Comparing the Conventional and Three Phases Plunge Grinding Cycles

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Abstract. *This work focus on the cylindrical plunge grinding process, in the presence of a radial gauge, that has the function of establish the moment in which the workpiece reachs its final dimension. This equipment has been more and more used in the industrial environment, aiming to automate the processes and guarantee higher accuracy of the workpiece. In this kind of grinding operation is usual the utilisation of a 3 phases cycle, the first rough phase, where the majority of the material to be removed occurs with high infeed and another two phases, in which the material to be removed and the infeed are reduced, in such a way that the elastic deformation of the wheel spindle and of the workpiece, generated at the first phase of the cycle, can be recovered and, thus, the desired quality of the workpiece is achieved. The goal of this work is to verify the influence of the feed and the amount of material to be removed in each of the phases of the cycle with three different feeds and establish a comparision in the ground workpiece quality, in the cycle time and in the wheel life between the conventional cycle and the 3 phases one. In order to reach this goal, several tests were done grinding ABNT 4340 steel workpieces with mean hardness of 55 HR_C and a grinding wheel ART FE 38A80K. The main conclusions were: to the cycle with 3 velocities, the phase 3 feed has the higher influence in the roughness of the workpiece at the beginning of the wheel life and the feed of the phase 1 is the most important to the grinding wheel wear and, hence, to the increase of the roughness as chips are been removed; the quality of the workpiece ground with the conventional cycle showed better, in terms of roughness and circularity error than the quality of the workpiece generated by the cycle with 3 feeds to the same volum of chip removed.*

Keywords. *cylindrical plunge grinding, process optimization, surface finishing*

1. Introduction

The grinding process is very used in the metal-mechanic industry, due to its aplications and peculiarities, such as the possibility of obtaining workpieces with very low roughness and close tolerances. Generally it is the last machining operation of the workpiece, carrying aggregated cost and times, rising the necessary care during this operation.

Although extensively used in industry, the grinding process does not have yet the same understanding level of other machining processes that uses a defined cutting tool geometry (turning, milling, etc.). Factors like the multiplicity of cutting edges with their non uniforme geometry, depth of cut variation in each grain, high temperatures and cutting forces that are not controlled, produce plastic deformation that make the understanding and, therefore the optimization, of this process a very hard task.(Oliveira and Purquério, 1989).

Several researchers are trying a better understanding about the behavior of the process variables on the workpiece quality. Abrão (1991) studied the thermal gradients in the workpiece and tool contact zone, since the temperature in this region can reach levels over 1000ºC. Silva (2000) verified that to specifics cutting conditions, the mineral oil content in the cutting fluid reduced the tangential cutting force, reducing thus the cutting temperature. Oliveira (1993) studied the influence of the grinding wheel wear on the workpiece superficial quality. Hahn and Lindsay (1986), Oliveira (1989) and Dedini (2000) studied the relation between the cutting forces and deformations involved in the grinding process. Malkin (1989) presented a model for the workpiece and wheel shaft elastic deformation mechanism based on the efforts inherents to the process. This elastic deformation will be subject of study in this work.

The cylindrical plunge grinding process is very used in the industries but, like the other grinding processes, lacks a better understanding to improve the workpiece quality and to optimize the cycle time. The reduction of the time spent in this process is very usefull, since, usually, it becomes the bottle neck in the manufacutre lines.

This work analyses the effects of cutting conditions and times of 3 phases cycles and conventional ones in the workpiece quality and wheel life. The cycle with three phases (three feeds) is used when there is a real time radial gauge available in the machine. This device, nowaday, is very common in shop floors. Its function is to indicate the moment the workpiece reaches its programed diameter. So, the wheel is supposed to return to its initial position. The traditional cycle that has a single constant feed, followed by a sparkout (period of time in which the grinding wheel remains in a determined radial position, without any feed) necessary to removes the elastic deformation occurred at the beginning of the cycle (figure 1a), do not use the mentioned device. This is due the fact that, the wheel retraction, commanded by the radial gauge, could happen at any moment of the sparkout. This would damage the workpiece surface and shape quality, since the sparkout would not be complete. Thus, it would be necessary to divide the grinding wheel feed in three different and decreasing phases (figure 1b), in such a way that the elastic deformation of the workpiece and wheel shaft, occurred in the first phase, can be released in the last two ones. In this kind of cycle, the radial gauge have to register the workpiece programmed diameter in the third step of the cycle, when the feed and the material to be removed are very small. The radial gauge has accuracy consistent with a grinding operation, but the feed must be very low at the moment the device is supposed to act. So, there is no generated inaccuracy in the workpiece.

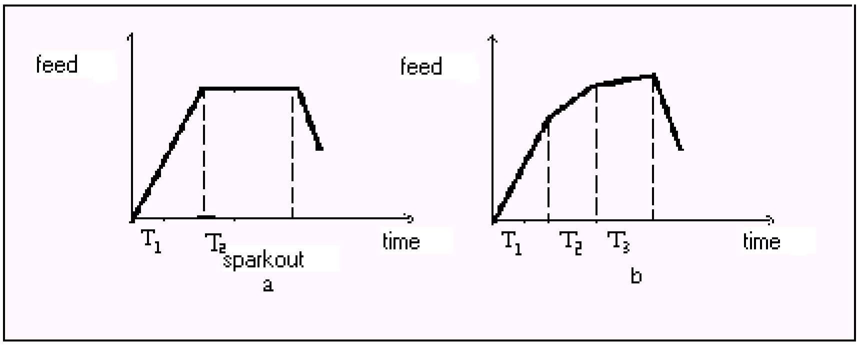

Figure 1: a) Traditional grinding cycle b) Cycle with three feeds

2. Experimental Procedures

The machine tool used for the tests was a cylindrical grinding machine Zema Zselics series Compakta G600, equipped with a CNC Fanuc 18 TC. It was decided to work with plunge cylindrical grinding, because it is simpler and the most used grinding process in industries. The dressing was done with a single point diamond. This diamond presented a width, b_d, equal 0,7 mm, measured at 0,03 mm from the point, (dressing depth). The dressing conditions can be characterized by the dressing overlap ratio U_d (Oliveira, 1988). This parameter is the ratio between the width of actuation of the dressing tool (b_d) and the dressing feed (S_d), according to equation (1).

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

It was used a U_d of 5 and as the b_d was 0,7mm the dressing feed was 0,14 mm/rev. The measurement of b_d was done using a microscope Leica Stereo Zoom 6 Photo, equipped with a amplification lens and a CCD camera. The camera was attached to a Pentium 133 MHz computer equipped with the software Global Lab Image versão 3.1, that allow image processing.

The tests were done using a FE 38 A 80 K V S grinding wheel from Norton Abrasives, recommended to sharpening and grinding of several kind of materials. The abrasive was the aluminum oxide (line FE 38 A), the grain size was 80, the hardness K and the bond was vitrified (V) with a modification (S), that make the abrasive grain more exposed, decreasing the risk of workpiece burning. The grinding wheel dimensions were: 355,6 mm initial outer diameter, 50,8 mm width and 127 mm hole diameter. The maximum recommended peripherical speed for this wheel is 33 m/s. In the tests, the wheel peripherical speed was kept constant and equal 30 m/s.

The workpieces used were made of ABNT 4340 steel tempered and quenched. The mean hardness obtained with the heat treatment was 56 HR_C. The figure 2 presents a draft of the workpiece.

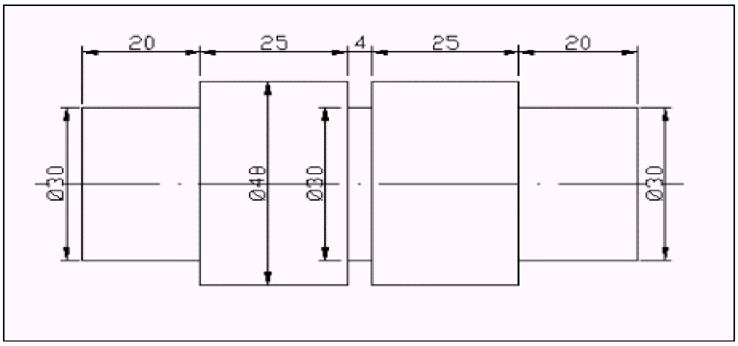

Figure 2: Draft of the workpiece used.

In the first phase of the tests just the cycle with three phases was done. The entry variables were the feed per revolution of the grinding wheel in each of the three phases of the cycle (figure 1b), trying to analyse the effects of them in the workpiece surface quality through the measurement of mean roughness (Ra) as the wheel worn out. The table 1 presents the values used to these variables and the table 2 presents the order in which the tests were done.

Table 1: Studied variables and their levels (Hassui, 1997; Zema Zselics,1997)

Variables	Inferior level (-)	Superior level (+)
Feed of phase 1 (mm/revolution)	0,007	0,009
Feed of phase 2 (mm/revolution)	0,002	0,0028
Feed of phase 3 (mm/revolution)	0,0004	0,0005

Table 2: Execution order with their respectives cutting conditions

Execution Order	Treatment	f_1	f_2	f_3
5	1	-	-	-
2	2	-	-	+
6	3	-	+	-
7	4	-	+	+
4	5	+	-	-
1	6	+	-	+
8	7	+	+	-
3	8	+	+	+

The workpiece speed v_w was kept constant and equal 15 m/min and the material to be removed in the workpiece diameter in each step of the cycle were: 0,28 mm in the first step, 0,013 mm in the second and in the third and last it was 0,007 mm. The dressing was done in 15 passes with depth of 0,03 mm in each one. It is worth to stand out that the values of material to be removed, feed of each phase and workpiece speed were chosen in preliminary tests, based on ground workpiece quality (roughness and circularity).

Each test consisted in grinding 66 workpieces without dressing, analysing roughness, circularity and volum of material removed each 5 workpieces done. The roughness was measured in a Mitutoyo Surftest 211 device, adjusted with "*cut-off*" in 0,8 mm and ISO pattern.

The next tests phase was done to establish comparisons between the conventional cycle with the three phases one based on workpiece quality and wheel life. In this tests phase, the sparkout of each cycle used was calculeted through the sum of the times involved in phases (feeds) 2 and 3 of the former phase tests, plus the time of one single workpiece revolution. The material to be removed was 0,3 mm and the entry variables were: a) wheel feed – the same level of feeds used in the phase 1 of the former tests; b) sparkout time – calculated according with the time spent in phases 2 and 3 plus one revolution of the workpiece in the first phase tests. The workpiece and grinding wheel speeds were kept constant. The table 3 presents the conditions used in the tests of this phase and the table 4 presents the execution order of these tests.

Also, in this phase, each test consisted in grinding 66 workpieces without dressing, analysing roughness, circularity and volume of chips removed each five workpieces done.

Table 3: Variables studied and their levels in the conventional cycle.

Variables	Inferior Level (-)	Superior Level(+)	Time (s) 1 workpiece rev.	Sparkou time
Feed of phase 1 (mm/rev)	0,007	0,009	0,5263	$(T_{f2}+T_{f3}+T_{1rev})$
Time of phase 2 (T_{f2}) *	1,70 seg	1,21 seg	0,5263	
Time of phase 3 (T_{f3}) **	4,57 seg	3,65 seg	0,5263	

** time spent in phase 2 of the cycle with 3 phases in the first set of tests (inferior level to f_2 = 0.002 mm/rev; superior leve to f_2 = 0.0028 mm/rev)*
*** time spent in phase 3 of the cycle with 3 phases in the first set of tests (inferior level to f_3 = 0.0004 mm/rev; superior level to f_3 = 0.0005 mm/rev)*

Table 4: Matrix of wheel life tests to the cycle with sparkout

Execution Order	Treatment	f1	T_{f2}	T_{f3}
3	1	-	-	-
4	2	-	-	+
1	3	+	+	+
2	4	-	+	+

3. Results and Discussions

Initially it will be verified the behaviour of the roughness at the beginning of the wheel life, to the conventional cycle as well as to the three phases one. The figure 3 presents the values of roughness at the beginning of the tests, that is, when there was a volume of chip removed equal 500 mm^3, to both kinds of cycles.

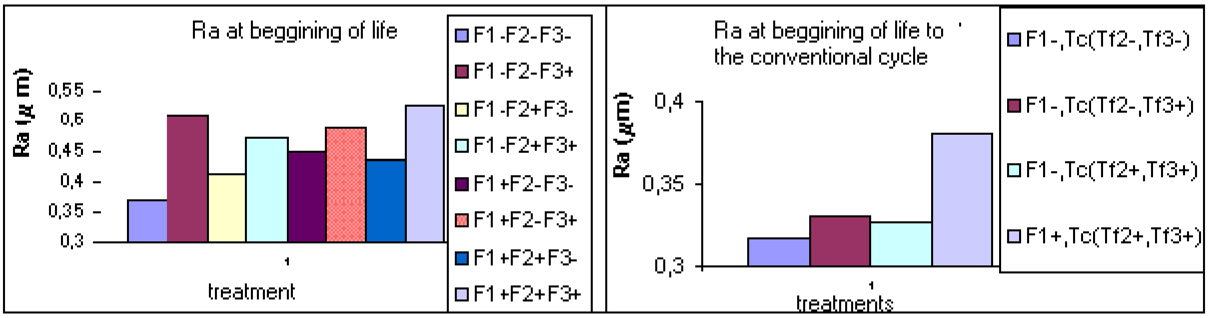

Figure 3: Comparison of roughness at the beginning of wheel life in each kind of cycle and their treatments

Initially, it can be seen in figure 3 that, to the cycle with 3 phases, all the tests done with the feed in the third phase at superior level, presented roughness higher than Ra = 0,45 µm, no matter the former feed levels. This shows the strong influence of this phase in the final quality of the workpiece. The conventional cycle, generated very low workpiece roughness in 3 of the 4 tests done. The roughness only increased strongly when it was combined a high feed of the cutting phase, with a low sparkout time.

It still can be noticed in figure 3 that the ground workpieces roughness obtained in the tests with three phases cycle were higher than that with the conventional cycle spending the same operation time. The faster condition of the conventional cycle (with sparkout time equal to the sum of the times of phases 2 and 3 of the cycle with three phases in their superior levels of feeds - f_{2+} and f_{3+}) generated values very close to the slowest condition of the cycle with three phases (with feeds f_{1-}, f_{2-}, f_{3-}). Such fact has relation to the real feed of the process in the last moments of cut. In the conventional cycle the real feed exists only at the final of the operation due to the elastic deformation recovering of the wheel shaft and workpiece happened at the beginning of the cut. In the cycle with 3 phases, the real feed at the last moments of the operation is the sum of this elastic recovering and the programmed wheel infeed for this third phase. If the elastic recovering does not start happening at the second phase of the cycle, the real feed in this phase will be greater than that in the conventional cycle. Probably, in the tests done using the three phases cycle, the second one did not contribute strongly to the elastic deformation of the wheel shaft and workpiece and, therefore, the workpiece quality obtained with the conventional cycle was better.

In a second phase of the results analysis, it was checked the mean roughness (Ra) behaviour. Again, the tests consisted in grinding 66 workpieces, without dressing the wheel. The goal of this analysis was to verify the roughness tendency as the volum of chip removed increased and the grinding wheel sharpness grew worse. The figure 4 shows this behaviour to the cycle with three phases and the figure 5 to the conventional cycle.

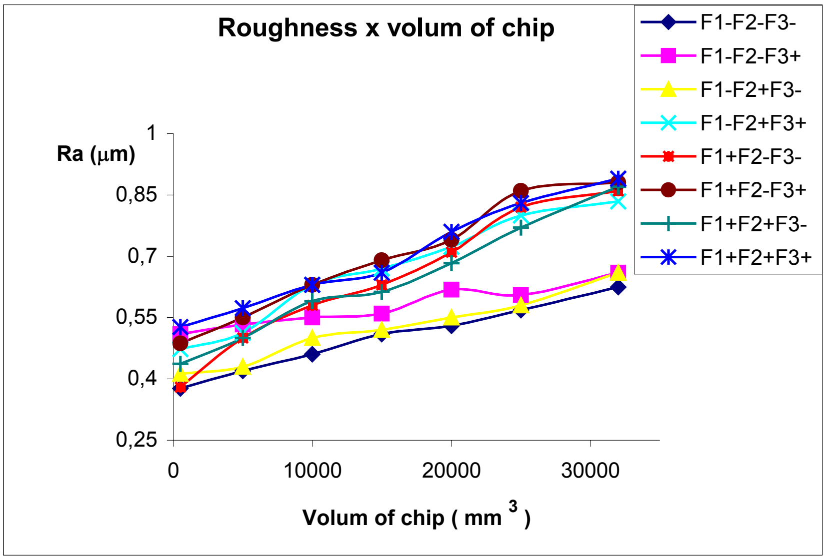

Figure 4: Roughness versus volum of chip removed - cycle with 3 phases.

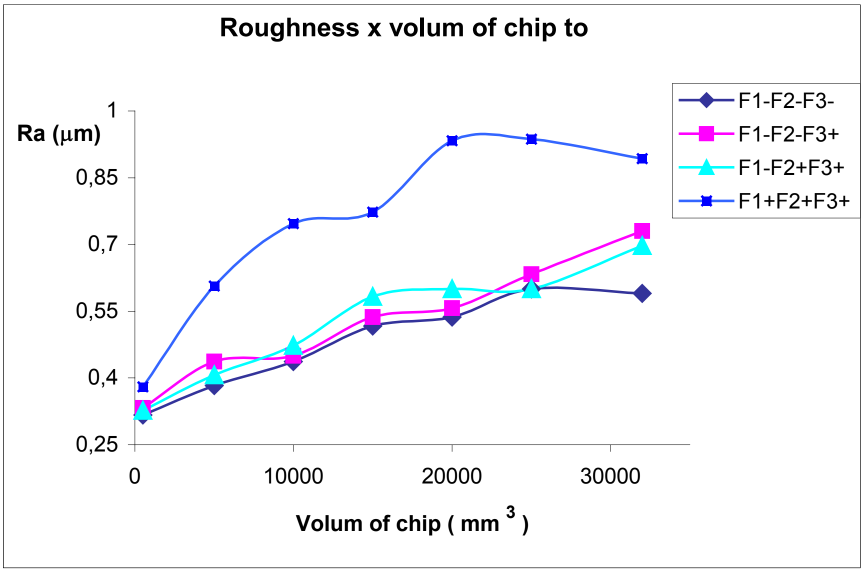

Figure 5: Roughness versus volum of chip removed – conventional cycle

Observing figures 4 and 5 it is possible to notice that the tests whose value of the phase 1 feed (f_1) was maximum, were those in that the roughness increased more through the tests. That is, those in which the wheel sharpness deterioreted more. Therefore, it can be concluded that the phase 1 is the factor that influence more the wheel sharpness. This was expected, since in this phase around 93% of all chip generated is removed. Another conclusion is that the roughness levels to both kinds of cycles, that iniatilly were lower to the conventional cycle, reached, at end of 32000 mm^3 of chip removed, similar values. This fact demonstrated that the conventional cycle deteriorates faster the wheel sharpness than the cycle with three phases. Probably this is due to the fact that, with the conventional cycle, the percentage of chip removed, in volum, with the higher feed is bigger than in the three phases cycle. Thus, analysing this figure, it can be concluded that, in terms of wheel wear, it is better to use the minimum feed value in phase 1, to the conventional cycle as well as to the three phases one. The phase 2 feed of the three phases cycle can be used in any level.

In the third phase of the tests it was checked the workpiece roughness to both kinds of cycle when the volum of material removed was 32000 mm^3, that is, when the grinding wheel was near its dressing moment as figure 6 shows.

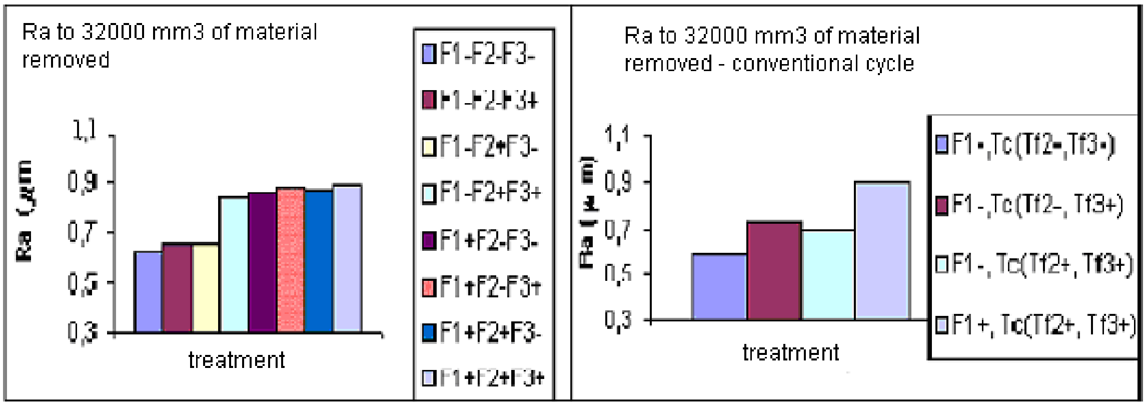

Figure 6:Comparison of roughness after 32000 mm^3 of chip removed to both kinds of cycle

It can be concluded from this phase of tests that, if the conditions f_{1+}, is used, the wheel life will be very short (depending on, of course, the Ra limit value), since the tests done with this feed level presented very high values of roughness when the volum of chip removed was 32000 mm^3 in the both kinds of cycles studied. As it was mentioned before, the phase 1 is that has more influence on the wheel condition and, therefore, on the workpiece roughness behaviour. Nevertheless, it is necessary a deeper study to conclude that the maximum feed of the phase 1 is not supposed to be used, since, although it implies in shorter lives of the wheel and, therefore, more dressings, it also generate shorter cutting time. So, it is necessary to verify, for a given workpiece batch, the fabrication time and cost to manufacture each part, considering the cutting and dressing cycles. But, analysing the figure 6, it can be concluded, that to the three phases cycle, if the goal is having longer wheel life, it must be used one of the three 3 following sets of feeds, that presented almost no difference in roughness when the volum mentioned in the figure was reached: f_{1-}, f_{2-}, f_{3-} or f_{1-}, f_{2-}, f_{3+} or even f_{1-}, f_{2+}, f_{3-}. It is logical that, in this choice, the better option is the set of values that gives a shorter cycle time (f_{1-}, f_{2-}, f_{3+}). To the conventional cycle the roughness behaviour followed the same trend, although the condition f_{1-} and Tc equal the Tf_{2-} plus Tf_{3-} presented a very lower roughness value than the other tests results. These results demonstrate that the value of f_3 do not influence the wheel wear. In the conventional cycle this value (that is considered as sparkout time) showed influent and when it was kept in its superior level, the sparkout time decreased, and the roughness increased.

In fourth and last phase of the tests it was checked the circularity at the beggining and at the end of the grinding wheel life for both kinds of cycle. The obtained values are displaied in tables 5 and 6.

Table 5: Values of circularity to the tests with three phases cycle.

Volum of chip removed mm^3	Circularity (µm)							
	Treatment							
	- - -	- - +	- + -	- + +	+ - -	+ - +	+ + -	+ + +
500	1,5	1	1,5	2	2	2	1,5	2
5000	2	1	1,5	1,5	1,5	2	1,5	2
10000	2	1,5	2	2	2	2	2	2
15000	2	2	1,5	2	2	2	2	1,5
20000	1,5	2	1,5	2	2	2	2	2
25000	2	2	2	2	2	2,5	2	2,5
32000	2,5	2	2	2,5	3	3	2,5	3

From the results presented in tables 5 and 6 it can be realized the following:

a) there is no trend of workpiece circularity increasing as the removed volum of chips increases. So, it can be said that the wheel condition did not influence the workpiece circularity;

b) the conventional cycle gave circularity values a little lower than the cycle with three feeds but, in any moment, the values of circularity reached a level that could be considered to high for a external cylindrical grinding operation. The highest circularity obtained was 3 µm. Considering that, in a workpiece (diameter 50 mm) that demmands IT5 tolerance, typical in grinding, the circularity level allowed must be 6,5 μm (half the dimensional tolerance). Thus, it can be concluded that the circularity is not supposed to be used as a factor of choice between the two types of tested cycles.

Table 6: Values of circularity to the tests with conventional cycle

Volum of chip removed mm^3	treatments			
	f1-f2-f3-	f1-f2-f3+	f1-f2+f3+	f1+f2+f3+
	Circ (μ m)	Circ (μ m)	Circ (μ m)	Circ (μ m)
500	1	1	1	1,5
5000	1,5	1,5	1,5	1,5
10000	1,5	2	1	1,5
15000	2	1,5	1,5	2
20000	2	1,5	1,5	1,5
25000	2	1,5	1,5	1,5
32000	1,5	2	1,5	1,5

4. Conclusions

Based in the obtained results in each phase of the tests, it can be concluded, to similar operations as tested, that:

- The roughness at the beginning of the wheel life to the cycle with three phases is more influenced by the third phase feed. When this was kept constant in its superior level the roughness were higher than Ra = 0,45 μm, no matter the feed level of the former phases, showing the strong correlation of the third phase with the workpiece quality. The ground workpiece roughness in the tests with three phases were higher than that obtained with the conventional cycle, spending the same time;
- After 66 ground workpieces, in both kinds of cycles, the phase 1 feed was the one that had higher influence in the wheel wear. The roughness obtained in the tests, initially was lower in the conventional cycle, but they reach, when the material removed was 32000 mm^3, similar values, showing that the conventional cycle deteriorate the wheel sharpness faster than the three phases cycle;
- At the end of 32000 mm^3 of material removed, if the conditions f_{1+}, are used, the wheel life will be very short (depending on, of course, the limite value of Ra) since the tests done with this feed presented very high roughness values to the two kinds of cycles studied. The phase 1 is that influenced more the wheel wear, therefore, the workpiece quality, but, it is not possible to affirm without doubt that the maximum feed in phase 1 is not supposed to be used, since, although the wheel life is short and the number of dressings increases, the cutting time is reduced.
- It was not observed a trend of workpiece circularity growing as the volum of chip removed increased. So, it can be concluded that the wheel condition did not influence the workpiece circularity. In the conventional cycle the circularity values obtained were a little smallers than that obtained in the three phases cycle, but the values obtained to this cycle did not reach 3 μm, what indicates that the circularity can not be used as a factor of choice between the two kinds of cycles.

5. Acknowledgements

AGENA.- Thanks to Eng.:Márcia Rios – to the cutting fluids
CAPES – to the financial support
SAINT GOBAIN ABRASIVES – to the grinding wheel

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