23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

THE INFLUENCE OF CUTTING SPEED AND FEED-RATE ON ROUNDNESS AND SURFACE ROUGHNESS OF MACHINED VALVE SEATS IN SERIAL PRODUCTION

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Abstract. *The machining of valve seats is essential for proper engine performance, once correct seating of the valves assures the correct sealing. Valve leakage will adversely affect the engine compression ratio and therefore the engine efficiency. The machined valve seats must comply with the roundness and roughness project requirements. This work investigates the influence of cutting speed and feed-rate on the boring of valve seats of internal combustion engines using polycrystalline cubic boron nitride (PCBN) tools in serial production. This study takes in consider the process capability and process performance* P_{pk} *index. It was observed that higher cutting speeds result in higher roundness variations. Besides, as the feed-rate increases the surface roughness variations decrease. The best results were found for the cutting speed of 55 m/min and feed-rate of 0.15 mm.*

Keywords: *boring, valve seats, machining*

1. INTRODUCTION

The current view of the market shows a high rate of growth of the automotive industry, driven by technological advances and great demand in this industrial branch. This increased demand for vehicles makes automotive components supplier industries constantly improve their manufacturing processes. Among these automotive components is the engine head (Fig. 1), which is an important piece for the proper functioning of a combustion engine. The engine heads manufacturing process involves the use of high technology, and presents some situations that require further study for process improvements. In this case, one can cite as examples the machining of high complexity parts of the engine head as camshafts housings, valve guides and sintered valve seats. Components produced by powder metallurgy such as valve seats have advantageous characteristics with respect to chemical, mechanical and functional properties. Consequently, the machining of these components is an emerging topic for industry and science (Saoubi et al., 2014).

Figure 1. Engine head of eight pre-mounted valves

The valve seats together with the mechanical valves form the pair ensuring the correct sealing of the combustion chamber (Fig. 2). The geometry of valve seats is critical in order to ensure leak proof operation of the engine especially during the compression and combustion strokes. Valve leakage will adversely affect the engine compression ratio and therefore the engine efficiency (Powalka, 2008).

Due to their mechanical properties, the valve seats have become difficult to machine parts. Roundness and surface quality of the valve seats are influenced by the cutting tool, machine tool rigidity, cutting conditions and vibrations during the machining process (Siqueira e Lacerda, 2010). In multiple valve engines the diameters are smaller and the materials to be machined are increasingly harder. These conditions and the aim for higher cutting speeds imply higher tool requirements in the process of machining (Rocha et al., 2004). Due to the difficulty in machining this component, it is important to study the influences of the cutting parameters such as cutting speed and feed-rate on the manufacturing process in order to determine appropriate values for these parameters. Roughness and circularity of valve seats have great importance once they are directly linked to engine performance, thus a deep understanding of these parameter behavior is an important issue.

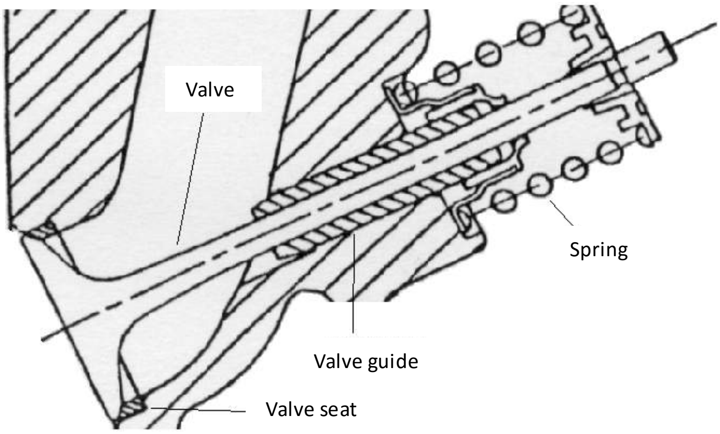

Figure 2. Scheme of an engine valve assembly (Hanna, 2003).

Due to the specific characteristics of the valve seats, some tolerances are very narrow, hence the requirement for a serial production becomes more complex. Therefore, there is a need for studies that analyze the process behavior concerning the process stability, in order to minimize the need for process control of the manufactured parts. This work aims to study and establish appropriate values for feed-rate and cutting speed in boring of sintered valve seats in order to find the combination that presents the best roundness and surface roughness values meeting the requirements of the product. In this work three different values of cutting speed (v_c) and two of feed-rate (f_z) were used to determine which combination offers a better process performance, considering the limits of 0.01 mm roundness and 7 μm R_z. The results of roundness and surface roughness measurements were analyzed by using Minitab software for statistical analysis of process capability. From these data, histograms and P_{pk} indexes were generated to identify which combination showed the best result.

2. MATERIALS AND METHODS

2.1 Samples preparation

A sintered ferrous valve seat material is made of powder mixture, comprising a hardening phase by sintering and another of finely dispersed carbides. The valve seats were pressed automatically with 4.5 ton into the engine head by a hydraulic press and auxiliary mounting devices.

2.2 Cutting tool

A boring tool of Hanna Integrated Solutions Manufacturer with single cutting edge, internal cooling, and effective diameter of 26.6 mm with TiN coated PCBN insert (TPGN 09 02 04) was used for the machining tests (Fig. 3). Radial and axial runouts were measured and held within the tolerance of 0.005 mm. New cutting edges were used for each new cutting parameters condition.

Figure 3. Cutting tool with PCBN insert

2.3 Cutting parameters

For this particular application it is recommended the use of cutting speed between 40 and 60 m / min, taking into account the sintered material to be machined with PCBN. Hanna (2003) recommends the use of 60 m / min and Mapal (2003), for the same application, recommends cutting speeds between 50 and 60 m / min.

Taking in consider the tool´s manufacturers recommendations, the cutting speeds used in this work were 50 m / min, 55 m / min and 60 m / min.

Hanna (2003) recommends feed-rates between 0.1 and 0.15 mm and Mapal (2007) between 0.08 and 0.12 mm for boring of sintered valve seats. Two feed-rates were used in the cutting tests: 0.1 and 0.15 mm.

2.4 Machine-tool

A horizontal machining center Mori Seiki NH5000DCG was used for the experiments. The machine has rapid speed of 50 m / min and maximum rotation speed of 15,000 rpm. The machine also has acceleration of 6.9 m / s^2, 730 mm travel in the X and Y axis and 850 mm in the Z axis and it has FANUC numerical control and MSX-701III interface.

2.5 Roundness and surface roughness measurements

Roundness of the valve seats were measured by an inspection gauge model M9VG produced by Marposs SpA Italy. Two specifically designed probes were used. One was placed on the valve seat, perpendicular to the seating surface, the other, in combination with a mechanical reference, was placed on the valve guide surface. The gage was inserted into the valve guide by the operator who starts the measuring cycle. A closed loop controlled motor rotated the gage plug in the bore forward and backward. The cycle time was approximately 4 s. The high precision motion control, together with a special transmission joint, minimized the operator influence. The measurement uncertainty of the system was 0.8 μm. All measurements were performed in controlled temperature room at 20º C.

Standard surface roughness parameter R_z was measured by surface roughness tester model Perthometer S2 produced by Mahr GMbH, Germany. Measurements were performed with a measurement length of 1.75 mm and cut-off of 0.25 mm.

2.6 Methodology

The experiments were carried out for six combinations of cutting speeds and feed-rates as shown in Tab. 1. The same position exhaust valve seat was analyzed for each engine head. A total of 180 samples were considered for the analysis. Roundness was measured for all the samples. Surface roughness was measured for 15 samples for each combination. In this case the samples have been aleatory chosen.

Table 1. Combinations of cutting speeds and feed-rates

Combination	Cutting speed (m/min)	Feed-rate (mm)
1	50	0.10
2	50	0.15
3	55	0.10
4	55	0.15
5	60	0.10
6	60	0.15

2.7 Statistical Analysis

All the results obtained in the measurements of roundness and surface roughness were analyzed by using Minitab software for statistical analysis of process capability. From these data, histograms and process perform (P_{pk}) indexes were generated to identify which combination showed the best result.

The results were analyzed taking into account the resulting P_{pk} index and also the data distribution within the histogram. The combination considered the best was the one that resulted in suitable P_{pk} index for each feature (roughness and roundness). It was stated that only process perform indexes above 1.33 would be accepted.

3. RESULTS AND DISCUSSIONS

Table 2 shows the minimum, maximum and average roundness and surface roughness values obtained for the different combinations performed.

Table 2. Results of roundness and surface roughness for the six combinations of parameters.

Roundness (mm)	**01**	**02**	**03**	**04**	**05**	**06**
Average	0.005	0.005	0.005	0.005	0.006	0.005
Maximum	0.008	0.009	0.008	0.008	0.012	0.009
Minimum	0.001	0.003	0.001	0.002	0.001	0.000
Amplitude	0.007	0.006	0.007	0.006	0.011	0.009
Surface roughness (μm)	**01**	**02**	**03**	**04**	**05**	**06**
Average	3.625	3.959	3.941	3.699	3.703	3.635
Maximum	5.090	5.270	4.830	4.620	5.000	4.850
Minimum	1.450	2.490	2.860	2.740	1.600	2.060
Amplitude	3.640	2.780	1.970	1.880	3.400	2.790

One can observe that the average values are very close for the different combinations. However, there is a significant difference between the amplitudes. In order to evaluate the stability of the process in a long range, it is necessary to carry out an analysis of the data amplitude and dispersion of the results as follow.

Figure 4 shows histograms related to variations in roundness of valve seats for all the six combinations.

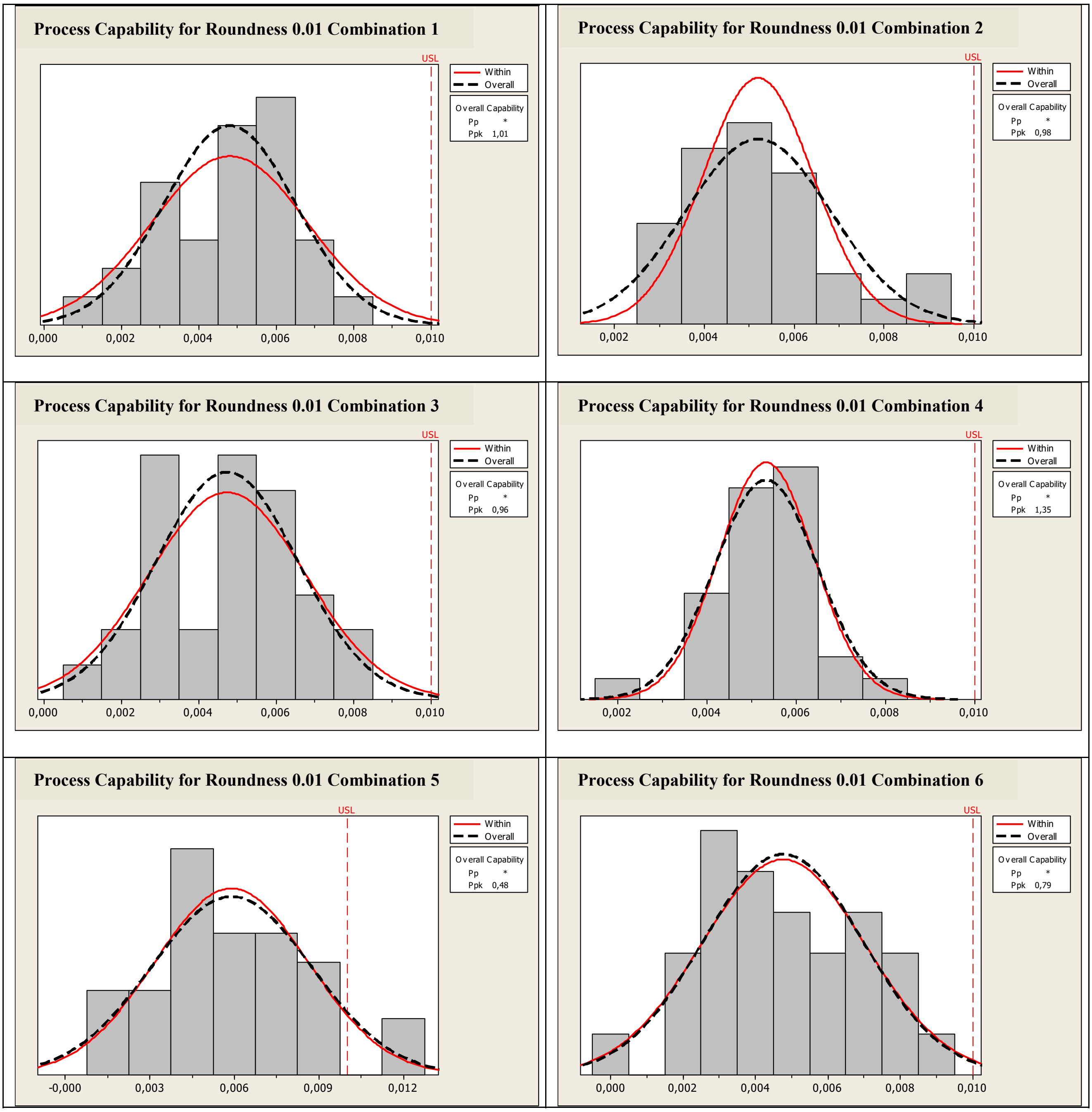

Figure 4. Results of roundness for different combinations of v_c and f_z.

For combination 1 (v_c = 50 m / min and f_z = 0.10 mm) one can see a wide dispersion of results, and these have a range between 0.001 mm and 0.008 mm and with most of the samples within 0.005 and 0.006 mm. This variation corresponds to 70% of the tolerance.

Combinations 2 and 3 show similar behavior. In the histogram of combination 2 (v_c = 50 m / min and f_z = 0.15 mm) there is a variation from 0.003 mm to 0.009 mm covering 60% of the tolerance. It can be seen in this histogram that the curve has a near ideal behavior, because even with a variation of 60% of the tolerance, the values are concentrated between 0.004 mm and 0.005 mm, which already show better stability and centralization of the process. Meanwhile the histogram of combination 3 (v_c of 55 m / min and f_z 0.10 mm) has a variation of 70% of the tolerance with data concentrated at 0.003 mm and 0.005 mm, however with a significant amount allocated at 0,006 mm .

Although the histogram of combination 4 (v_c = 55 m / min and f_z = 0.15 mm) also presents a variation of tolerance of 60%, it has a unique characteristic, since 60% of data are concentrated at 0.005 and 0.006 mm. This indicates a large stability and repeatability of the process for this combination. The shape of the curve indicates that data are concentrated near the center of the tolerance.

Combinations 5 (v_c = 60 m / min and f_z = 0.10 mm) and 6 (v_c = 60 m / min and f_z = 0.15 mm) presented the worst results among the tests. The histogram of combination 5 has a variation of 100% of the tolerance with values outside the specified range reaching 0.012 mm, and the data are scattered throughout the allowable tolerance range. The histogram of combination 6 has variation of 90% of the tolerance and data are completely spread throughout the tolerance range. Thus, the use of these cutting parameters resulted in great instability of the process.

After all the analysis performed, it is possible to conclude that the best results for roundness were found for combination 4.

Figure 5 shows histograms related to variations in surface roughness of valve seats for all the six combinations.

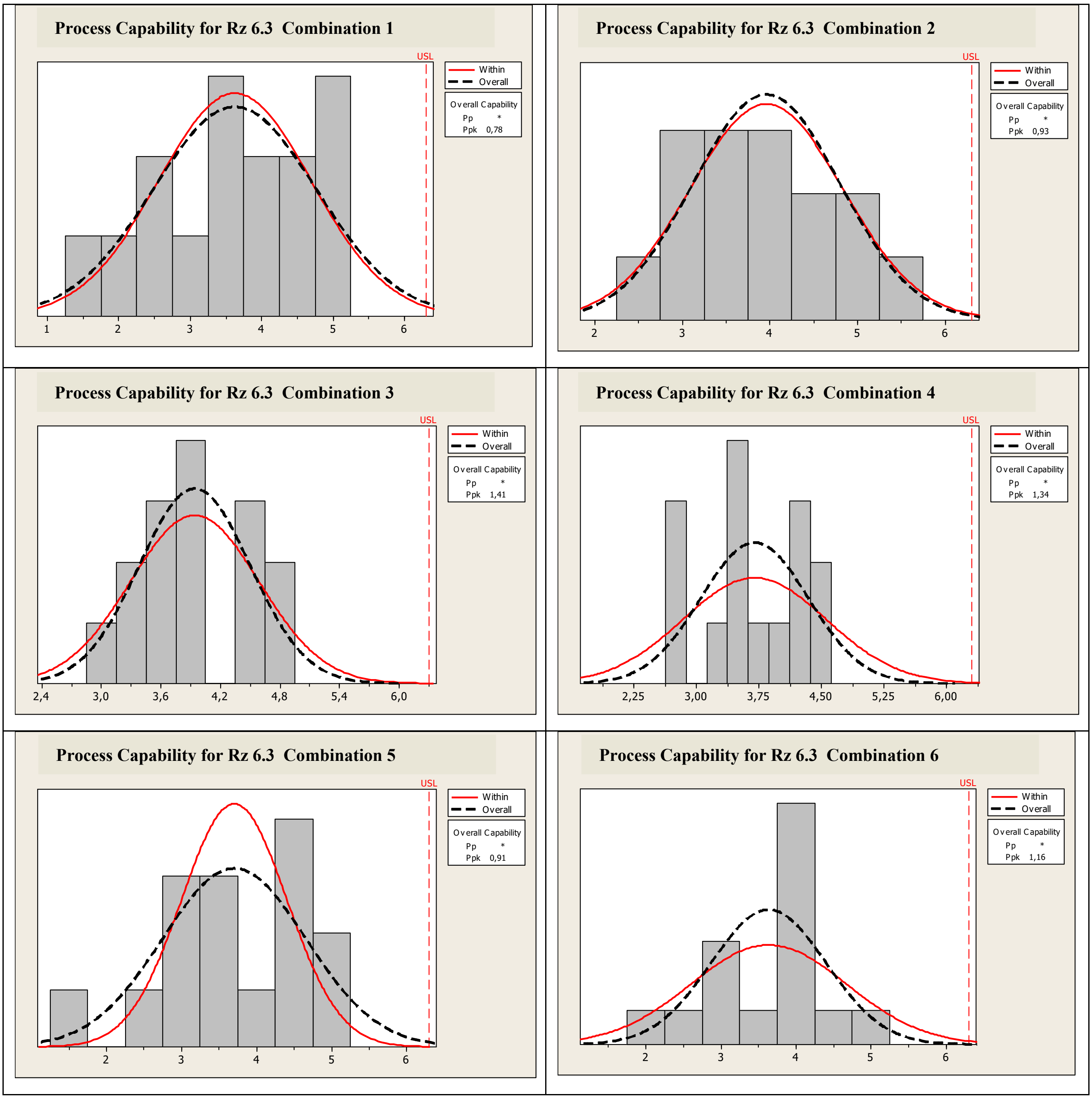

Figure 5. Results of surface roughness for different combinations of v_c and f_z.

For the first combination (v_c = 50 m / min and f_z = 0.10 mm) the variation of surface roughness is between 1.450 µm and 5.090 µm with an average of 3.625 µm. It can be seen in this histogram a 57% variation of the tolerance. The histogram of combination 2 (v_c = 50 m / min and f_z 0.15 mm) has a similar behavior to histogram of combination 1, with close averages and upper and lower limits. The combinations 3 (v_c = 55 m/min and f_z = 0,10 mm) and 4 (v_c = 55 m/min and f_z = 0.15 mm) provided the best results. The variation of surface roughness is between 2.860 μm and 4.830 μm with an average of 3.941 μm for combination 3, and it has a variation of 31% of the tolerance. For combination 4 the variation of surface roughness is between 2.740 μm and 4.620 μm with an average of 3.699 μm, and it has a variation of 30% of the tolerance. These combinations have similar results, however in combination 3 the data is more concentrated among six main families, what makes it a better choice than the combination 4. It can be noticed that the histogram of combination 3 presents data arranged closer to the mean value.

In the histogram of combination 5 (v_c = 60 m/min and f_z = 0,10 mm) the variation of surface roughness is between 1.600 μm and 5.00 μm with an average of 3.703 μm and it has a variation of 54% of the tolerance. In the histogram of combination 6 (v_c = 60 m/min and f_z = 0,15 mm) the variation of surface roughness is between 2.06 μm to 4.850 μm with an average of 3.635 μm and it has a variation of 44% of the tolerance.

The best results for surface roughness were found for combination 3.

Table 3 presents the P_{pk} indexes for roundness and surface roughness for the different combinations. Based on P_{pk} indexes, combination 4 is the best one for roundness and combination 3 is the best one for surface roughness.

Combinations 3 and 4 present similar results for roundness and surface roughness. Combination 4 can be considered the best one because P_{pk} indexes for both evaluated characteristics (roundness and surface roughness) are above the specified criteria 1.33.

Tabel 1. Process capability results.

ID	Characteristics	P_{pk}
1	Roundness 0.01 _ Combination 1	1.01
2	Roundness 0.01 _ Combination 2	0.98
3	Roundness 0.01 _ Combination 3	0.96
4	Roundness 0.01 _ Combination 4	1.35
5	Roundness 0.01 _ Combination 5	0.48
6	Roundness 0.01 _ Combination 6	0.79
1	Surface roughness Rz 6.3 _ Combination 1	0.78
2	Surface roughness Rz 6.3 _ Combination 2	0.93
3	Surface roughness Rz 6.3 _ Combination 3	1.41
4	Surface roughness Rz 6.3 _ Combination 4	1.34
5	Surface roughness Rz 6.3 _ Combination 5	0.91
6	Surface roughness Rz 6.3 _ Combination 6	1.16

4. CONCLUSIONS

The results presented in this paper demonstrate how accurate the boring process of valve seats is. The average values of roundness and surface roughness were very close for the different combinations. However, there was a significant difference between the amplitudes. Among all the measured samples, it was found surface roughness (R_z) between 1.45 μm and 5.27 μm and roundness between 0.000 and 0.012 mm.

It was observed that higher cutting speeds result in higher roundness variations and as the feed-rate increases the surface roughness variations decrease.

By the analysis of the the P_{pk} index, it was possible to conclude that the best combination of parameters is cutting speed of 55 m / min and feed-rate of 0.15 mm. This combination of parameters results in a stable and capable process for the evaluated characteristics, therefore the process control frequency can be minimized. Based on the P_{pk} index of 1.35 for roundness and 1.34 for surface roughness, it is possible to state that the probability to produce nonconforming parts is 0.006% or 64 parts per million for this particular process.

5. REFERENCES

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