ELASTIC DEFORMATION ANALYSIS ON GRINDING CYCLES THROUGH VIBRATION SIGNALS

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Abstract: This work deals with plunge cylindrical grinding process of hardened steel. In this kind of operation the three phases cycle is usual: the first phase, the rough one,in which a large percentage of the stock is removed and and other two phases, in which the stock and the feed are reduced, in order to relieve the elastic deformation of the workpiece and wheel spindle generated in the first phase of the cycle, in such a way that the desired quality of the workpiece may be reached. The main objective of this work is to estimate, using vibration signals extracted from the workpiece, the deformation levels occurred in each one of the phases of the cycle and also to show the correlation between these signals and the surface and geometrical quality of the workpiece. Aiming these goals, several grinding experiments were carried out on ABNT 4340 steel with 55 HRc of hardness and wheel code ART FE 38A80K. The main conclusions were: vibration signals showed clearly that vibration is one of the factors which generates surface roughness and also that 60 to 75% of the chip volume removed in the second and third phases of a three phase cycle is due to the recovery of the elastic deformations caused by the former phases of the cycle..

Keywords: Grinding, vibration, elastic deformation

1. Introduction

Grinding process is largely used in metal-mechanic industries due to its ability to provide low surface roughness and tight tolerances to the workpiece. Generally, grinding is the last machining operation carried out on a workpiece, what makes it a very expensive operation. Therefore, this process must be very well controled, through a very precise selection of cutting parameters which may guarantee the desired quality in the shortest cutting time and cutting cost.

Several researchers searched a better understanding of the variable influences on workpiece quality. Abrão (1991) studied the temperature gradients on the contact zone between tool and workpiece, once the temperature in this region may reach values over 1000ºC and also it goes deep in the workpiece, reaching depths around 0.1 mm, causing lost of mechanical properties of the workpiece, like reduction of fatigue strength. Silva (2000) concluded that, for some cutting conditions, the level of mineral oil in the cutting fluid reduces tangencial cutting forces and, therefore, reduces also the cutting temperature. Oliveira (1989) correlated the wheel wear with the equivalent chip thickness and, from the results, observed that these parameters are inversely proportional. Hahn and Lindsay (1986) experimentally determined that the normal grinding force is proportional to the specific rate of chip removal. Malkin (1989) presented the mechanism of the elastic and plastic deformation of workpiece and wheel spindle in grinding process as a function of the forces involved in the process and, based on it, he affirmed that the elastic deformation of the system causes a smaller removal of material than it was expected for a certain feed. Pereira (2003) demonstrated that the conventional grinding cycles (with just one feed velocity) guarantee a better workpiece surface finish in the beginning of tool life when compared with cycles with three phases in some cutting conditions, when grinding SAE 4340 steel. He also concluded that, during the whole tool life, the conventional cycle wears the wheel more than the three phase cycle.

Among the grinding operations, the plunge cylindrical grinding operation is largely used in industries and, like other grinding operation, it needs a better understanding to improve the workpiece quality and to minimize the cycle time, as already cited. The kind of cycle of this process can be classified in: a) conventional, with just one feed velocity, followed by the spark out phase (in which the wheel does not have a programmed feed and the initial elastic deformation is relieved), according to figure 1a; b) three phase cycle, with a first phase with a high feed velocity (f_1) for roughing, a second phase with a smaller feed velocity (f_2) for semi-finishing and, finally, a third phase with a very low feed velocity (f_3) for finishing, figure 1.b.

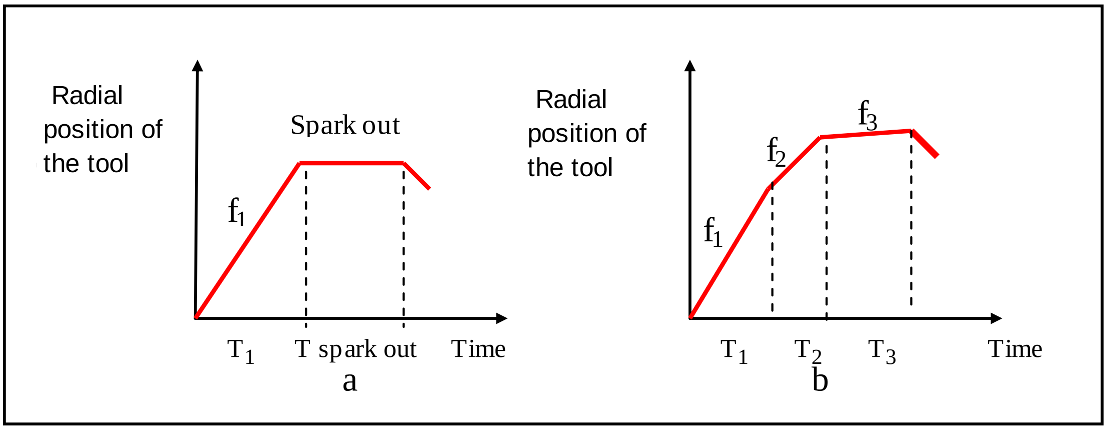

Figure 1 : a) conventional grinding cycle. b) three phase grinding cycle.

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2 Experimental Procedures

The machine tool used was a CNC cylindrical grinder and the operation was the plunge cylindrical grinding. The wheel dresser was a single point diamond with width, *bd*, equal to 0.7 mm, measured at 0.03 mm from the point. The overlaping dressing ratio, *Ud*, ($Ud = b_d/S_d$ (Oliveira, 1988), where S_d is the feed per revolution of the wheel) was 5 and, as *bd* was 0.7mm, S_d was fixed on 0.14 mm. Each dressing was made in 15 passes with dresing depth of 0.03 mm pass.

The acquistion of the vibration signal was carried out using a Kistler accelerometer fixed on the tailstock of the machine. Figure 2 shows the set up for the vibration signal measurement.

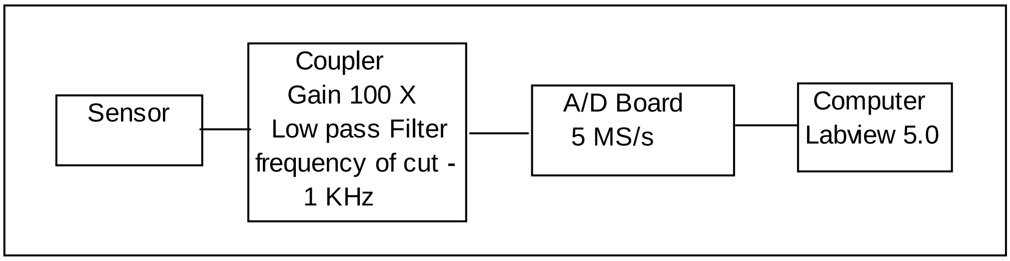

Figure 2: Set up for vibration signal measurement

2.1 Conditions of the experiments

The code of the wheel used in the experiments was FE 38A80KVS (Norton Abrasives). Its peripheral speed was kept constant an equal to 30 m/s. The workpieces were made of quenched and tempered ABNT 4340 steel, with average hardness after heat treatment of 56 HRC. Figure 3 presents a scheme of the workpiece used in the experiments. Grinding was carried out on the workpiece surfaces with 25 mm of width.

In order to make comparisons about the elastic deformation level still on the wheel-workpiece system between phases 2 and 3 of the cycle, it was necessary to monitor vibration during a whole grinding cycle, in such a way it could be possible to know the vibration of phase 2 with the deformation imposed by phase 1 and also to know the vibration of phase 3 with the deformation still present on the system after phases 1 and 2. In this experiment 160,000 vibration points were acquired with a sample rate of 8,000 points/s, during 20 seconds of acquisition.

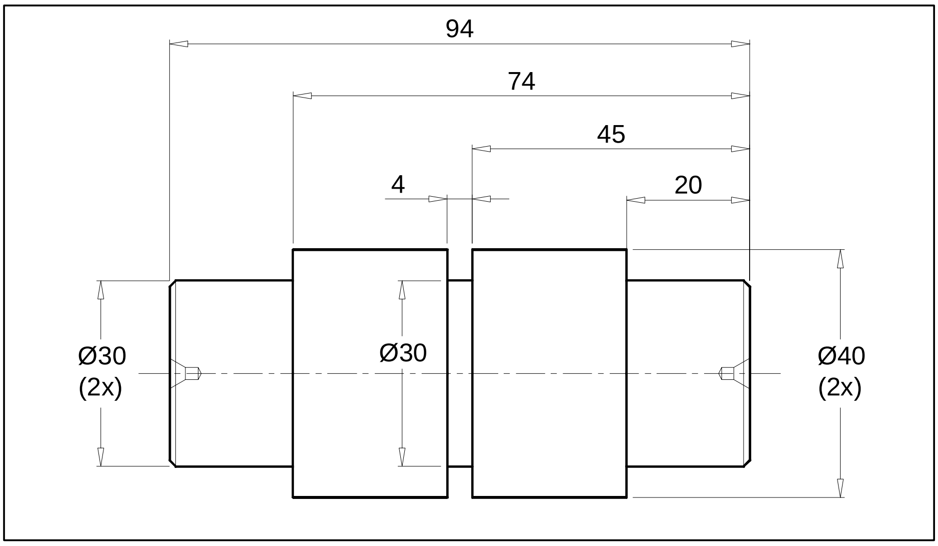

Figure 3: Workpiece used in the experiments.

The workpiece velocity *vw* was constant and equal to 15 m/min, the whole stock removed by phase 1, S_1, was 0.28 mm and the stock of phase 3, S_3, was 0.007 mm. The experiments consisted in the grinding of 2 workpieces for each condition (8 conditions) summing 16 ground workpieces. The input variables with their respective values are shown on table 1 and table 2 presents the matrix of these experiments.

Table 1: Variables and their levels for vibration analysis.

Variables	Lowest level (-)	Time (seg)	Highest level (+)	Time (seg)
Phase 1 feed (mm/rev)	0.007	10.8	0.009	8.40
Phase 2 feed (mm/rev)	0.002	1.756	0.0028	1.254
Phase 3 feed (mm/rev)	0.0004	4.73	0.0005	3.782

Table 2: Matrix of experiments for vibration analisys.

Order of experiments	f_1	f_2	f_3	Time (sec) $(f_1+f_2+f_3)$ + one workpiece revolution
1	+	+	+	13.435
2	+	+	-	14.382
3	+	-	+	13.94
4	+	-	-	14.886
5	-	+	+	15.84
6	-	+	-	16.78
7	-	-	+	16.34
8	-	-	-	17.28

The calculus of the time of each phase followed equation 2:

$$T_{f_i} = \frac{S_{mi}/2 * \pi.D}{15000.f_i} * 60(seconds) \quad (1)$$

Where:
Sm_i stock removed in the *ith* phase, in mm;
f_i is the feed of the *ith* phase in mm/rev;
D is the workpiece diameter in mm.

Workpiece roughness and roundness values were also measured and compared with vibration levels. Roughness was measured using a portable roughness meter with *cut-off* of 0.8 mm. The measurements were carried out 4 times on each workpiece with 90° of diference between each measurement. Workpiece roundness was measured turning the workpiece, fixed between tailstocks of the machine, with a milesimal dial gage measuring it.

Later, other experiments were carried out aiming to verify the deformation level through the vibration signal generated in each particular phase. So, feed values usually used for phase 2 and 3 were used in a phase with just one cycle. Therefore, the diference between the vibration values obtained in an operation using just feeds f_2 or f_3, without any previous phase and the values obtained when the operation was carried out with the complete cycle (three successive phases) would depict the amount of elastic recovery in these phases. In these experiments 50,000 vibration points were acquired with a sample rate of 4,000 points/s, in 10 s of acquisition. Two workpieces were ground in each condition (4 conditions - f_2+, f_2-, f_3+, f_3-) summing 8 ground workpieces. Table 3 present the feed values with the time related to each condition. The time required for one workpiece revolution was added to the time of the cycle.

Table 3 : Variable values for the experiments with just one phase.

Experiment	Lowest level (-)	Time (sec)	Highest level (+)	Time (seg)
Feed similar to f_2 (mm/rev)	0.002	1.756 +0,54*	0.0028	1.25 + 0.54
Feed similar to f_3 (mm/volta)	0,0004	4.7 +0,54	0.0005	3.78 +0.54

* *time of one workpiece revolution.*

3 Results and discussions

Figure 4 shows the correlation between surface roughness of the workpiece obtained in a three phase cycle and vibration of the phase 3 with the conditions shown on table 2.

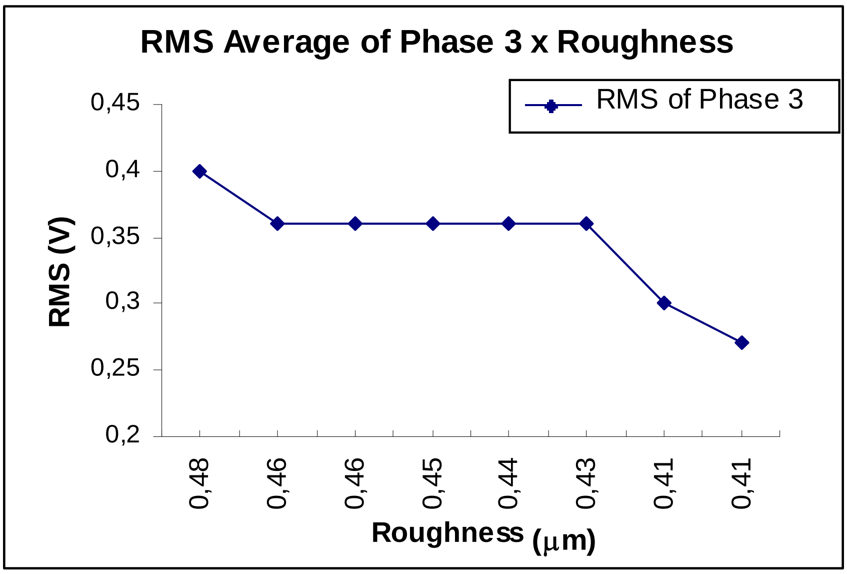

Figure 4: RMS vibration measured on phase phase 3 against workpiece roughness for a three phase cycle.

The vibration values were got by the RMS value taken at each 1,000 points. It can be seen on this figure that, as vibration decreased, surface rughness also decreased. When the RMS of vibration decreased from 0.397 to 0.267 V (reduction of 32%), roughness decreased from 0.477 to 0.405 μm (around 15%). It is important to point out that for roughness variations between 0.458 to 0.427 μm (6.76%) variations in the vibration level were not verified. However, it is also important to note that, due to the dispersion of roughness measurements in a given workpiece, it is not correct to say that a value of Ra = 0.458 μm is statistically different from Ra = 0.427 μm. Therefore, it can be said that roughness was constant while vibration was also constant. As vibration is one of the key factors to generate workpiece roughness, the roughness behavior against vibration shown on figure 4 is very plausible.

Figure 6 presents the RMS vibration signal for the 8 experimental conditions shown on table 2. It can be seen in this figure that the lowest vibration values were obtained when f_1 and f_3 were simultaneously kept on their lowest levels. Most of the elastic deformation of the system occurrs during phase 1 and, depending on the conditions of phases 2 and 3, it is more or less relieved up to the end of the cycle. It can be said that vibration is strongly dependent on the volume of material being removed per unity of time (Hassui, 1997). The material removed on phase 3 is the sum of the material which comes from the recovery of the elastic deformation still present and the material that would be regularly removed with a cycle with f_3 feed. Therefore, we can figure out the reason why the lowest vibration values were obtained when f_1 and f_3 were simultaneously kept on their lowest levels. In this case, phase 1 generated low elastic deformation and the material regularly removed with such a small feed (f_3) is also very small. When the two initial phases were kept in their minimum feeds and, consequently, little elastic deformation was generated in the beginning of the cycle, but the feed of the last phase was in its maximum feed (f_3+), workpiece vibration also presented a high value (at the same level of other experiments), what demonstrates the importance of having a low feed in the last phase. It is important to remember that the two experiments (with f_{1-} and f_{3-}) were the same in which the smallest values of surface roughness were obtained (figure 4), proving again the close relationship among cutting conditions, vibration and surface roughness.

Table 4 presents the matrix of experiments and the results obtained for workpiece roundness, roughness and the RMS vibration for the experiments with feeds f_2 and f_3, without any prior phase, i.e., the cycle had just one phase with small feed (similar to the feeds of the second phase and the third phase). Some conclusions can be extracted from the comparison of the values of this table and values of figures 4 and 5. Roughness values obtained with f_3 are around half of the values obtained with the whole cycle, showing that the spark out process was not completed on phase 3 and some of the elastic deformation was still present. Even roughness obtained with f_2 values was smaller than those obtained with the whole cycle (figure 4), showing that the volume of material actually removed on the third phase of a complete operation is bigger than the material removed by a phase with feed f_2 without any prior phase, since roughness is influenced by the volume of material removed per minute.

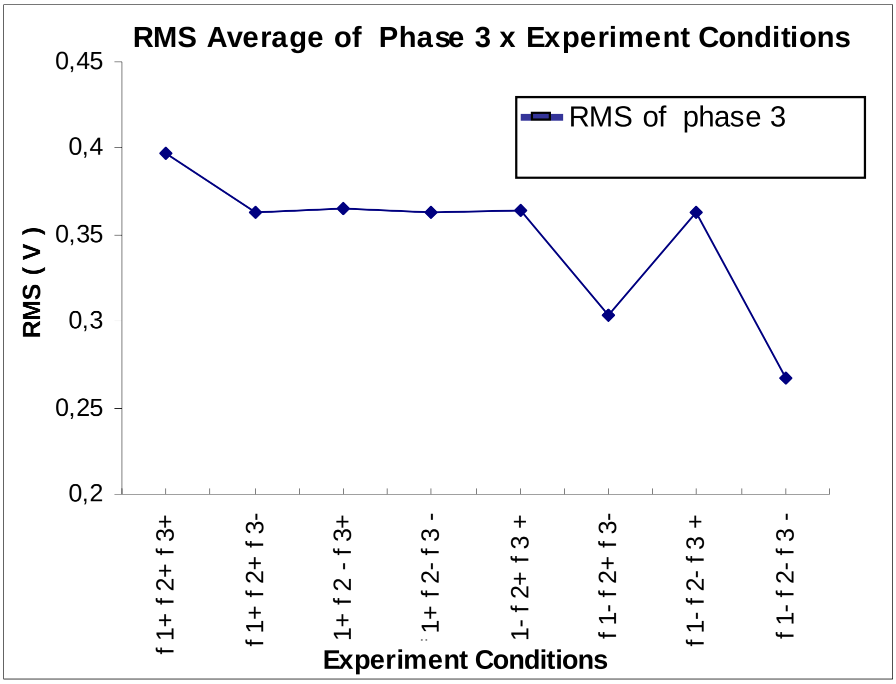

Figure 5: Average RMS of vibration for the conditions experimented.

Figure 6 presents a comparison of vibration levels when phases 2 and 3 of the cycle occurred together with other phases in a complete cycle and when they occurred without any prior phase. When they occurred in a complete cycle, the prior feeds were fixed in their maximum values f_1+ f_2+, i.e., (f_1+) when phase 2 was analyzed (f_2) and (f_1+, f_2+)

when phase 3 was analyzed. It can be seen in this figure how larger is tool vibration when those feeds occurred in a complete cycle than when they occurred without any prior phase. The former vibration signals were from 2.5 to 4 times bigger than the second signals. Assuming that vibration level is proportional to the volume of material removed per unit of time (Hassui, 1997), it can be said that 60 to 75% of the chip removed on phases 2 and 3 of a complete cycle is due to the recovery of the elastic deformation caused by the prior phases of the cycles, depending, of course, on the cutting conditions used in these phases.

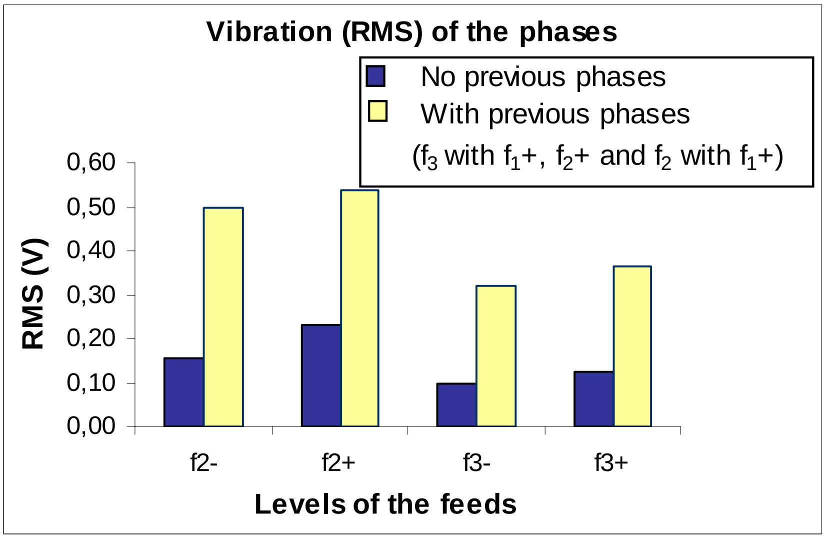

Figure 6: Average RMS of vibration for the complete cycles and cycles with just one phase.

Table 4: Experimental matrix and results obtained for cycle with just one phase.

Order of experiments		**feed**	**Results**						
		mm/rev	**Time**	**Roundness**		**Roughness Ra**		**Vibration**	
1°	2°		(s)	(μm)		(μm)		RMS (V)	
1	3	f_2+	1.25+0.54	2	2	0.37	0.39	0.143	0.1329
2	4	f_2-	1.756+0.54	2	1.5	0.35	0.33	0.12	0.121
3	2	f_3+	3.78+0.54	0.5	0.5	0.26	0.28	0.092	0.0806
4	3	f_3-	4.7+0.54	0.5	0.5	0.22	0.21	0.0742	0.0733

4. Conclusions

Based on the results, it can be concluded that, for conditions similar to those experimented in this work that:

- Vibration is one of the key factors which generated workpiece roughness;
- The smallest values of vibration and roughness were obtained when feed values of phases 1 and 3 were kept in their minimum values;
- Vibration level of phases f_2 and f_3 inside a complete cycle (with prior phases) was 2.5 to 4 times bigger than the level obtained when grinding was carried out without a prior phase (with just a phase), indicating that 60 to 75% of the chip removed on phases 2 and 3 of a cycle with 3 feeds are due the elastic recovery of the deformation caused by the prior phases of the cycle.

5. References

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