

DIMENSIONAL AND GEOMETRIC TOLERANCES AFTER MACHINING

CASE HARDENED AISI 5115 STEEL

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ABSTRACT: The present work is concerned with the surface finish and the dimensional and geometric (form and orientation) deviations produced after turning and plunge grinding AISI 5115 case hardened steel (58-66 HRC). Two grades of mixed alumina tools (coated and uncoated) were tested when face turning one type of gearbox sleeve. A second type of sleeve was machined through both facing and turning with polycrystalline cubic boron nitride (PCBN) and plunge grinding with Al_2O_3 wheels. The results indicated that when turning using mixed alumina inserts, better surface finish was obtained using the uncoated insert and appreciable differences between the two grades were not observed for the dimensional and squareness deviations. When comparing turning with PCBN and plunge grinding, considerable differences in the surface roughness results were observed, i.e., when generating a tapered surface, lower Ra values were given by grinding, whereas when producing a flat surface, best results were recorded after face turning. With regard to the dimensional tolerances, in general tighter limits were obtained after turning. Finally, when considering the geometric deviations both processes were able to keep them within the tolerance range, except for squareness, for which neither turning nor grinding was able to maintain the required limits.

Keywords: Turning, grinding, case hardened steel, dimensional and geometric deviations.

1 INTRODUCTION

Case hardened steels combine a highly wear resistant surface and a tough core, therefore they are broadly used in the manufacture of gears, connecting rods and shafts. The hardness and depth of the case generally varies from 45 to 70 HRC and from 0,2 to 5 mm, respectively, depending on the surface hardening process, the temperature applied and the work material. For instance, when carbonitriding a low carbon or alloy steel at temperatures ranging from 700 to 900°C, a case with hardness of 50-60 HRC and depth of 0,02-0,7 mm is produced.

Finish and continuous cutting of case hardened steels (approximately 65 HRC) can be effectively undertaken by polycrystalline cubic boron nitride (PCBN) compacts at high cutting speeds as reported by /1-3/. The latter authors found that titanium nitride bonded PCBN outperformed metal bonded PCBN due to its ability to maintain a higher hardness at elevated temperatures.

According to /4/ the correct PCBN tool geometry for optimum tool life and surface finish in continuous cutting should utilise a negative inclination angle between 30° and 35°, a negative land width longer than the tool-chip contact length, a nose radius of 0,8mm and a hone radius of 0,05 mm. It has been reported by /5/ that when hard turning AISI 52100 steel, the average surface roughness value increased with the cutting edge hone radius (due to the ploughing action) and decreased as the workpiece hardness increased. The latter phenomenon may be explained by the fact that less lateral plastic flow will occur when machining harder materials, contributing to improve the workpiece surface quality /6/. Additionally, the same author asserted that the radial force is the most sensitive to changes in the cutting edge geometry (edge chamfer and nose radius).

Interrupted machining of case hardened steels at high cutting speeds can be satisfactorily undertaken by PCBN tools /7-8/. Conventional ceramic tools can be used at lower cutting

rates, but they are prone to fracture. The utilisation of a land on the flank face when intermittent cutting is recommended in order to retard tool failure by spalling. When milling flame hardened Cf53 steel (62 HRC) with PCBN tools it was observed that when inserts with a larger nose radius were used ($r_{\epsilon}=4,0$ mm against $r_{\epsilon}=0,8$ mm), better surface finish was obtained even with a feed rate of up to 0,6 mm/tooth at a cutting speed of 100 m/min /9/. Similarly, /10/ reported that when turning heat treatable DIN 50CrMo4 steel (55 HRC) using PCBN tooling, flank wear land values were 30% lower when using a round insert ($r_{\epsilon}=6,35$ mm) than when using a square insert with $r_{\epsilon}=0,8$ mm.

1.1 Surface finish and accuracy

It is well known that the main points in favour of grinding are its ability to provide very high surface finish quality and component accuracy, however, whereas in turning only the workpiece is rotating, in cylindrical grinding both the wheel and workpiece are rotating. This may cause lobing on the work surface /11/, which is undesirable. In addition, the surface produced by turning is by the very nature of the process, round; in contrast, a ground surface is made up of microflats.

Turning and milling can offer much higher metal removal rates than grinding and similar surface roughness values, however, due to the fact that single point cutting requires a minimum depth of cut, equivalent dimensional accuracy is not readily achievable, possibly because of elastic deformations of the machine tool and workpiece as a result of high cutting forces /9/. Additionally, these forces may result in vibrations which will cause dimensional and geometric alterations.

Similar surface roughness values ($R_a=0,20 - 0,23\mu\text{m}$) when grinding and single point cutting hardened AISI 4340 steel were obtained by /12/, but the ground surface produced larger R_{max}

values than when hard part machining. In addition to that, /2/ and /13/ reported that a PCBN turned surface has a more regular and uniform texture than a ground surface, which often incorporated debris, tear marks and scars. When turning DIN 50CrMo4 case hardened steel (55 HRC) with PCBN tools the surface quality showed little or no deterioration with increased cutting time (after a cutting time of 32 minutes the R_t value increased by only 2 μm) /10/.

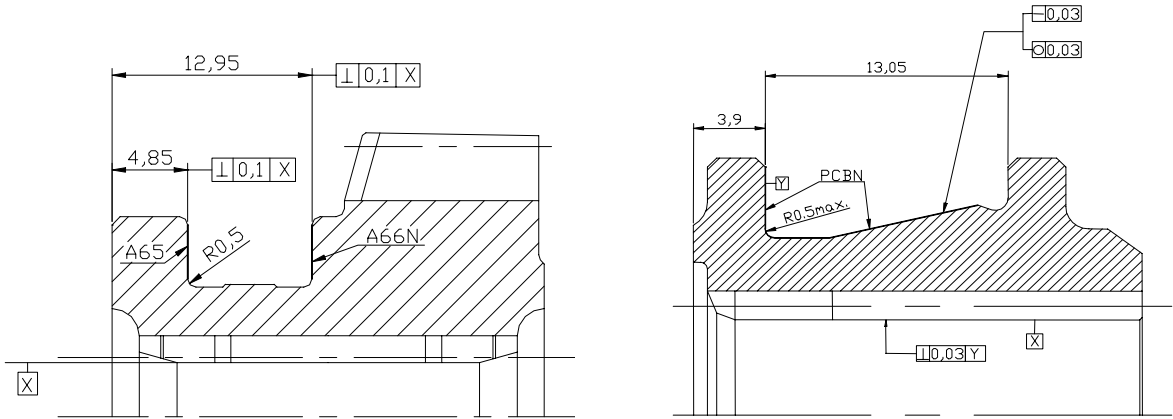
The effect of feed rate on surface finish when turning case hardened 50CrMo4 steel (55 HRC) with PCBN tools was investigated by /9/. As expected, the surface quality decreased as the feed rate was increased. However, an acceptable surface finish was obtained up to 0,16 mm/rev feed rate.

According to /14/ asserts that tolerances of 15 μm ($\pm 7 \mu\text{m}$) are typical of hard turned bearing surfaces. It has also been reported that under favourable conditions PCBN tools can produce surface finish values down to $R_a=0,3\mu\text{m}$ while conventional ceramics can only achieve $R_a=0,6 \mu\text{m}$, however both tool materials can hold tolerances down to $\pm 10 \mu\text{m}$ /15/. Geometric tolerances corresponding to ISO IT6 can be considered as the maximum level of quality to be expected when using currently available lathes /16/, which is considered insufficient to replace many grinding operations.

It has been reported /17/ that with the advent of superabrasive machining using CBN grinding wheels, which are much more wear resistant and tougher than alumina wheels, considerably higher metal removal rates (in some cases comparable to single point cutting operations) can be achieved when grinding steels harder than 50 HRC, nickel and cobalt-based alloys above 35 HRC and hard cast irons. Similarly, /18/ suggest that while hard part turning and milling can satisfactorily be employed as a substitute in some conventional grinding operations, it is less likely that this will happen in those sectors of the metal working industry where superabrasive grinding is already established.

2 EXPERIMENTAL PROCEDURE

The experimental work was carried out in the shop floor of a large car manufacturing company using two production lathes and one grinding machine working under actual cutting conditions. Additional support was given by the metrology laboratory. The work material used in the experimental procedure was AISI 5115 steel (DIN 19MnCr5G) subjected to carbonitriding to reach a surface hardness of 66HRC. This material is employed in the manufacturing of the gearbox sleeves shown in Figure 1. Two grades of mixed alumina (Kyocera A65 and A66N) were employed for the facing work of distinct surfaces on the first/second gear sleeve (see Figure 1.a). The fifth gear sleeve shown in Figure 1.b was machined using one grade of PCBN compact (Sumiboron BNX20) for facing and taper turning. Cylindrical plunge grinding of the fifth gear sleeve was also performed employing an Al_2O_3 wheel (Norton grade 38A80-30VSB) aiming to compare its performance with turning with PCBN.



(a) First/second gear sleeve.

(b) Fifth gear sleeve.

Figure 1: First/second gear sleeve (a) and fifth gear sleeve (b).

The mixed alumina inserts differ only by the fact that one of them (A66N) is coated, but both substrates present the same physical and mechanical properties. Their geometry code is VNGA 160408 T082025 and they were mounted on a tool holder coded MVJNR 2525 M16. The PCBN inserts used were ISO VNMA 160404 T01525 and were mounted on the same tool holder. Thus, the following angles were obtained: cutting edge angle $\chi_r = 93^\circ$, included angle $\varepsilon_r = 35^\circ$, normal rake angle $\gamma_n = -9^\circ$ and cutting edge inclination angle $\lambda_s = -5^\circ$. The corner radii (r_ε) were 0,8 mm for the ceramics and 0,4 mm for the PCBN.

Turning tests were carried out in two different CNC lathes, one of each type of gear sleeve. The cutting conditions were as follows: turning at a cutting speed $v_c=180$ m/min, feed rate $f=0,08$ mm/rev and depth of cut $a_p=0,15$ mm and plunge grinding at a wheel speed $v_s=60$ m/s and an infeed speed $v_f=0,75$ mm/min.

Samples of machined gear sleeves were collected at regular intervals for analysis of the dimensional and geometric (form and orientation) deviations. Ten samples of sleeves machined using the coated ceramic insert were collected from a batch of 1000 parts, which represented a total cutting length of 4400 mm. The same happened to the uncoated ceramic tool. For the PCBN, 10 samples were collected from a batch of 200 sleeves, corresponding to a cutting length of 3186 mm, and finally, five samples were sequentially collected to evaluate the grinding operation, resulting in a cutting length of 79,65 mm. At the end of the batch, tool wear for all cutting edges was inferior to $VB_C=0,2$ mm. The grinding wheel was not dressed throughout the experimental work.

The components average surface roughness (Ra) was measured with a S8P Perthern Mahr roughness meter using a 0,8 mm cut-off length. The dimensional and geometric deviations presented in Figure 1 were measured using a 262 Taylor Hobson unit. For the first/second gear sleeves only the squareness deviation was measured (due to the fact that this is the

principal deviation affecting the performance of the component), whereas for the fifth gear the squareness, roundness and straightness deviations were recorded.

3 RESULTS AND DISCUSSION

The results are presented in two parts: in the first part the data concerning turning using ceramic tools are shown, and in the second part the results for turning with PCBN and grinding are presented.

3.1 Turning with ceramics

Figure 2 shows the Ra results against the cutting length when facing the first/second gear sleeve using both uncoated and coated mixed alumina inserts. It can be seen that lower and more stable Ra values are produced when using the uncoated ceramic. In addition to that, the surface finish produced using the coated ceramic exceeded the maximum value fixed in $Ra=0,8 \mu\text{m}$. Since the tools possess similar mechanical properties and presented comparable wear evolution, one possible reason for such difference may be due to the fact that the sleeves were clamped in the chuck on their left side (see Figure 1.a), therefore, the uncoated insert worked under a more favourable condition.

The dimensional deviations obtained after face turning with the ceramic inserts are presented in Figures 3 and 4. Figure 3 refers to a nominal value of 4,85 mm and the uncoated insert, whereas Figure 4 shows the results for a nominal value of 12,95 mm and the coated ceramic. In both cases the measured values increased with cutting length as a consequence of the evolution of tool wear and did not exceed the established tolerance range of $\pm 0,05\text{mm}$,

although the upper limit was nearly reached by the coated ceramic. Additionally, the uncoated insert fractured after cutting a length of 3960 mm.

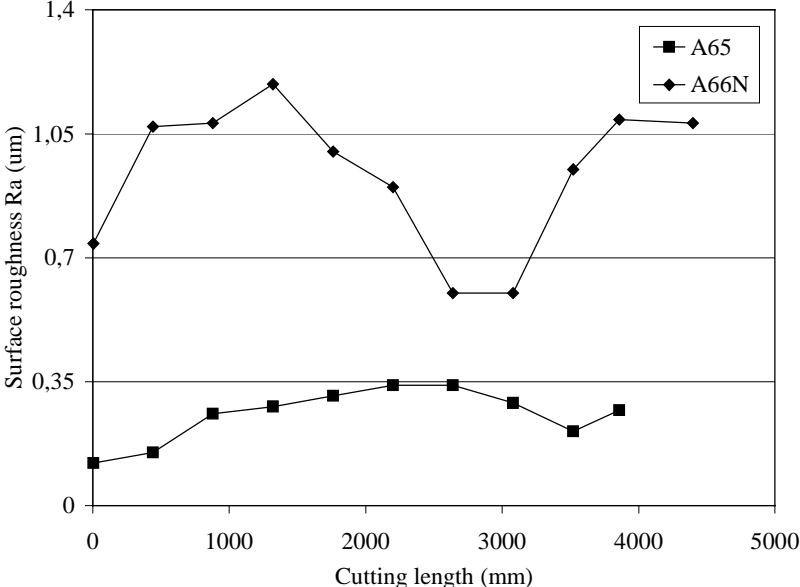


Figure 2: Average surface roughness against cutting length after face turning with mixed alumina inserts.

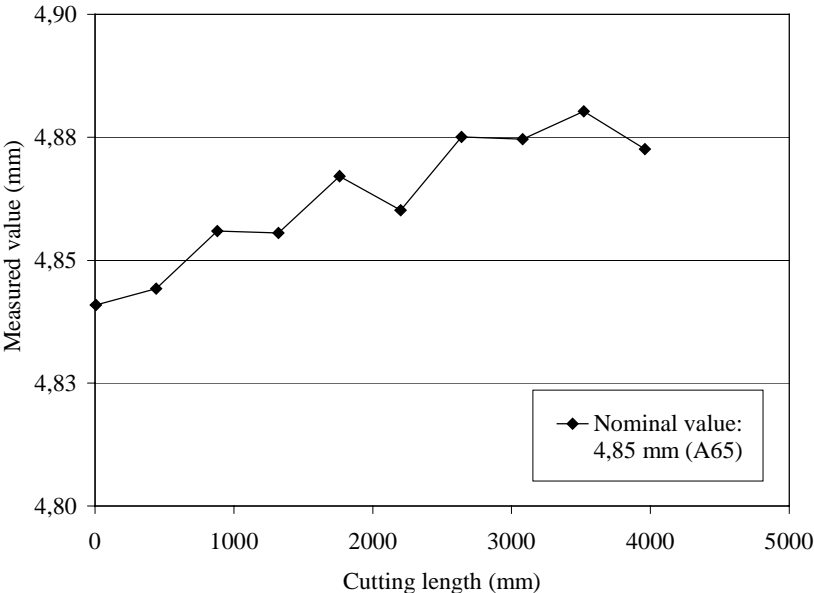


Figure 3: Dimensional tolerancing after face turning with uncoated mixed alumina (limits: $4,85 \pm 0,05$ mm).

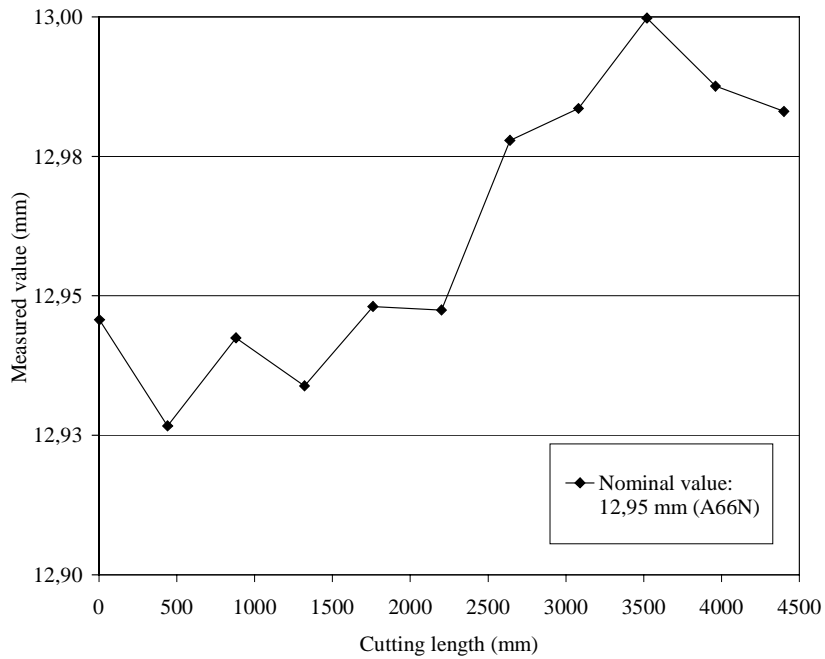


Figure 4: Dimensional tolerancing after face turning with coated mixed alumina (limits: 12,95 \pm 0,05 mm).

Irrespective of the nominal values observed in Figures 3 and 4, a tolerance ISO grade IT10 was attained in both cases after machining 1000 components. This tolerance is not as narrow as that presented in the literature review, nevertheless, it is sufficiently low to ensure a satisfactory performance to the machined component.

Figure 5 shows that similar results concerning the squareness deviation were obtained when face turning with uncoated and coated mixed alumina tools, all of them within the tolerance range of 100 μ m. In contrast to Figure 2, similar results were obtained for both processes, suggesting that the clamping system did not affect the performance of the cutting tools.

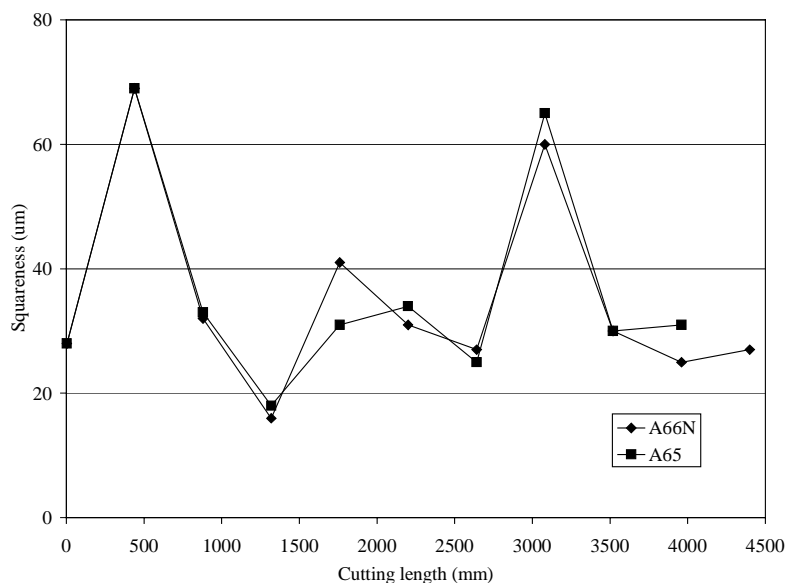


Figure 5: Squareness deviation against cutting length after facing with mixed alumina inserts.

3.2 Turning with PCBN and grinding

The surface roughness results obtained after facing and taper turning the fifth gear sleeve using PCBN inserts are presented in Figure 6. In this case, the Ra values produced were higher than when machining the first/second gear sleeve with ceramics. This can be explained by the fact that the corner radius of the PCBN tool is half of the ceramics. With a corner radius much smaller than recommended, the cutting edge deteriorates at a higher rate, causing a drastic increase in the component surface roughness, as can be seen in Figure 6.

With regard to the surface finish produced by grinding, Figure 7 indicates that the values obtained on the tapered surface were lower than those provided by facing with PCBN, whereas on the flat area the PCBN outperformed the grinding operation, in spite of the difference in both cutting lengths. These results suggest that the selected infeed speed may be excessively high.

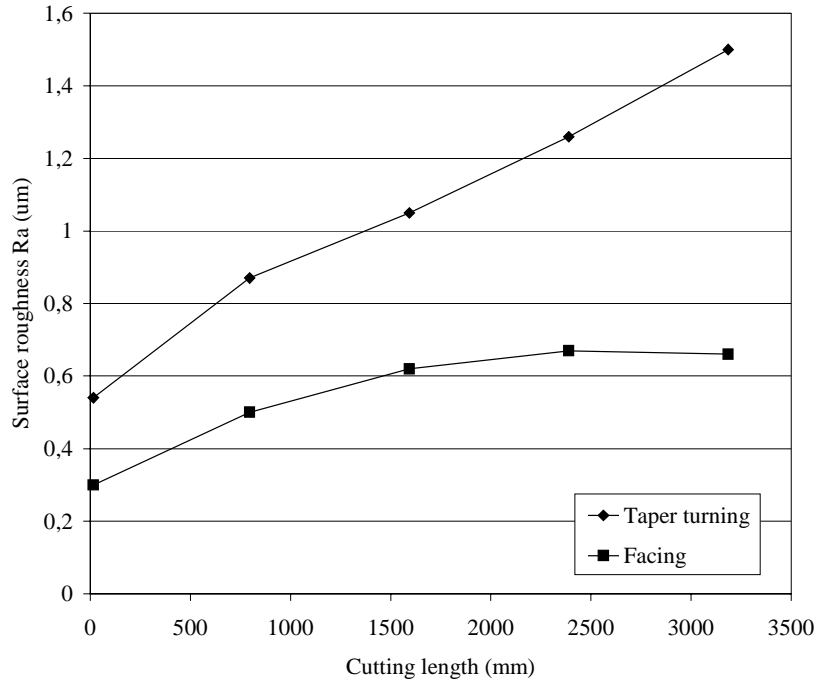


Figure 6: Average surface roughness against cutting length after taper turning and facing with PCBN.

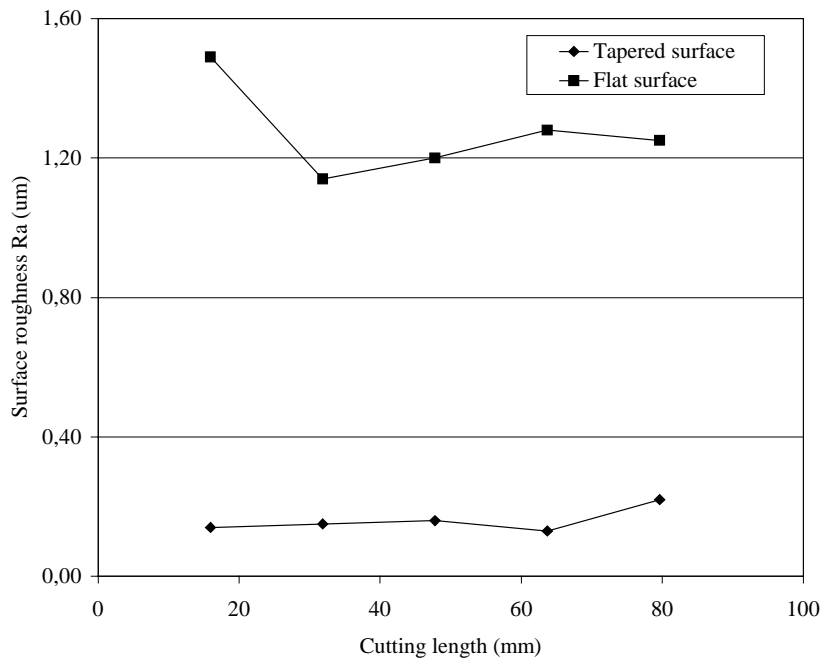


Figure 7: Average surface roughness against cutting length after plunge grinding.

The dimensional deviations measured after turning and grinding the fifth gear sleeve are presented in Figures 8 and 9 for nominal sizes of 3,90 mm (tolerance range of $\pm 0,100\text{mm}$) and 13,05 mm (tolerance range of $\pm 0,05\text{ mm}$), respectively. It can be seen that the tolerances of the machined components remained within the recommended range, particularly in Figure 9, where the narrower values are expected. Figure 8 also shows that better results were obtained after turning, in which a tolerance ISO grade IT 9 was attained. Unfortunately, the reduced number of workpieces available for the grinding tests resulted in a rather short cutting length and did not allow the observation of the overall scenario for the manufacture of a larger batch.

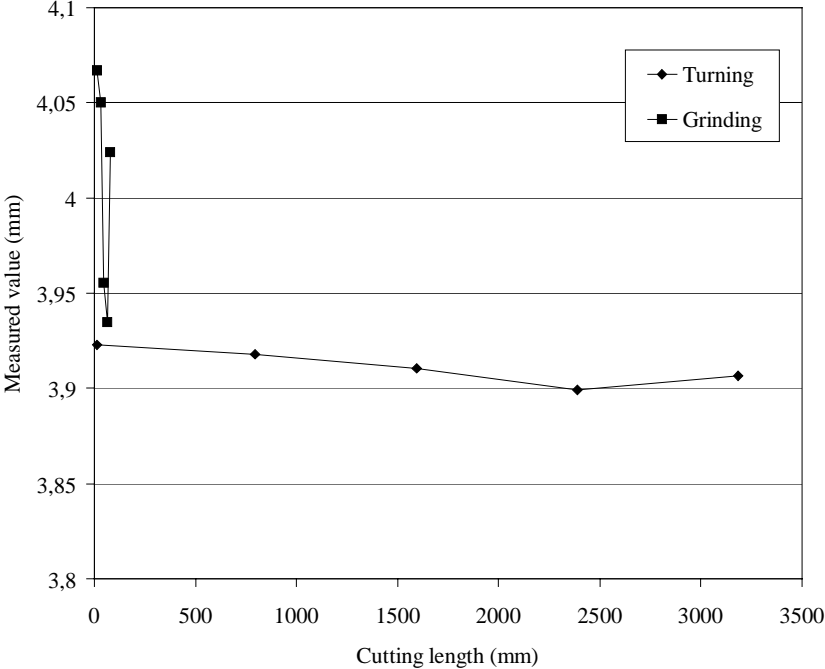


Figure 8: Dimensional tolerancing after turning with PCBN and plunge grinding (limits: 3,90 $\pm 0,100\text{ mm}$).

The results concerning the squareness deviation are presented in Figure 10. It can be seen that the tolerance of 30 μm was exceeded when both turning and grinding, the latter providing a slighter lower deviation.

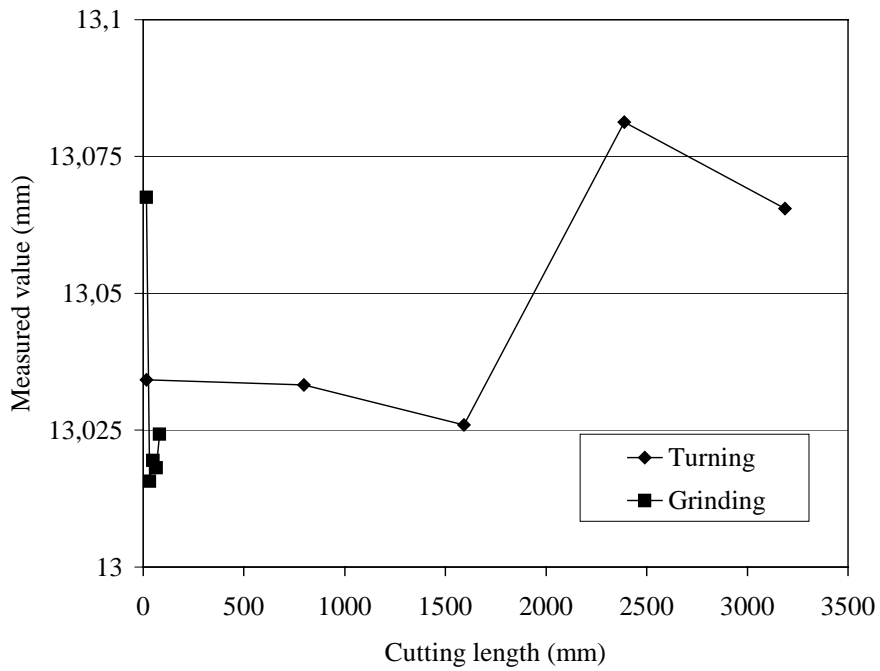


Figure 9: Dimensional tolerancing after turning with PCBN and plunge grinding (limits: $13,05 \pm 0,05$ mm).

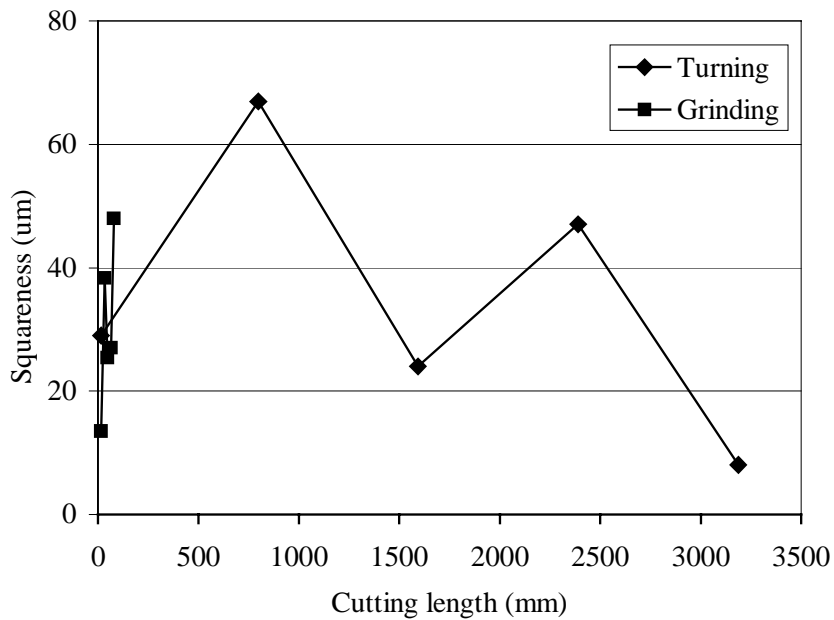


Figure 10: Squareness deviation after turning with PCBN and plunge grinding.

Figure 11 and 12 show the results concerning the roundness and straightness deviations, respectively, after turning with PCBN and grinding with an alumina wheel. In both cases the tolerance value fixed in 30 μm was not exceeded, although best results were produced by turning. As a matter of fact, this was expected for the roundness deviation, due to the reasons previously explained in this work. With regard to the straightness deviation, see Figure 12, it seems that the grinding wheel surface deteriorates quickly as the cutting length progressed, promoting high straightness values. This behaviour was not observed when turning using the PCBN compact.

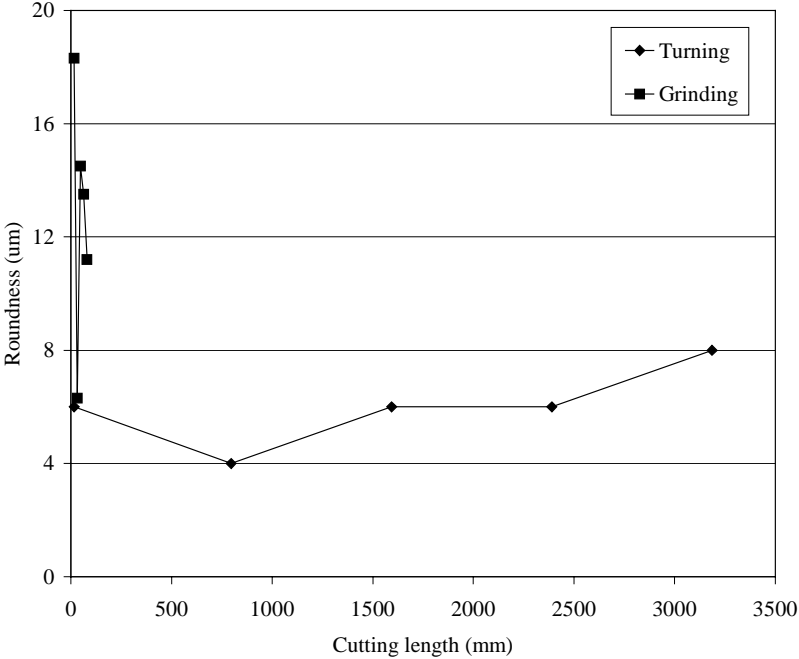


Figure 11: Roundness deviation after turning with PCBN and plunge grinding.

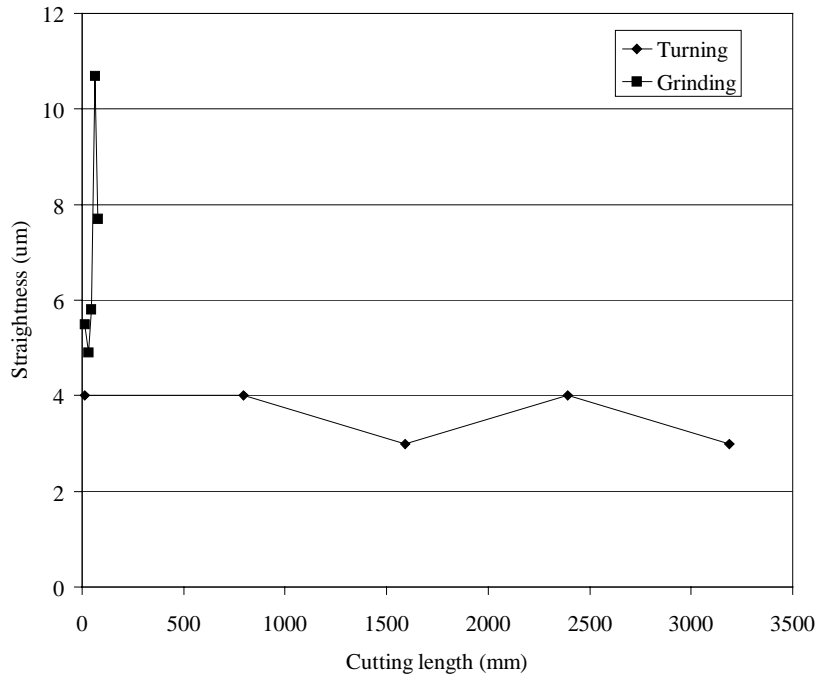


Figure 12: Straightness deviation after turning with PCBN and plunge grinding.

4 CONCLUSIONS

The following conclusions can be drawn from the present work, concerned with the machining of case hardened AISI 5115 steel:

- ◆ After turning using mixed alumina tools, lower surface roughness results were produced by the uncoated insert, whereas similar results were obtained for the dimensional and squareness deviations, all of them within the established tolerance range;
- ◆ After turning with PCBN and grinding using an Al_2O_3 wheel, significant differences in the surface roughness results were observed, i.e., when generating a tapered surface lower Ra values were given by grinding, whereas when producing a flat surface lower best results were obtained after face turning.
- ◆ With regard to the dimensional tolerancing produced after turning with PCBN and grinding with alumina wheels, in spite of the longer cutting length undertaken by turning, this

process was able to produce less scatter and to keep the deviation within the allowed range, particularly for a nominal dimension of 3,90 mm. For a nominal size of 13,05 mm, the results were similar for turning and grinding;

◆ With regard to the squareness deviation, neither turning nor grinding were able to maintain the tolerance of 30 μm , whereas for roundness and straightness deviations, tight tolerances were ensured by both processes and again, less scatter was observed after turning (8 μm against 18 μm for roundness and 4 μm against 11 μm for straightness).

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