INVESTIGATION ON THE QUALITY OF HIGH SPEED MACHINED SURFACES

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Abstract. *Cast iron workpieces were high speed machined. They had several roughness parameters measured and these values were plotted in terms of roughness versus depth of cut charts. It could be noticed a relation between these values, but not the classical roughness increase of depth of cut. Moreover, the metalographical analysis was performed for these workpieces, in a search for phase changes on the carbon iron structure which indicate high temperatures at region caused by the high cutting speed.*

Keywords. Machining, HSM, roughness, manufacturing

1. INTRODUCTION

The high speed machining for cast iron parts is an opportunity to improve several aspects of its conventional machining processes [Toenshoff 2000]. Not only it shows ways to reduce costs but also to increase the flexibility of manufacturing lines which can replace one or more operations for high-speed ones.

An attempt to understand the behavior of this machining processes, regarding relations between its cutting parameters (such as cutting speed, feed rate and depth of cut) and its finished part characteristics (such as roughness, dimensional tolerances and waviness) becomes necessary.

Trough this effort, better applications of this process may be found, and perhaps other machining process can suitably be replaced by high speed machining operations. In that direction, other authors have considered replacing cylinder grinding operations by hard turning (Diniz et al. 2003, Matsumoto et al. 2001 and Sudo et al. 2001. It is the case of Klock et al. 1995, Toenshoff et al 1999 and 2000, Koenig 1987 and Poulachon & Moisan 1998. They suggest that not only this substitution is cost effective, but is also brings several improvements for environmental issues (hard turning doesn’t need coolant fluids) and for the flexibility of manufacturing processes (cylinder grinding is highly inflexible). Therefore, if it could be assured that any better conclusions are drawn by the possibility of high-speed hard turning, and trough the analysis of its finished part characteristics, an even better improvement can be reached.Attempting to reach that improvement, this paper refers to the analysis of high-speed machined part roughness, regarding concepts discussed in Tomita 1999, Dewes & Aspinwall 1997, Batalha & Stipkovic 2000. A further comparison between this process and other ones is made to elaborate whether advantageous to use high speed operations or not, regarding flexibility, costs and quality. Some of the items presented by Toenshoff et al 1999 and 2000 are reviewed here for a better understanding. In another part, referring to the same experiments, will describe the microstructure of the parts after high speed machining, attempting to understand the conditions of the cut, its mechanisms, the temperature distribution and the heat transfer from tool to workpiece.

2. EXPERIMENTAL METHODOLOGY

2.1 Material workpiece and experimental facilities

Three different samples of cast iron parts were prepared of several high-speed cuts through face milling: The test pieces came from blanks extracted from automotive press molds. Their metallographic microstructures are described below, on figure 1.

A Deckel Maho DMC 63V High Speed vertical machining center was used to perform down milling machining processes, with a five insert tool holder. As tools it was employed hard metal inserts, ISO K10, nominal diameter 7 mm, nominal thickness 2.38 mm, having an ISO code equivalence: REUW 0702M0 produced by Depo Fraestechnik. The roughness was evaluated and measured trough a Surfcorder roughness device, model SE 1700 α, with a spherical probe of 2 μm radius. The cut-off level was 2,5 mm, as suggested by the DIN 4768 standard. The roughness spectra were later analyzed by MatLab 5.3 mathematical software, running under a PC platform. An Olympus BX60 microscope connected to a PC took the pictures of the microstructure.

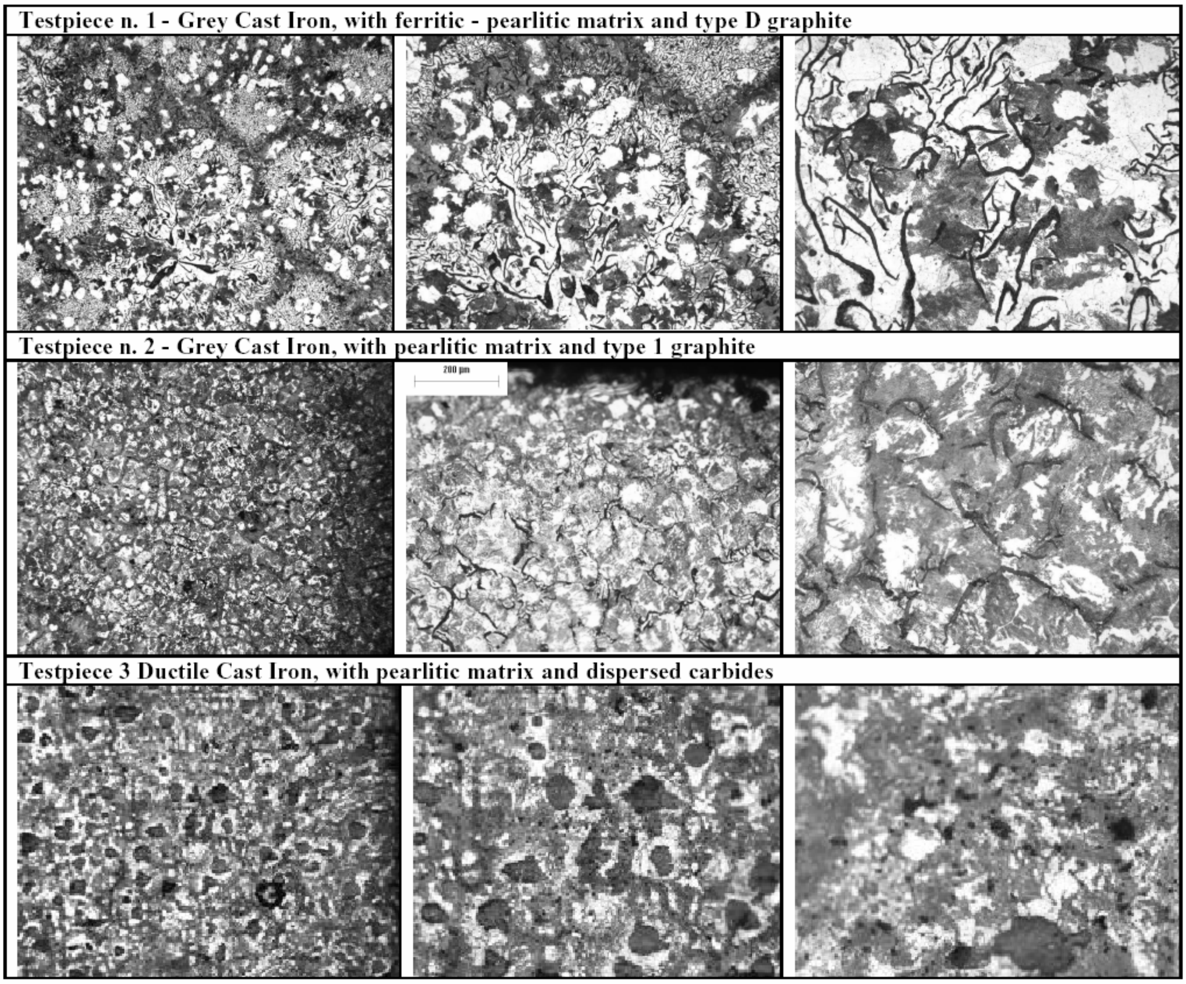

Figure 1. Testpieces and its metallographic microstructure for the high speed machined workpieces (nital etching).

2.2 Experimental planning

Over the three workpieces described on previous section 2.1, the machining center performed 25 cuts, with different cutting depths, to simulate machining operations as finishing, intermediate and roughing cuts. The arrangement of the experiments is described below, on Table 2.

Table 2. Experimental planning

Experiment number	Workpiece number	Cutting depth (mm)	Simulated machining operation	Experiment number	Workpiece number	Cutting depth (mm)	Simulated machining operation
1	1	0,1	Finishing	14	2	0,8	Intermediate
2	1	0,25	Finishing	15	3	0,9	Intermediate
3	1	0,4	Finishing	16	3	1	Roughing
4	1	0,5	Finishing	17	3	1	Roughing
5	1	0,5	Finishing	18	3	1	Roughing
6	1	0,5	Finishing	19	3	1	Roughing
7	1	0,5	Finishing	20	3	1	Roughing
8	1	0,5	Finishing	21	3	1	Roughing
9	1	0,5	Finishing	22	3	2	Roughing
10	2	0,5	Finishing	23	3	2	Roughing
11	2	0,5	Finishing	24	3	3	Roughing
12	2	0,6	Intermediate	25	3	3	Roughing
13	2	0,7	Intermediate				

The cutting parameters used for the experiments other than the depth cut, were

- cutting speed : 1000 m/minute
- Feed rate per tooth: 6000 mm/minute

As the cuts were performed, its roughness spectra as well as conventional roughness parameters R_a, R_z, R_y and S_m were acquired. Four different charts could then be plotted, arranging the roughness parameters versus the depth of cut. Through the mathematical processing of the roughness spectra could be found another roughness parameter, the fourth spectral moment (m_4). Its mathematical definition is described below.

$$m_4 = AVG\left[\left(\frac{d^2y}{dx^2}\right)^2\right] \tag{1}$$

For this equation, AVG (f) stands for the average of the values described by f, in a given interval. This interval can be described as the acquired roughness spectra, as y is the height of the peaks, taken over the distance described by x. Then, for each experiment a different m4 was found, and likewise the other charts, the fourth spectral moment was plotted versus the depth of cut. The machined workpieces had their surface etched with natal in a 10 % solution, in order to expose their metallographic microstructure. Three photos were taken for each test piece with different magnitudes: 100x, 200x and 500x. They perform 9 metallographic registers of the test pieces before the high speed experiments.

2.3 Results and discussion

In order to plot the measured results in form of charts, the following methodology was adopted: An average line was traced between all the points on the chart. Two other parallel lines to this average line were traced, over the maximum values observed. The region inside these two parallel boundaries (traced with segmented lines, while the average line is continuous) represents the achievable value for this operation; another two parallel lines were traced, between the maximum lines and the average and between the minimum line and the average. These medians could then isolate the common values regions (the gray area on the charts) from the possible values. The chart can be observed below:

Initially, the dispersion among roughness values when compared to its average is a common occurrence, when these are analyzed in an industrial basis. Moreover, several other deviations factors must be considered, such as those induced by perfilometers and roughness measurements and those implied by the nature of the machining process adopted: an interrupted cut trough face milling can contribute with another component to roughness spectrum. High feed rates, such as the one adopted for the experiments, may induce a lower frequency component to the spectrum, and therefore increase the roughness values.

Another possible effect that must be considered is the cut-off and the cut-off levels suggested by the adopted standard (DIN 4798). Cut-off algorithms work well for statistical patterns of not too irregular roughness, with frequency distributions more or less equal for all the bands. Therefore, in case these conditions cannot be fully assured, the suggested cut-off level may not be ideal, or even contribute to hide important characteristics for the understatement of the phenomena.

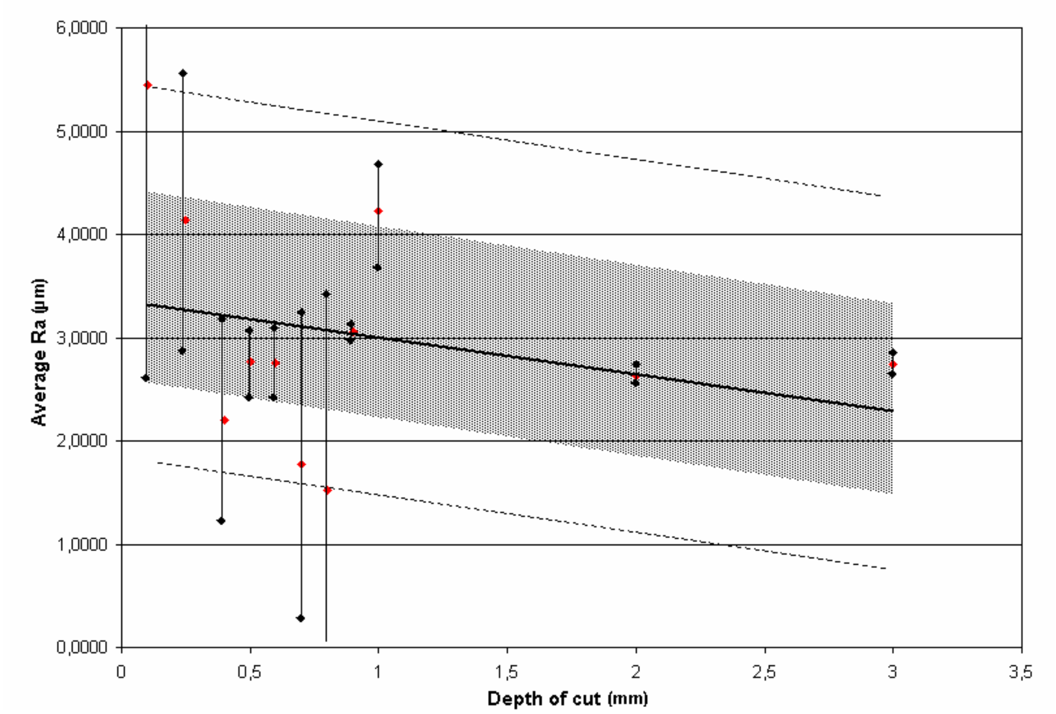

Figure 1. Roughness parameter Ra versus the depth of cut.

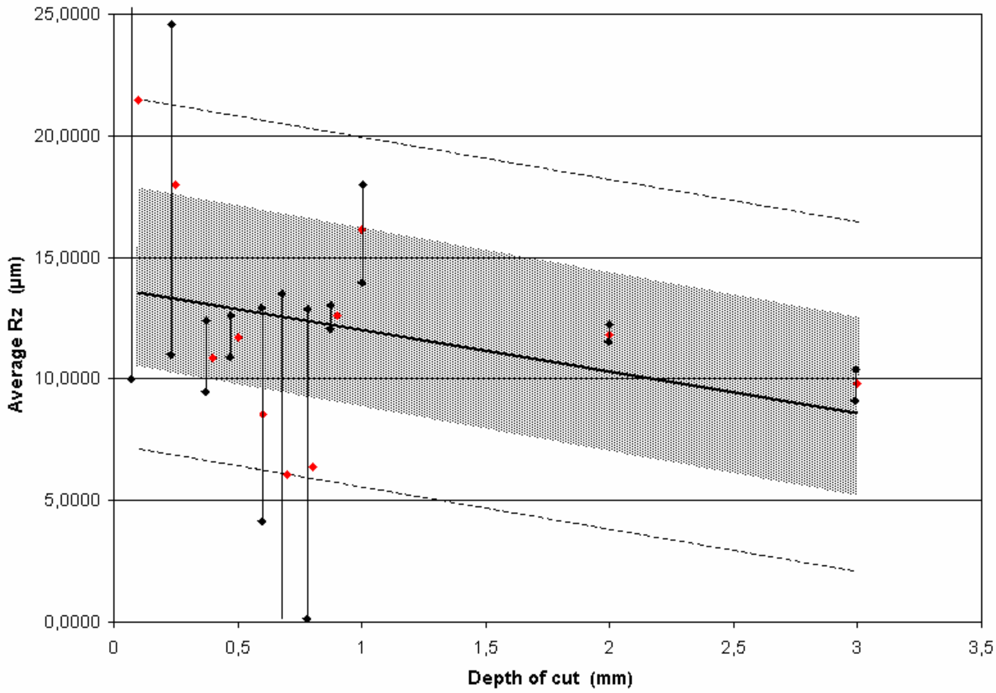

Figure 2. Roughness parameter Rz versus the depth of cut

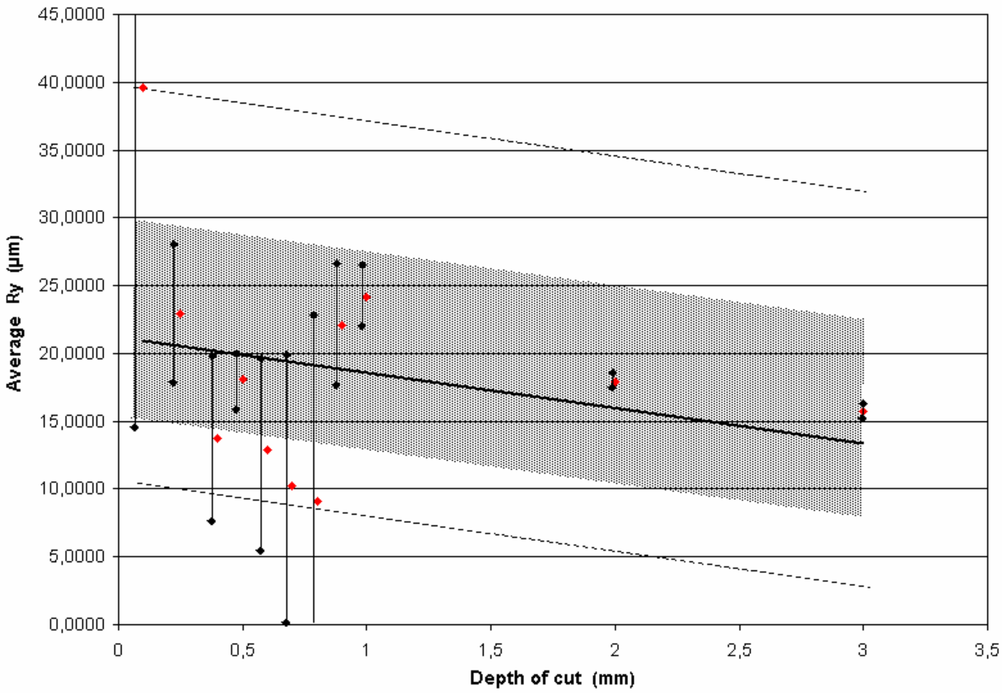

Figure 3. Roughness parameter Ry versus depth of cut.

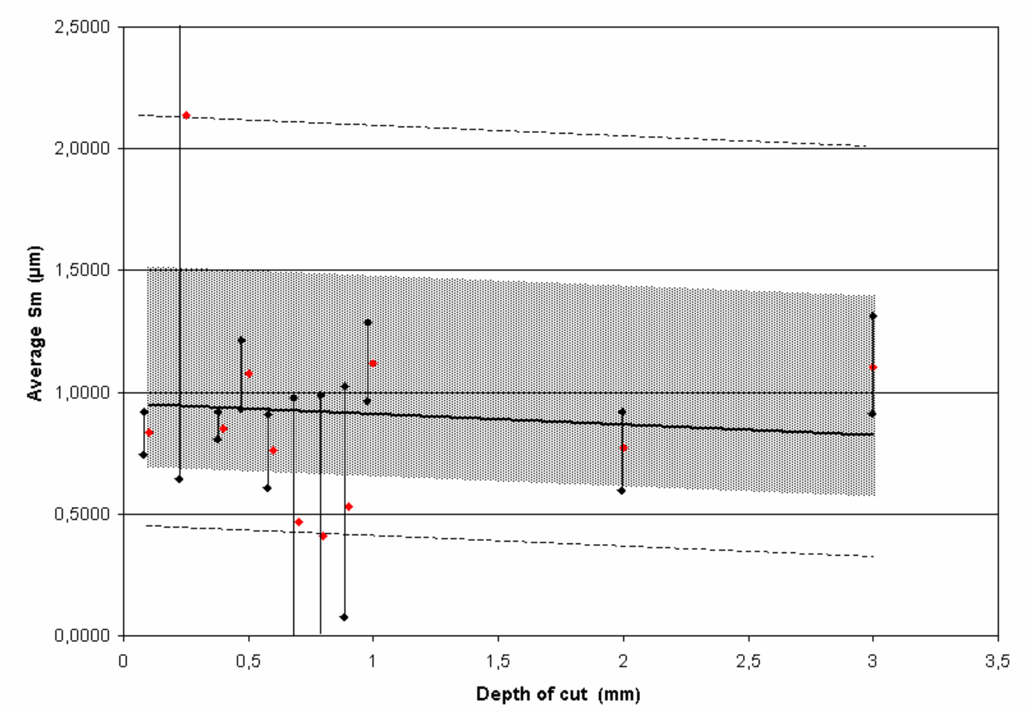

Figure 4. Roughness parameter Sm versus depth of cut.

The vibration must also be considered for the dispersion of the data. Not the one caused by unbalance of the tool-spindle assembly, but the vibration produced by the not continuous cut. The face milling in this case leads to vibration of harmonics proportional to the spindle rotation, which are transmitted to the part (and to the roughness profile which will be measured later), every time there is an impact of an insert of the tool for material removal.

Concerning the average roughness (Ra) measured; the values are compatible to the expected on the roughness standard DIN 4766. However, the decreasing condition of the average roughness related to the increase of the depth of cut is ambiguous. Classically, the contrary would be expected, since a greater volume of material to be removed (due to the increase of the depth of cut) would demand greater cutting strengths.

Those cutting strengths would make a surface with an average roughness every time higher, due to the fact that the speeds of chip formation and of surface formation are always the same, but with a growing volume of material.

When examining the distribution of values of the Rz parameters, searching for a better understanding, the evidence of high peaks and low valleys is typical from the rough face milling. Decreasing tendency related to the increase of the depth of cut is equally unexpected. The same goes for the analysis of Ry values: a greater volume of material to be removed apparently does not contribute to increase the value of this roughness parameter. However, the parameter of the average peak spacing (Sm) remained practically constant for all the samples. The low dispersion, together with a stable tendency for all the depth of cut covered, agrees with a machining that, although uses interrupted cut, makes regular surface patterns. These results are fully compatible to the expected, since there were not any sudden variations for the feed rate during the machining. Besides, these data help to prove the stability of the experiment initial characteristics during its time. Other interesting contribution can be taken from the chart below, which makes a relation between the fourth spectral moment (m_4) and the depth of cut. Trough this last roughness parameter a growing trend can be observed. It means that, as the depth of cut increases in high speed face milling, the peaks and valleys of its roughness tend to increase its size, as well as the sharpness of its summits. This is quite reasonable, since the greater volume of material removed at each insert cut would make surfaces built in a harsher way. This condition for quicker surface formation is confirmed by the variation of the roundness of the peaks and valleys, since the time for smooth formations (generally elastic formations) is compatible for small depths of cut and match smaller values for the fourth spectral moments. The same goes for this type of formation concerning the size of peaks and valleys.

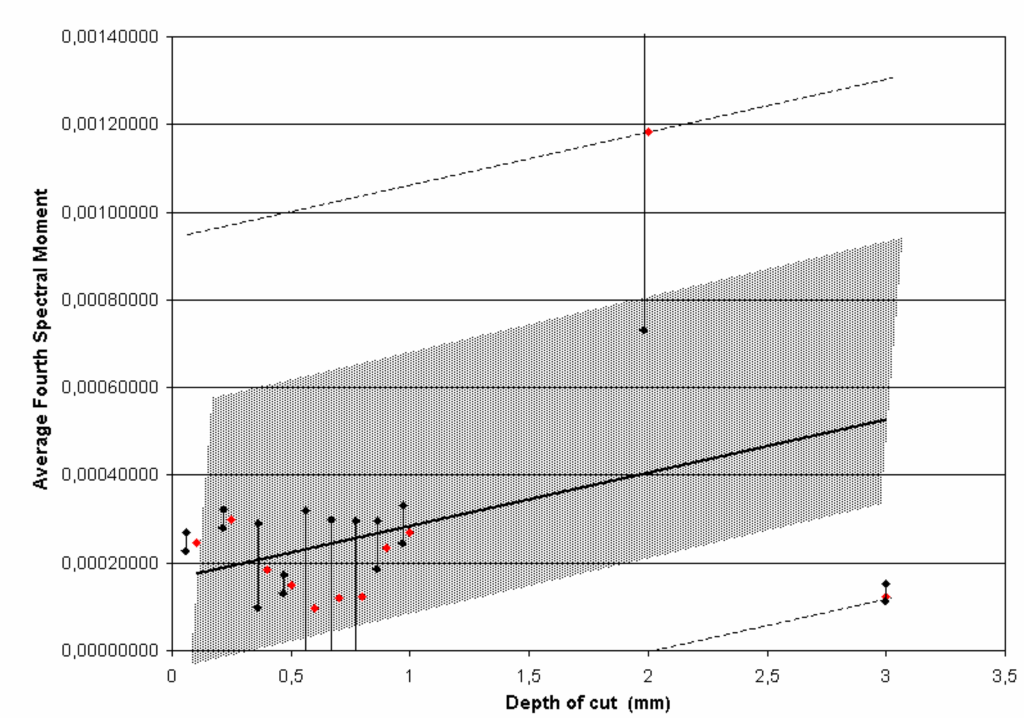

Figure 5. Average fourth spectral moment (m_4) versus the depth of cut.

It must be remembered that the cut-off level has a small influence over this parameter. As the fourth spectral moment comes out of four successive derivations of a signal, this result brings less sudden variations (which are filtered by the cut-off level), exactly because these variations are far from the derivation profile.

To sum up, concerning the obtained and analyzed data, the only parameters which agree with the classicaly expected are the average peak spacing (Sm) and the fourth spectral moment (m4). Altough certain critics may rise due to the low quantity of experiments which assure the exclusion or reduction of relevance for the other parameters (Ra, Rz and Ry) a greater attention must be paid to these two parameters of classical behavior, every time when investigating the surface quality of high speed machined parts.

Related to the high speed machining process itself, as a segment of a productive process, certain critics may be made; for example, the replacement of conventional machining process by other that involve high speed machining may be studied in a similar way which Toenshoff et al. (2000) [1] proposed for comparing cylindrical grinding and hard turning. They presents, as a basis for economical viability for both proceses, the surface rate (Å). Using typical values for both processes, the hard turning is more flexible and productive than the cylindrical grinding, since its surface rate is smaller.

This concept can suggest that cylindrical grinding would be more economically productive only when its large surface tax could be fully used (for example, in certerless grinding lor large batches or large parts).

Using the same concept, and the data valid for the experiments described before, as an analogy for high speed turning, the table 3 can be built.

As can be seen in Table 3, using common industrial parameters, such as cutting speed (Vc) and feed rate (f), there is a even greater benefit when moving from cylindrical grinding to high speed hard turning. The range of typical values for its surface rate reaches the minimal typical for hard-turning (therefore assuring flexibility and productivity at least equivalent) as well as the maximal values near to the typical for cylindrical grinding, allowing a concurrence for the operations of larger batches or longer parts.

This table is quite interesting, but only for specific economical studies. A better understatement of the process can be inferred when analysing other factors, such as machine purchasing costs, tooling costs and others. This van be illustrated by Table 4.

The following considerations can be made regarding Table 4. Despite the processing time is always shorter, the removal rate be shorter, enhancing the flexible characteristic, or large, improving ists large batch capacity. Certainly the costs for machine and tooling acquisition are the greatest obstacles present today.

Table 3. Comparison between cylindrical grinding, hard turning and high speed hard turning

	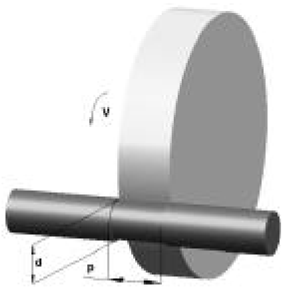	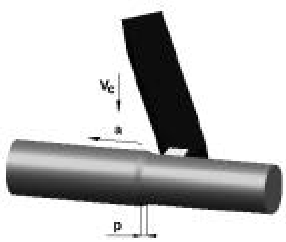	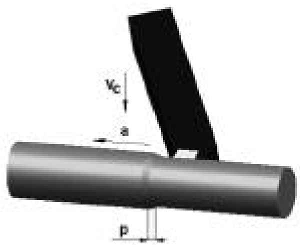
Process	Cylindrical Grinding	Hard turning	High speed hard turning
Material removal rate	$Q = a_p \cdot Q'$	$Q = p \cdot a \cdot V_c$	$Q = p \cdot a \cdot V_c$
Specific removal rate	$Q' = d \cdot \pi \cdot V_a$	$Q' = p \cdot a \cdot V_c / l_c$	$Q' = p \cdot a \cdot V_c / l_c$
Surface rate	$Å = p \cdot V_a$	$Å = a \cdot V_c$	$Å = a \cdot V_c$
Characteristic parameters	p = 5 - 20 mm V_a = 1 m/s	p = 0,05 - 0,3 mm a = 0,05 - 0,2 mm V_c = 150 m/min	p = 0,05 - 0,3 mm a = 0,05 - 0,2 mm V_c = 1000 m/min
Typical values	Q' = 2 - 12 $mm^3/mm.s$ Q = 10 - 240 mm^3/s Å = 5000 - 20000 mm^2/s	Q' = 22 - 242 $mm^3/mm.s$ Q = 6 - 150 mm^3/s Å = 125 - 500 mm^2/s	Q' = 154 - 1694 $mm^3/mm.s$ Q = 42 - 1000 mm^3/s Å = 833 - 3333 mm^2/s

Table 4. Comparison between cylindrical grinding, hard turning and high speed hard turning for global aspects.

		Hard turning	Cylindrical grinding	High speed machining Hard turning
Economical aspects	Processing time	☺/☹*	☺/☹*	☺
	Removal rate	☺	☹	☺/☹
	Acquisition costs	😐/☺**	😐/☹**	☹
	Tooling costs	☹	☺	☹
Flexibility	Multi face machining	☺	☹	☺
	Profile machining	☺	☹/😐	☺
Ecological Aspects	Power consumption	☺	☹	☹
	Cooling fluid	☺	☹	☺
	Chip recycling	☺	☹	☺
Quality	Finished part quality	?	☺	☺ / ?
	Process assurance	?	☺	☺ / ?
	Surface integrity	?	☺	☺ / ?

☺ : positive evaluation 😐 : neutral evaluation ☹ : negative evaluation ? : Indeterminate

Observations:
* Depending on the application, a rate of 1:10 to 10:1 is possible.
** Special machines or grinding centers are frequently needed.
The multi-face and profile machining are obvious advantages for the high-speed processes over the grinding, as long as the power comsuption does not prevent the application. Since the majority of high speed processes does not demand cooling fluids, a pumping unit can be discarded, and the recycling for the chips improved.
As for the quality, there has been some controversy on that matter, since the final result is directly dependent on the tool performance during the cut. Grinding wheels may have an adavantage, but not always, due to its self-sharpening nature.

3. CONCLUSIONS

For the investigated experiments, the following conclusions can be made:

- The investigation on the roughness quality for high speed machined surfaces trough the high speed face milling, using several roughness parameters, could indicate that in several occasions the classical increase of the parameter related to the depth of cut increase did not happen.
- Regarding the dispersion among roughness parameters, it can be suggested that, dor the parameters here reviewed, those which better fulfil the needs for the machining process are the average peak distance (Sm) and the fourth spectral moment (m_4).

As further regardings it could be also stated:

- The high speed machining process are, in a common sense, more productive and flexible, when compared to the conventional machining processes. This evidence is even greater when the machine and tooling cost are note considered.
- New possibilities for manufacturing sequences are possible, and an immediate example for this operation is the high speed turning of short parts, like crankshafts, CV joints and axle tips.

4. REFERENCES

1) Tönshoff, H. K. et al., 2000, "Cutting of Hardened Steel", Annals of CIRP, Vol. 49/2, p. 547–66
2) König, W. et al., 1987, Alternative Processes For Cost Reduction", Annals of CIRP, 36/2, p. 443 - 44
3) Tönshoff, H. K., Amor, R. B. e Andrade, P., 1999, "Chip formation in high speed cutting (HSC)", Society of Manufacturing Engineers 253, p. 1-12
4) Poulachon, G., Moisan, A., 1998, "Contribution to the study of the cutting mechanisms during high speed machining of hardened steel", CIRP Annals of Manufacturing Technology 47
5) Diniz, A. E. , Ferreira, J. R. & Teixeira Filho, F., Influence of refrigeration / lubrication condition on SAE 52100 hardened steel turning at several cutting speeds, International Journal of Machine Tools and Manufacture, 43, 3, February 2003, 307-15.
6) Matsumoto, H. , Pedrosa, E. A. & Diniz, A. E. Substituição do processo de retificação pelo torneamento de aços endurecidos em peças forjadas, Proc. 16th Brazilian Congress of Mechanical Engineering, Manufacturing Process, v. 14, p. 453-60.
7) Klocke, F. , Koenig, W., Koch, K. F. & Schroeter, R. B. , 1995, Torneamento de precisão: Uma opção para o acabamento de peças de aço temperado, Máquinas & Metais, pp. 56-67.
8) Sudo, T. T. , Braghini Jr., A. & Coelho, R. T. – Desgaste de ferramentas em torneamento com alta velocidade de ferro fundido GG25, Proc. 16th Brazilian Congress of Mechanical Engineering, Manufacturing Process, v. 14, p. 133-142.
9) Tomita, K., 1999, "O atual estágio da HSM e dos materiais de ferramentas de corte", Máquinas e Metais, No. 405, pp. 20-39, out.
10) Dewes, R. C. & Aspinwall, D. K., 1997, "A review of ultra high speed milling of hardened steels", Journal of Materials Processing Technology n. 69, p. 1 -17
11) Batalha, G. F. & Stipkovic Filho, M. "Analysis of the contact conditions and its influence on the interface friction in forming processes", In: Metalforming 2000, Pietrzyk et al. (eds), Balkema, Rotterdam, 2000, ISBN 90 5809 157 0, pp. 71-7.
12) McCool, J. I., 1988, "The Distribution of Microcontact Area, Load, Pressure and Flash Temperature under the Greenwood-Williamson Model", Trans. of the ASME, Journal of Tribology, Vol. 110
13) Zhang, G. & Kapoor, G., 1991, "Dynamic Generation of Machined Surfaces – Part 2: Construction of Surface Topography", Trans. ASME – J. Engineering for Industry, 113, p. 346.
14) Salles, J. L. C., Gonçalves, M. T. T. & Corrêa, L. O.- Roughness surface in turning, , Proc. 16th Brazilian Congress of Mechanical Engineering, Manufacturing Process, v. 14, p. 316-26.

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