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ANALYSIS OF FORM ERROR AND ROUGHNESS OF HARDENED STEEL WORKPIECES INTERNALLY TURNED WITH DIFFERENT TOOLS IN LONG OVERHANGS

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Abstract

Internal turning process is a very important and widely used process for enlarging and finishing holes. Especially for the components that work with external members, this operation needs to assure surface and geometric quality. In that case, the correct definition of working parameters will directly contribute to the quality of component. Aim of the current research was to analyse the form error and the roughness of workpieces submitted to internal turning process using boring bars in long overhangs with three different internal tools (steel, carbide and antivibrating tool). For the experiments, heat-treated DIN EN 1.2842 (ISO 90MnCrV8) steel with 58 HRC of hardness was submitted to boring process using CBN (cubic boron nitride) inserts, and a boring bar with the most possible rigid clamping system (Easy Fix). The workpiece roughness and circularity were measured using a profilometer and a form error measuring machine. The measurements provided the data to identify the boring bar levels of stability, and the workpiece micro and macro geometric errors. The experiments allowed to conclude that, for all toolbars, the evaluated errors kept constant with increasing L/D ratio during stable clamping conditions, without any vibration. On the other hand, higher values of overhangs, limited to L/D>4.25 for steel tool, can cause serious damages in the cutting system if the antivibration tools or the carbide will be not used.

Keywords

Internal turning process, roughness, circularity, boring bar, clamping condition

INTRODUCTION

Turning is the most widespread technological operation by which it is possible to machine cylindrical, conical and shaped rotating surfaces. It can produce external or internal surfaces by turning [1]. Internal turning is one of the most widespread operations to produce the conical or cylindrical internal surfaces of rotating parts. In this operation, the surface and dimensional quality of the workpiece are relevant parameters for the process. Achieving excellent roughness and dimensional accuracy values is difficult when using a toolbar with a high length to diameter L/D ratio [2]. Besides, due to the large (L/D) ratio, deep hole tools are subjected to compressive stress and torsional moment [3]. The surface roughness and dimensional quality of the turned workpiece depend on its material and mechanical properties, stability of the clamping system, cutting parameters, tool geometry and regenerative vibrations that are present during the cutting process [4, 5, 6, 7].

In the production of deep holes, long and narrow toolbars are used, which, in combination with poor chip evacuation, might cause deteriorated roughness and dimensional accuracy of machined surfaces. In addition, the wear rate of the cutting tool has a great influence on the magnitude of the self-excited vibration (chatter) of the cutting tool. As the wear rate of the tool increases, the vibrations of the tool increase and the surface quality deteriorates [8].

The quality of the machined surface during internal turning of deep holes has been discussed in several articles. Badadhe [2] investigated the influence of cutting parameters on the quality of the machined surface. Feed rate, spindle speed, depth of cut and length to diameter (L/D) ratio of the boring bar were taken as control factors. Analysis of variance (ANOVA) was performed to find significant factors and their individual contribution. Using the Taguchi method, the optimal combination of cutting parameters was determined, which led to a better surface roughness with a minimum machining cycle time.

Sabev [9] studied the effect of cutting parameters on surface roughness during the hole boring operation of aluminium with an anti-vibration boring bar. Based on the results, he developed a mathematical model to predict the surface quality in relation to different cutting conditions. It was found that the anti-vibration bar has excellent dynamic stability.

Diniz [10] used the spheres inside a cavity manufactured in the toolbar to minimize vibrations while internal turning operation of deep holes. The spheres of three different sizes were used to dampen the vibrations, which were compared to the performance of a solid steel bar in terms of workpiece surface roughness, tool life and tool vibration. It was found that the use of spheres in the cavity of the cutting tool acts as a dampener of the vibrations generated during the machining process, which allows increasing the overhang of the tool without damaging the surface roughness and shortening the tool life.

If considering an ideal turned surface in which the tool tip geometry is constant and the chip thickness undisturbed, it would be observed that, with the increase in feed rate, the surface roughness would be higher and consequently degraded. Some roughness peaks may periodically occur on the turned surface after the tool passes along the part, and increase as machining feed increases. Therefore, we can state that cutting advance is the machining parameter that most influences surface roughness of a part [11]. With industrial demands being firmly focused on precision manufacturing, requiring even tighter geometric tolerances such as greater precision of circularity, the need for better shape control is justified. Over the past 60 years, measurement systems have been developed with greater levels of sophistication to measure circularity of a component and its associated parameters. It is important that engineers, designers, machine tool operators and inspectors have a basic understanding of the working principles of these instruments, along with their capabilities and limitations, and how to interpret the subsequent circularity results. In addition, circularity inspection results can be used to monitor a range of process-related component manufacturing capabilities. Typically, machine tool performance and tool wear are effects resulting from inadequate operating procedures or production problems [11].

It is important to say that a circular cross-section is the most fundamental shape generated by the manufacturing process used in industry. We can also point out that, due to the symmetry of a component with a circular cross section, it can present uniform mechanical strength in all directions that are symmetrical to the axis. The dimensional and geometric characteristics of a part will have a significant effect on the components in-service performance [11].

The obtained surface roughness values did not interfere in the geometric dimensions of the workpiece. It does not matter how large surface roughness values can be achieved.

Figure 1 shows the decrease in circularity deviations for different manufacturing processes. The first of them presents drilling with the largest deviations of circularity, going through the internal turning process, and reaching finishing with reamers, in which the circularity obtained in the hole has high dimensional accuracy (up to five times greater compared to the drilling operation) [11].

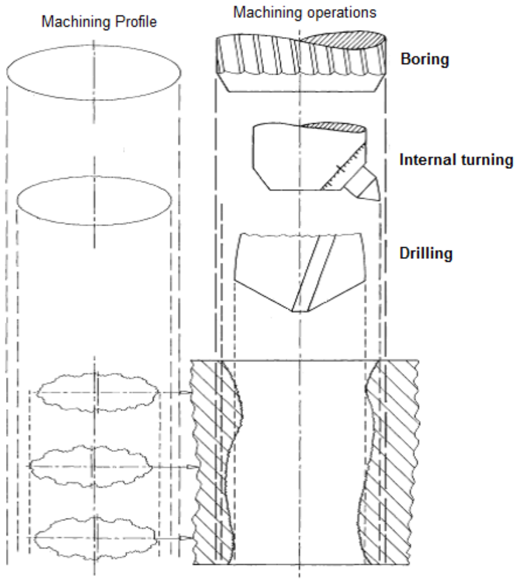

Fig. 1 *Circularity profile for different machining process [11]*

It is possible to predict that the errors introduced by the drilling process are quite large, as shown by the profiles in Fig. 1. The errors are also generated due to the high ratios between length and diameter of the tool. The tool stability, in turn, will influence the geometry and roughness of the hole. If the tool is very long and does not have a stable clamping system, geometric deviations will inevitably occur in the hole. The stability of the tool displays an important hole to guarantee the surface quality of the workpiece. In long holes, vibrations due to tool overhang are very common. Vibrations are quite undesirable in the process, as in addition to compromising the surface finish, they can damage the equipment, damage the tooling and reduce its lifespan [6].

Another factor that can affect the quality of the machining is the way in which the tool is clamped in the turret. This attachment requires special care and requires a rigid attachment for effective vibration control.

Therefore, to achieve better geometric and surface quality of the hole, it is often appropriate to use the internal turning and boring operation, as these operations do not follow the hole contour and, as such, eliminate drill-induced errors. Finally, the boring operation will convey the dimension of the finished hole, while simultaneously improving the circularity and texture

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of the surface. In particular, the precision internal turning operation can, in fact, eliminate the need for the subsequent boring operation, providing significant savings in machining costs [11].

If the clamping system is rigid enough, the occurrence of chatter in internal turning will directly depend on the dynamic stability of the tool. It is due to the dynamic interaction of the L/D ratio and the stiffness of the tool-holder assembled in the machine turret [12].

Replacing a steel boring bar by a carbide one is necessary for an L/D ratio between 4 and 7, since higher modulus of elasticity and higher density make carbide bars more rigid than steel bars, as we can see in the Equations 1 and 2 [13, 14].

The use of dampers in internal turning is recommended for cases where the tool is subjected to an L/D between 7 to 14 [15, 16].

Kassab and Khoshnaw [17] and Neseli et al. [18] studied the influence of tool overhang on the surface quality. They concluded that, as the L/D ratio of tool increases, the deflection increases exponentially, as seen in the Equation 3. Therefore, there is an increase in the vibration of the tool, which results in an increase in the roughness of the workpiece.

$$K = \frac{3\,.E.I}{L^{3}} \tag{1}$$

$$\zeta = \frac{c}{2\sqrt{K.M}} \tag{2}$$

$$\delta = 6.8.\frac{F_C}{E}.\left(\frac{L^3}{D^4}\right), \tag{3}$$

where δ is the bar deflection, F_C is the cutting force, L is the bar overhang, E is the elasticity coefficient of the tool material, I is its inertia moment, D is the tool diameter, K is the static stiffness of the tool, ζ is the damping ratio, c is the damping coefficient and M is the mass of the tool.

MATERIALS AND METHODOLOGY OF EXPERIMENT

The main concern of this experiment consisted in the effect of L/D ratio over circularity and roughness of the workpiece while using different internal turning tools.

All the internal turning experiments of this project were performed using a DMG CTX alpha 500 CNC turning centre with 20/27 kW (100/40 % ED) of power in the main motor and maximum spindle rotation of 5000 rpm.

The selected tools for the experiments were 16 mm of diameter: one with high hardenability ANSI 4140 steel – code A16R SCLCR 09-R, one with carbide – code E16R SCLCR 09 R and the last one was an antivibrating tool (Silent tool) code 570-SCLCL-16-06 for the support and code 570-3C 16 156 for the antivibrational bar – It was supplied by Sandvik Coromant [19].

As for the tool insert, an adequate insert for finishing operations on smooth surfaces of hardened steels was chosen. It was composed of CBN (50 % wt.) and a ceramic phase of TiCN and Al_2O_3; it is the ISO code is CCGW09T308S01020F 7015 (class ISO H10) for Steel and Carbide tools while for the Silent tool the code is CCGW 060208 S01030F 7015 [19]. The advantage of the chosen tool inserts, when compared to others with a greater CBN content, is its chemical stability in relation to iron. Besides, its toughness is enough to preserve its cutting edge, even though it is reduced when compared to other inserts with a greater CBN content. The DIN EN 1.2842 (ISO 90MnCrV8) steel used in the fabrication of the test specimens is a widely employed material in the metal mechanical industry. It presents high hardenability, bad weldability, and reasonable machinability, as well as a good resistance to torsion and fatigue – its hardened to hardness 58 HRC. The cutting conditions and the machine setup (tool overhang) were tested in a maximum flank wear (VB_{max}) of 0.2 mm according to the ISO 3685 [20]. The tests were carried out without a cooling system and constant cutting parameters, with a cutting speed (v_c) of 360 m/min, feed rate (f) of 0.14 mm/revolution and depth of cutting (a_p) 0.1 mm. The conditions for clamping the boring bar in the turret were determined considering the distance from the tool tip to the beginning of the tool holder. The condition of clamping the tool were according to the following distribution in L/D ratio parameter (ratio between the length "L" and the diameter "D" of the tool): 3 to 8 with intervals of 0.25.

The roughness of the cylindrical surface of the workpiece was measured 5 times and verified at three equidistant points (120°) at a controlled laboratory temperature of 20 °C. Therefore, to quantify the finish obtained during the turning process, a profilometer SURFCOM 1900SD2 model, Accretech brand, was used, with resolution on the X axis and Z axis equal to 0.04 µm, measuring force of 0.75 mN and expanded uncertainty of 0.01 µm (k=2), following the DIN 4768 (1990-2005) [21] standards. In addition, to treat the roughness profile, a Gauss filter was used, and the sampling length (cut-off) used was equal to 0.8 mm, following the ISO 4288:1996 [22] parameters. The arithmetic mean deviation of the profile (R_a) and the total height of the profile (R_z) were chosen. To measure the circularity deviation of the samples, a form deviation measuring machine was used, measurement velocity 15 mm/s in 5000 points. CenterMAX coordinate measuring machine with VAST XTR gold head from Zeiss Company. The maximal permissible error at 26 °C is 1.5 + L/250.

ATTAINED RESULTS

In this section, the influence of roughness and form error on the static stiffness of the turning bar was analysed in the internal turning process of hardened steel with long overhangs. The static stiffness of a bar is its ability to resist a bending force (a force perpendicular to the main axis of the turning bar) under static conditions. Since a structure is more rigid as it deflects less under the action of a force, therefore it is recommended to assembly the turning bar as short as possible in order to obtain the highest static stiffness of the tool, but in deep hole operations long overhangs is required, so that damper tools should be used instead of conventional solid bars.

In the case of internal turning, the tool overhang is, together with the cutting parameters, fundamental to obtain a high finish surface on the workpiece. Figure 2 shows the behaviour of the roughness represented by parameters R_a and R_z, as a function of the L/D ratio for three different tool types (steel, carbide and silent tool (antivibration tool).

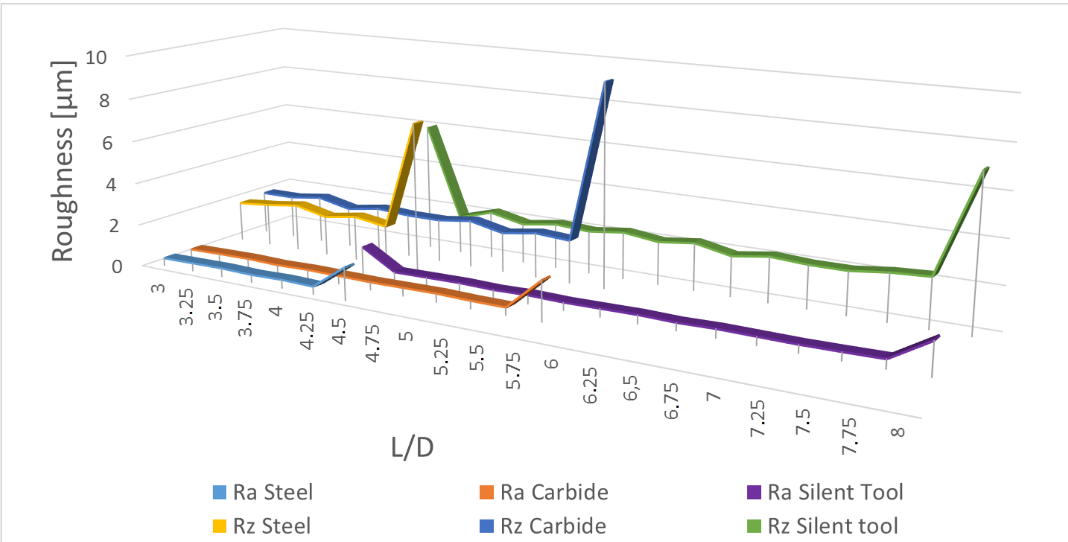

Fig. 2 *Effect of the L/D ratio over the roughness in the workpiece with different types of boring bars with a standard deviation of Ra ±0.02 µm and Rz ±0.06 µm*

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The circularity deviations, in micrometers, are presented in Figure 3 with different tools and overhangs (L/D ratio).

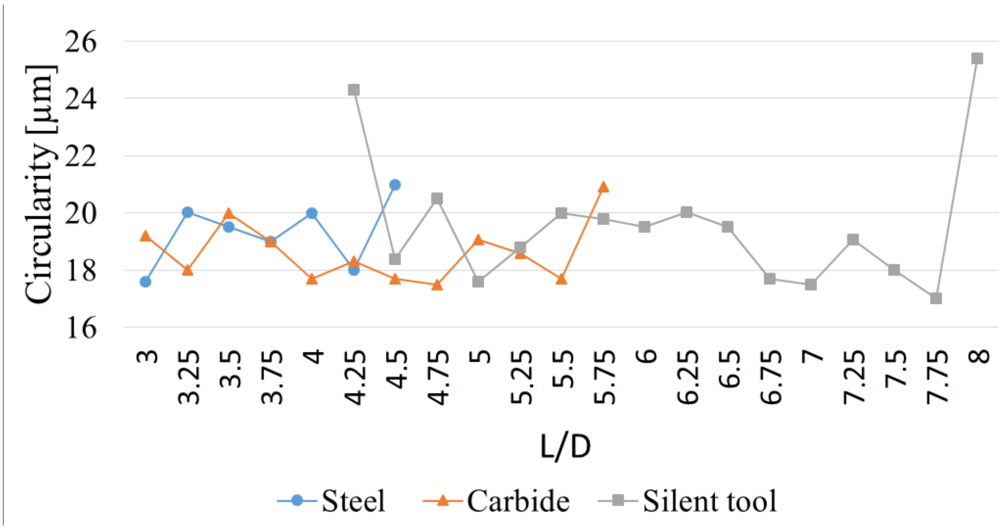

Fig. 3 *Effect of the L/D ratio over the circularity in the workpiece with different types of boring bars with a standard deviation of circularity ±0.01 µm*

Figure 4 and Figure 5 present the profile of the roughness and circularity, as a consequence of the cutting parameters and the stability of the tool in a stable and unstable regimes.

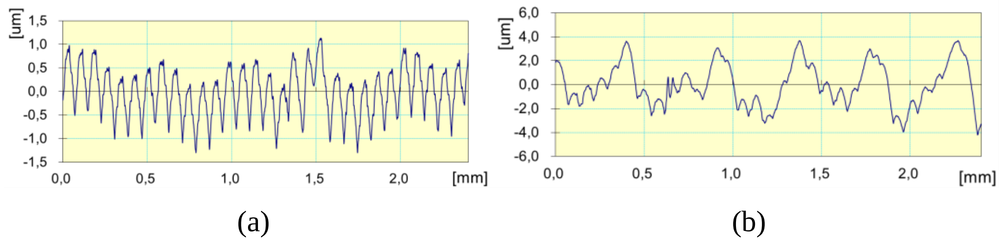

Fig. 4 *Roughness profile of a silent tool in (a) stable condition – overhang equal to 124 mm and (b) unstable condition (chatter) – overhang equal to 128 mm*

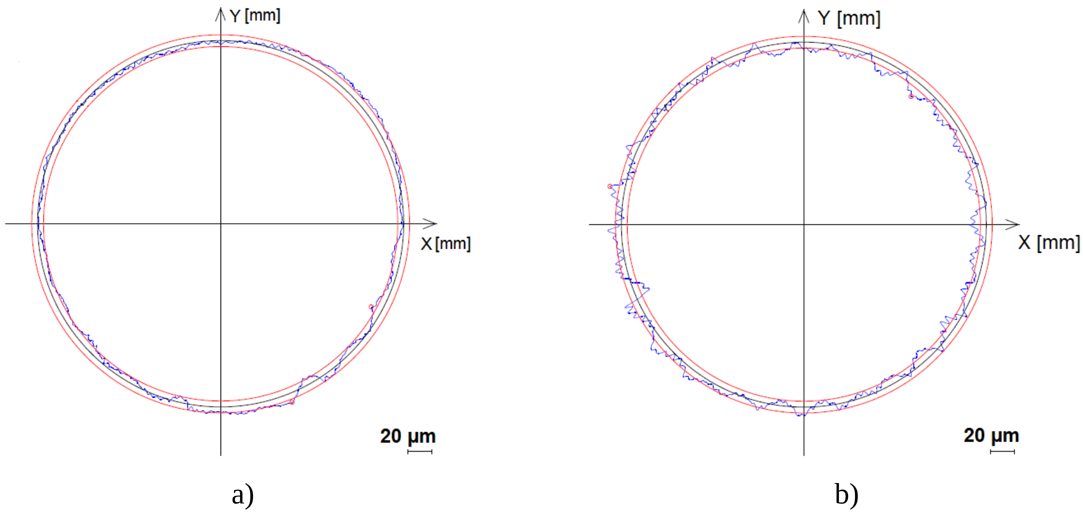

Fig. 5 *Circularity profile of a silent tool in (a) stable condition – overhang equal to 124 mm and (b) unstable condition (chatter) – overhang equal to 128 mm*

As a general result of this experiment, Table 1 summarizes the findings describing the overhang limits of each tool during internal turning operation for constants cutting parameters.

In order to define the critical L/D ratio of boring bar, the dynamic stability of internal turning was experimentally observed and classified as stable: arithmetic average roughness (R_a) was lower than 0.8 μm and no chatter marks in the workpiece surface or unstable: arithmetic average roughness (R_a) was higher than 0.8 μm and chatter marks were present in the workpiece surface due to the self-excited vibration, as illustrated by Figure 6.

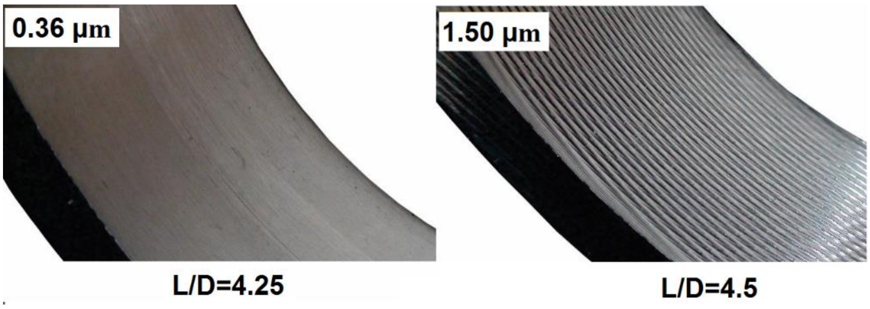

Fig. 6 *Illustration of surface textures in boring with the same cutting conditions, steel boring bar and different L/D ratios - Ra values*

Table 1 Effect of the L/D ratio over the roughness and circularity in the workpiece with different types of boring bars with a standard deviation of R_a ±0.02 μm, R_z ±0.06 μm and circularity ±0.01 μm

Tool	***Overhang (L/D)***	***Overhang [mm]***	***Stability***	***R_a [μm]***	***R_z [μm]***	***Circularity [μm]***
Steel	4.25	68	Stable	0.36	1.86	18.0
	≥ 4.5	≥ 72	Unstable	1.50	7.00	21.0
Carbide	5.5	88	Stable	0.35	2.00	17.7
	≥ 5.75	≥ 92	Unstable	1.83	9.44	20.9
Antivibration (*Silent Tool*)	L/D_{min}= 4.5	72	Stable	0.36	1.73	18.4
	L/D_{max}= 7.75	124		0.41	2.29	17.0
	L/D_{min}≤ 4.25	≤ 68	Unstable	1.30	6.01	24.3
	L/D_{max} ≥ 8	≥ 128		1.48	7,00	25.4

DISCUSSION

It can be seen in Figure 2 that, for measured parameters, the workpiece roughness is independent of the tool overhang up to a certain value, from which the roughness increases abruptly. It was also observed that, in the range of overhangs in the stable limits (Steel L/D = <4.25, Carbide L/D = 5.5 and Silent tool 4.5≥L/D ≥7.75), the roughness parameter R_a and R_z are very close and below 0.8 μm (similar to grinding process) with a regular profile, see Figure 4(a), while for unstable limits (Steel L/D ≥ 4.5, Carbide L/D ≥ 5.75 and Silent tool 4.25≤ L/D ≥8) is where the influence of tool vibration over the roughness and the form error begins letting them increase to values that is detrimental to surface quality and geometric shape of the workpiece.

It was also possible to observe that just an antivibrational tools (overhang equal to 128 mm) was able to turning deep holes 88.2 % longer compared to the steel tools (overhang equal to 68mm) with similar circularity and roughness values in the stable cutting zone. However, the damper mechanism (TMD – Tuned mass Damper) of that antivibrational tool can only operate stable in a limited range of overhangs, but such limitation can be compensated by selecting steel and carbide tools.

Since the feed rate, depth of cut and the tip radius of the tool, which form the theoretical roughness of the part (geometric contribution of the feed rate and tip radius to the roughness), were constant during the tests, the vibration was observed. The main factor that affects the stability of the machining process is the static stiffness of the toolbar which was tested in a variety of overhangs. Therefore, it is possible to say that the stability of the machine-tool-workpiece system has a huge impact in the surface finish and not, for this time the cutting conditions.

Finally, the limits of L/D ratio which increased the roughness abruptly, showing the irregular profile in Figure 4(b), are caused by the low stability of the machine-tool-workpiece system, making the use of longer overhangs unfeasible.

As observed in the roughness results, it is possible to state that the instability of the tool, due to the low static stiffness of the internal turning tool in long overhangs, generates a deflection such that it interferes with the circularity profile of the turned workpiece as observed in Figure 5(b).

Any movement in the radial direction of the tool influences both the roughness and the dimensional and geometric tolerance of the workpiece. Thus, the increase in the overhang can cause fluctuation of the form errors, as seen in Fig. 3, and when the tool stability limit is exceeded a premature breakage of the insert is imminent, generating an irregular geometric profile, illustrated in Figure 5(b), which impairs the interchangeability of the parts.

Although errors in the circularity profile cannot be eliminated, one recommendation to keep the error values to a minimum, see Figure 5(a), is to adjust the tool clamp to the smallest overhang (L/D = 3) possible for the operation. As pointed out by Thomas et al. [23], among other efficient techniques to increase the stability of the system and reduce vibration in internal turning operation with deep holes.

CONCLUSION

It is concluded that the tool overhang influences the roughness and form errors of the part under certain limit. For tool overhang values where the cutting is stable, Steel L/D =< 4.25, Carbide L/D =< 5.5 and Silent tool L/D =< 8, the roughness remains practically constant, let the turning toolbar being used for holes deeper than L/D ratios equal to 3.

Therefore, when the cutting system is in stable condition, the tool vibration amplitude is small, and micro and macro geometric errors are considered acceptable for this operation. However, there is limit value of L/D ratio in which the deviation of circularity and the roughness of the part grow up sharply and suddenly, due to the unstable operating regime.

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