-, f_2^- and f_3^- and the vibration value for the isolated f_3^- without previous phases is lower than the difference occurred for the experiment with f_1^+, f_2^+ and f_3^+. As it was supposed to occur, when f_1^-, f_2^- and f_3^- were used, the complete sparkout (no elastic deformation to be recovered at all) was much closer than when f_1^+, f_2^+ and f_3^+ were used. But, it is important to remember that the infeed rates f_1^-, f_2^- and f_3^- used are very low. Therefore, in order to have complete sparkout using a three-phase cycle, it is necessary to have low infeed rates in the three phases.

Figures 8 and 9 show the behavior of RMS vibration signal for conventional cycles with the following conditions: Fig. 8 – infeed rate f_1^- and sparkout time T_{spk-}; Fig. 9 – infeed rate f_1^+ and sparkout time T_{spk+}.

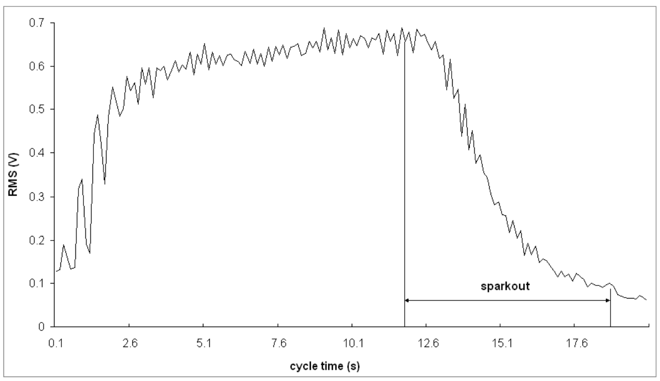

Figure 8. Vibration behavior for the condition f_1^- T_{spk-} conventional cycle.

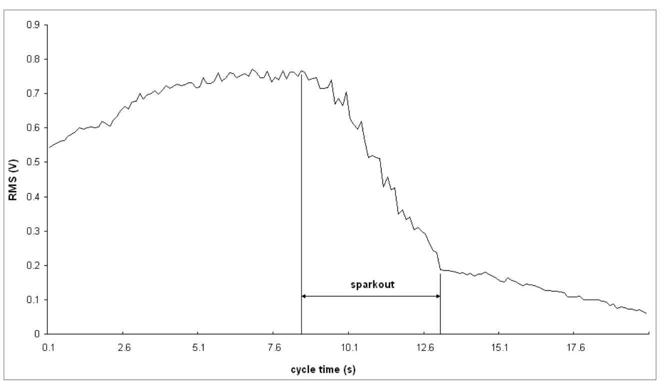

Figure 9. Vibration behavior for the condition f_1^+ T_{spk+} conventional cycle.

Figure 8 shows that, when the wheel was retracted at the end of sparkout time, most of the elastic deformation of the workpiece-wheel spindle system had been already recovered, since the vibration signal was very close to stabilization. This never occurred when the three-phase cycle was used (Fig. 6 and Fig. 7).

It can be seen in Fig. 9 that the vibration signal was still not stabilized at the end of the cycle, showing that the complete sparkout (end of elastic deformations) had not been reached. However, it can also be seen that the vibration value was very close to the value obtained when the wheel was retracted, what did not happened when the corresponding three-phases cycle was used (Fig. 6). Therefore, it can be concluded that when a conventional cycle is used, the recovery of the elastic deformations, which occurred in the beginning of the cycle, is more efficient, and produces workpieces with better surface quality. The explanation for the worst performance of the three-phase cycle is that the elastic recovery takes place at the same time as the wheel is moving in the opposite direction.

Figure 10 presents a comparison between the workpiece surface roughness obtained with the isolated phase f_3 and the one generated when the cycle had the three phases (f_3 with the previous f_1^+ and f_2^+). It can be seen in this figure that the isolated phases, as was supposed to happen, presented lower surface roughness than the workpieces ground with three phases. It can be supposed that, if the complete sparkout had been reached in the three-phase cycle, workpiece surface roughness would not be elastic recovery anymore and, so, the actual infeed would be the programmed one. The roughness values obtained with the isolated phases are the minimum values possible to be obtained using a three-phase cycle.

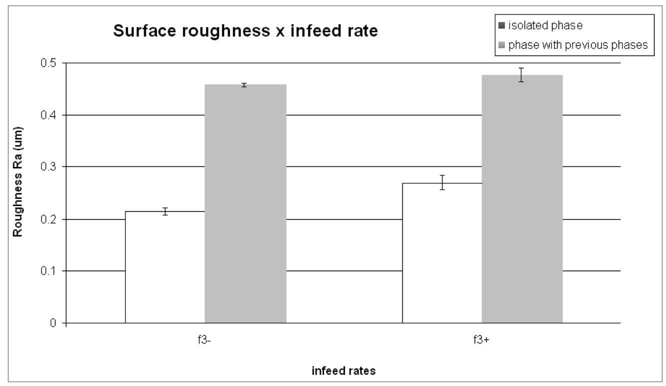

Figure 10. Workpiece surface roughness of isolated phases and three-phase cycle.

It is important to state before ending this discussion that workpiece surface roughness is obtained by the conditions at the end of the grinding cycle. The most important variable for surface roughness is the amount of material removed in this moment, as mentioned by Malkin (1989). The higher the amount of material removed in this moment, the higher is the workpiece vibration and, consequently, the grater the surface roughness. Therefore, the roughness obtained in the workpiece is dependent on how close to the complete sparkout is in the cycle, when the wheel is retracted. The conventional cycle generated lower workpiece roughness because with it, at the end of the sparkout time, the amount of workpiece material still to be removed is lower than when three-phase cycle is used with the same cycle time.

Conclusions

From the discussed results, it can be concluded that for the experimental conditions used:

- The roughness obtained in the conventional cycles was roughly 28% lower than those obtained in the three-phase ones;

- Sparkout in the conventional cycle was more efficient than in the three-phase one to retrieve the elastic deformation and, consequently, to decrease the amount of material being removed at the end of the cycle;

- The vibration signal presented a good correlation with the amount of system deformation;

- To get good workpiece surface roughness using the three-phase cycle it is necessary to have very low infeed rates in all the three phases;

- Surface roughness increased as cutting conditions became more aggressive for the three-phase cycle and remained almost constant for the conventional one, no matter the infeed rate used;

- The elastic recovery takes place at the same time the wheel is moving toward the workpiece in the three-phase cycle.

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