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Comparison between the performances of different boring bars in the internal turning of long overhangs

Wallyson Thomas*, Zsombor Fülop, Attila Szilágyi

István Sályi Doctoral School of Mechanical Engineering Sciences – University of Miskolc – Egyetemváros, 3515, Miskolc, Hungary
**Corresponding author, e-mail address: szmwally@uni-miskolc.hu*

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ABSTRACT

Impact dampers are mainly used in the metal-mechanical industry in operations that generate too much vibration in the machining system. Internal turning processes become unstable during the machining of deep holes, in which the tool holder is used with long overhangs (high length-to-diameter ratios). The devices coupled with active dampers, are expensive and require the use of advanced electronics. On the other hand, passive impact dampers (PID – Particle Impact Dampers) are cheaper alternatives that are easier to adapt to the machine's fixation system, once that in this last case, a cavity filled with particles is simply added to the structure of the tool holder. The cavity dimensions and the diameter of the spheres are pre-determined. Thus, when passive dampers are employed during the machining process, the vibration is transferred from the tip of the tool to the structure of the boring bar, where it is absorbed by the fixation system. This work proposes to compare the behaviours of a conventional solid boring bar and of a boring bar with a passive impact damper in turning while using the highest possible L/D (length-to-diameter ratio) of the tool and an Easy Fix fixation system (also called: Split Bushing Holding System). It is also intended to optimize the impact absorption parameters, as the filling percentage of the cavity and the diameter of the spheres. The test specimens were made of hardened material and machined in a Computer Numerical Control (CNC) lathe. The laboratory tests showed that when the cavity of the boring bar is totally filled with minimally spaced spheres of the largest diameter, the gain in absorption allowed of obtaining, with an L/D equal to 6, the same surface roughness obtained when using the solid boring bar with an L/D equal to 3.4. The use of the passive particle impact damper resulted in, therefore, increased static stiffness and reduced deflexion of the tool.

1. INTRODUCTION

One way to attenuate internal turning vibration is to reduce the cutting forces by changing the machining parameters (decreasing depth of cut, cutting speed, and feed rate). These changes reduce productivity dramatically. Another way is to use active or passive dampers attached to the boring bar to avoid or minimize vibrations [1].

That vibrations might be quite undesirable, as they not only compromise the performance of components but may also cause damage beyond repair. Therefore, vibration control techniques are important in the study of vibrations. The function of dampers in vibratory systems is to dissipate the energy generated by the vibratory movement, thus decreasing the vibration amplitude. The particle impact damper is a device that increases the dampening capacity of the structure by inserting particles within a cavity in a vibrating structure [2].

Picture a structure that vibrates over a certain time period. In a given instant, this structure contains a certain amount of kinetic energy and a certain amount of deformation or potential energy; the kinetic energy is associated with its mass and the deformation energy is associated with its stiffness. Besides that, a real structure, when deformed, dissipates part of the energy. This energy dissipation, called damping, is a conversion of mechanical energy into heat energy [3].

The principle of operation of a particle damper is based on the energy dissipation through multiple inelastic collisions and the friction among particles and between the particles and the cavity wall. The resulting system is non-linear, as its vibratory response is mostly dependent on the excitation amplitude. The damping capacity depends on the level of acceleration undergone by the cavity. There are many parameters that affect the performance of a particle damper [4]. The predominance of one dampening mechanism or another is related to the dynamic characteristics of the machining process, as, unfortunately, the transference of linear moment that happens during the collisions is insufficient to dissipate most of the vibration energy, while the friction is efficient to dissipate energy only at high vibration frequencies and might even hinder the system performance at low frequencies [5].

With the modern technology in viscoelastic materials, vibration neutralizers became easy to both produce and apply to almost any structure, no matter how complex it is [6]. An example of this are Sandvik's anti-vibration boring bar (Silent Tools), that have pre-tuning system for the frequency, related to the tool overhang required by the fixation system. Its efficiency may achieve an L/D (length-to-diameter ratio) of 10 for steel tools and of 14 for cemented carbide tools. Boring bar made of materials with a high elastic modulus, as cemented carbides, are frequently used as absorbing elements, have greater dynamic stiffness and allow of performing stable cuts with L/D up to 7 [7].

The dampening effect generated by an impact damper happens as part of the energy of the vibrating structure is transferred to the particles, or spheres, that collide against each other. Traditional absorbers, such as the ones made of viscoelastic materials (Silent Tool), convert elastic deformation energy into heat and noise. One should add that, similarly to impact dampers, traditional absorbers have a series of applications, but are efficient only in certain conditions, as they lose much of their efficiency in environments where the temperatures are too high or too low, degrading more rapidly than impact dampers [8,9]. The latter, on the other hand, may be used in cutting tools, television towers, turbine blades, axes, panels, and others [10]; as they low cost and simple to build, of easy maintenance and may work for large frequency spectrums [11]. Besides that, an important advantage is that their efficiency (damping capacity) is not affected by temperature. Additionally, their implementation is simple and does not damage the surface of the machined part. Finally, they're tools to control the noise and the vibration that result from the interaction between the tool and the machined part. One of the disadvantages of impact dampers is their remarkable non-linearity, which implies difficulties in adjusting the absorption parameters – such as the stiffness and the restitution coefficient of the boring bar, and the space between the spheres and the cavity – at each time the mass of the system changes [12]. Also, it should be kept in mind that the particle impact damper is efficient at only a specific frequency range. The challenge, therefore, is to find that frequency range of greater efficiency. Hence, it is important to notice that, because of that limitation, this type of damper is rarely used in applications where the operating conditions change [13].

2. LITERATURE REVIEW

The efficient use of the particle impact damper requires a careful configuration of its parameters – such as the diameter, density and dimensions of the particles, the shape of the cavity and the type of excitation (vibration) from the primary system. Other important factors to configure the damping system are the force and frequency of vibration, the masses of the particles and of the structure, the stiffness and the damping capacity of the structure, the space between the particles and the main system, the natural frequency of the main system, the initial displacement and the restitution coefficient [10]. Hence, the study of the damping mechanism is quite complex [12,13].

In dampers with micro particles whose cavity in the boring bar is small, the damping action takes place as the particles get stacked in layers – this happens in such a way that the movement of the inferior layers is minimized and a more intense movement is created in the upper layers. This results in reduced kinetic energy transference and an effective decrease in the damping capacity. As for the cavities in average size boring bar, the damping system is more sensitive to the particle size – if the particle size is decreased, the vibration is not decreased, as it depends on the gap between the particles and the cavity. As for large cavities, any type of particle may be used, as the energy dissipation by the collisions among the particles in the cavity is inefficient. When large spheres are used, the directions of the impact against the cavity wall and the direction of excitation are practically parallel, being that this impact energy is low compared to the mass of the whole system. It is possible to say that, if the diameter of the spheres is smaller than 2 times the diameter of the cavity, no collision between the spheres and the cavity walls might happen. This may be the case when the direction of the excitation is perpendicular to the wall, in such a way that the spheres collide sporadically against the upper and lower walls of the cavity [15, 16].

Olson and Drake (1999) performed experiments using a PID (Particle Impact Damping) system which had a medium sized cavity, in a boring bar fixed to a laboratory device and excited in different frequencies by an electrodynamic shaker. It was concluded that the spheres move in only one direction and do not collide in other directions. As the spacing between the spheres and the cavity is small, or pre-determined, the spheres collide in a relatively orderly manner and in only one direction, which improves their dampening capacity, as the impact of the collision is concentrated in a small region. This avoids the energy waste that would happen if the spheres collided against various regions, with linear moments of multiple directions. Such concentration of the collision force enhances the system efficiency in dissipating energy [8].

If some variables are held constant – such as the frequency of excitation, the diameter of the spheres and the amount of spheres in the cavity, among other factors – and only the spacing between the spheres (gap) is modified, the absorption efficiency of the system, as well as the damping factor, increase dramatically. The work of Friend and Kinra (2000) shows the possibility of estimating theoretically this gab by using some equations, as well as through FEA (Finite Element Analysis) [17]. These authors also relate the gap and the decay rate of the vibration amplitude of the structure. Greater gaps imply greater rates, whereas smaller gaps imply reduced rates, albeit a greater number of impacts occur in the last case – this shows that the number of impacts is not the main factor that affects the energy dissipation.

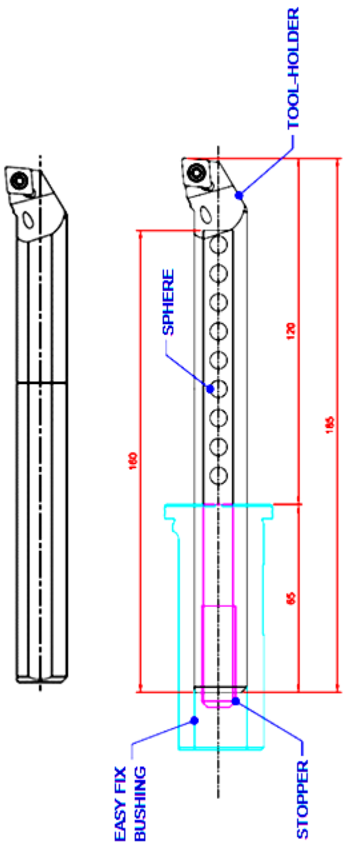
The friction, among other factor, reduces the speed of the moving particles. The material of the sphere, the friction coefficient between the spheres, the amount of particles, the number of particles and the volume fraction of the cavity occupied by the particles affect the friction phenomena within the cavity [12]. Zhiwei and Wang (2003) estimated that the maximum volume fraction that may be occupied by spheres in a cavity is would correspond to values between 52 and 74 %. Those values are, respectively, equivalent to the maximum and minimum atomic packing factors found in cubic crystalline structures. The minimum and maximum spacing between the spheres may be determined, which allows of previewing some parameters, such as the number of sphere layers, the size of the spheres, the cavity dimensions and the volume occupied by the spheres [18].

3. MATERIALS AND METHODS

The main concern of this work consists in the comparative analysis of the tool vibration in the internal turning of hardened materials while using a conventional boring bar and a boring bar containing a passive impact damper.

Two 20 mm diameter boring bars (ISO code A20S-SCLCR 09-R 1M 0866943) were chosen – they were kindly supplied by Sandvik Coromant. The boring bar with a passive impact damper has cavity (hole in the axial direction) to accommodate the steel spheres, and a pre-adjustment system, as illustrated in figures 1 (a) and (b).

One of the steel boring bars was modified to accommodate the particle impact damper. The tool was drilled in its longitudinal direction and a thread was made in one of its extremities, in such a way as to create a closed compartment. The hole had a 10.5 mm diameter and a 160 mm length, as depicted in figure 1 (b). This cavity was then filled with steel spheres. The spheres used in the experiments were of AISI 52100 chrome steel and had diameters of 9, 10 and 10.32 mm. They were grinded, polished, free of surface defects and had a hardness of 60 - 66 HRC.



(a) (b)

Figure 1. Conventional boring bar (a) and boring bar with cavity (b).

As for the tool insert, an adequate insert for finishing operations on smooth surfaces of hardened steels was chosen. It was composed of CBN it's ISO code is CCGW09T308S01020F 7015 (grade ISO H10). The advantage of the chosen tool insert, 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 tough it is reduced when compared to other inserts with a greater CBN content.

The FRFs (Frequency Response Function) of the tool holders were obtained for different overhangs (length of the tool holder that protrudes from the turret) through impact tests (hammer impact test). In each test, the boring bar was fixed to the turret of the machine tool used in the turning tests, as it is further described, with the desired L/D. An accelerometer was installed on the boring bar, which was then hit with an instrumented impact hammer. Each impact was considered a measurement – 5 measurements were done for each L/D and each one of the boring bars used. In the data acquisition, a frequency range of 0 to 10000 Hz was used, with a resolution of 1 Hz, the smallest possible in data acquisition software used. For each test, the software calculated an average of the 5 measurements that were executed and made the results available. Boring bar overhangs corresponding to length-over-diameter ratios (L/D) greater than 3 were experimentally evaluated, as smaller ratios do not yield interesting results for this research, as it has also been evaluated by Hoshi (1990) [19, 20].

The 4340 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 hardness after quenching varies from 54 to 59 HRC. Its chemical composition is presented in Table 1.

The dimensions of the test specimens are shown in figure 2, where the 30 mm hole that was machined during the tests is shown. The tool swept its surface several times as it was machined, in

Table 1. Chemical composition of the material of the test specimens (% wt).

C	Si	Mn	Cr	Ni	Mo	V
0,4	0,25	0,65	0,76	1,68	0,23	0,003

Ti	Al	Cu	P	S	Ceq
0,002	0,015	0,11	0,018	0,02	0,83

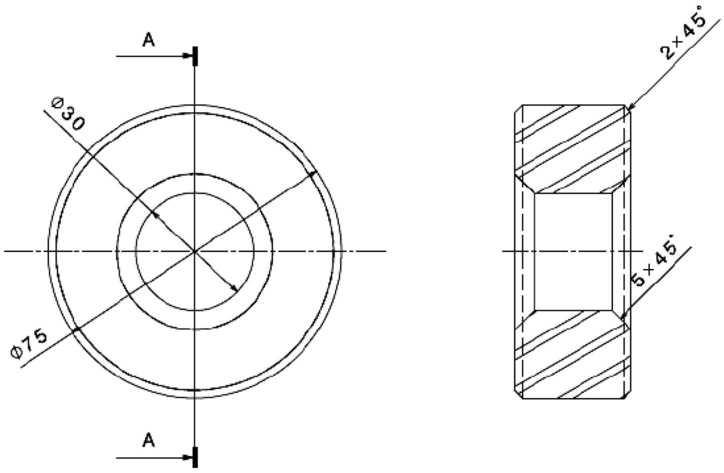
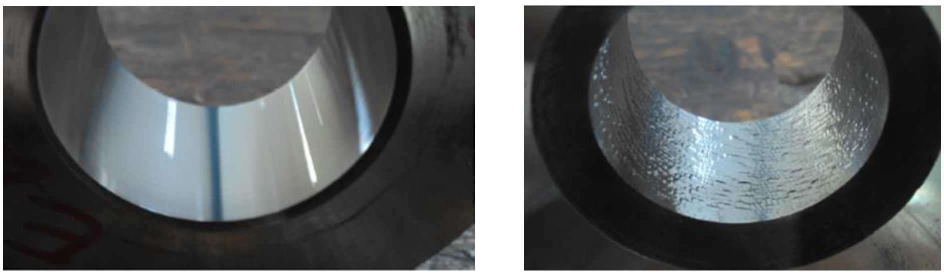


Figure 2. Dimensions of the test specimen, in millimetres [mm].

such a way that the hole's diameter grew during the test. When the diameter reached a limit dimension of 50 mm, the test specimen was discarded, in order to make sure that there would be no substantial hardness variation on the machined surface.

After testing the conventional boring bar, tests with the boring bar containing a cavity were done. By using the conditions described in table 2, it was searched to obtain the best performance of this last tool, that is, a machining process with no chatter and an average roughness of the machine surface lower than to 0.8 µm. The spheres were employed with the aim of increasing the system's stiffness and damping the machining vibrations. Hence, the following procedure was adopted: the boring bar was fixed to the turret with one of the L/D in table 2, and its cavity was filled with spheres correspondingly. The boring bar was also tested with an empty cavity.

After each test, the FRF of the bar configuration was obtained as previously described. Then, to



(a) (b)

Figure 3. Surface generated by a (a) stable cut and (b) unstable cut [5].

Table 2. Set up conditions of the tool with a cavity.

TOOL OVERHANG (L) [mm]	L/D	Ø SPHERE [mm]	VOLUME FRACTION (VF) [%]
120	6	10.32	70%
		10	60%
		9	50%
110	5.5	10.32	70%
		10	60%
		9	50%
100	5	10.32	70%
		10	60%
		9	50%
90	4.5	10.32	70%
		10	60%
		9	50%
80	4	10.32	70%
		10	60%
		9	50%
70	3.5	10.32	70%
		10	60%
		9	50%
68	3.4	10.32	70%
		10	60%
		9	50%

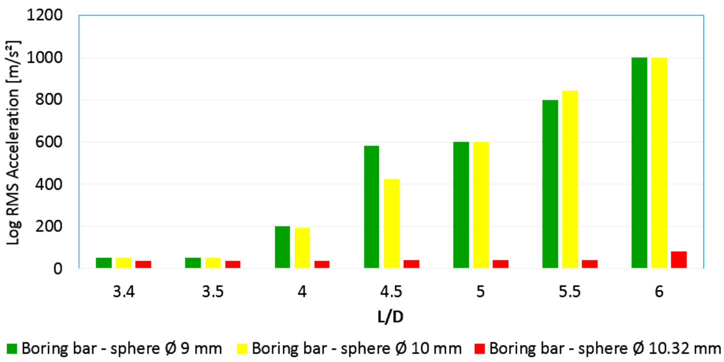
measure its radial acceleration, an accelerometer was fixed on the boring bar and a 15 mm length was machined in the 30 mm hole in the test specimen. Next, the roughness of the machined surface was measured as the test specimen was still fixed in the lathe. The roughnesses of the machined surfaces were measured with a portable Mitutoyo roughness tester (SJ-201P model) connected to a computer. The software SurfTest, which was installed in this computer, was used to obtain the data and the surface roughness profiles.

It is important to define some expressions employed in this work, which are:

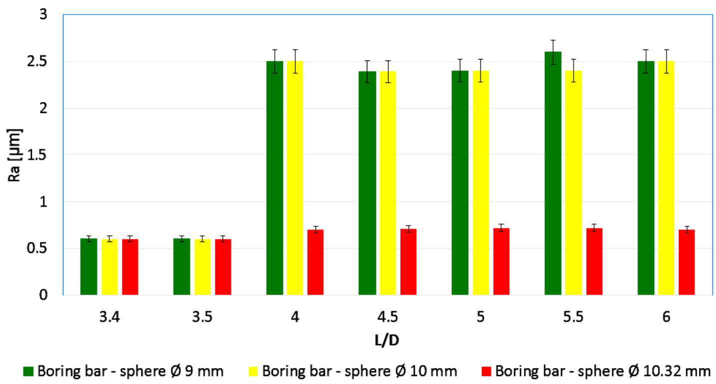
- Stable cut: internal turning operation where the vibrations present acceleration signals inferior to 100 m/s2; and which yields a surface whose roughness is less than 0.8 µm and that is free from chatter marks, as shown in figure 3 (a);
- Unstable cut: the surface roughness of the machined surface and the acceleration in turning exceed the values cited above as acceptable for a stable cut. A surface as the one shown in figure 3(b) may be generated;
- Conventional boring bar: boring bar with no cavity, spheres, or threaded bar (stopper), as illustrated in figure 3 (a);
- Boring bar with cavity: boring bar with a longitudinal inner hole, filled or not with spheres to damp vibration, as illustrated in figure 3 (b). One may notice that the cavity should be made as close as possible to the tip of the tool, where the greatest deflexions occur.

4. RESULTS

At first, an optimal configuration of the boring bar filled with spheres was searched, aiming a stable cut, that is, with no chatter or noise. Thus, the average roughnesses (Ra) of the surfaces machined with different L/D, as well as the average accelerations (RMS), were compared. Figure 4 (a) presents the surface roughnesses values obtained after the internal turning operations performed with boring bar filled with 9, 10 and 10.32 mm diameter spheres. For all L/D tested, the roughness values are close when 9 and 10 mm spheres are used. It



(a)



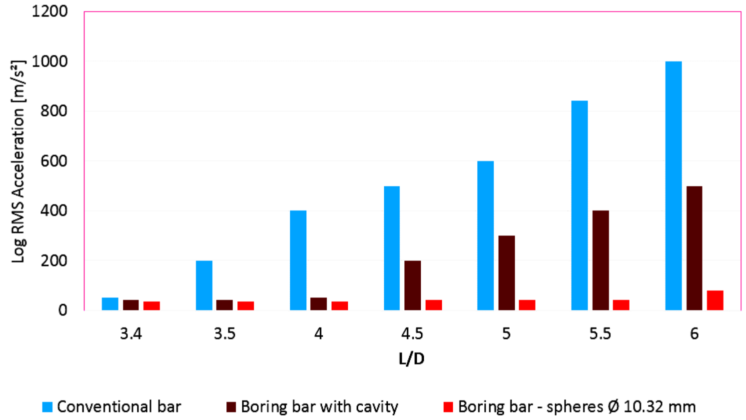
(b)

Figure 4. (a) Acceleration values and (b) average surface roughness (Ra) obtained with the too-holders filled with Ø 9, Ø 10 and Ø 10.32 mm diameter steel spheres.

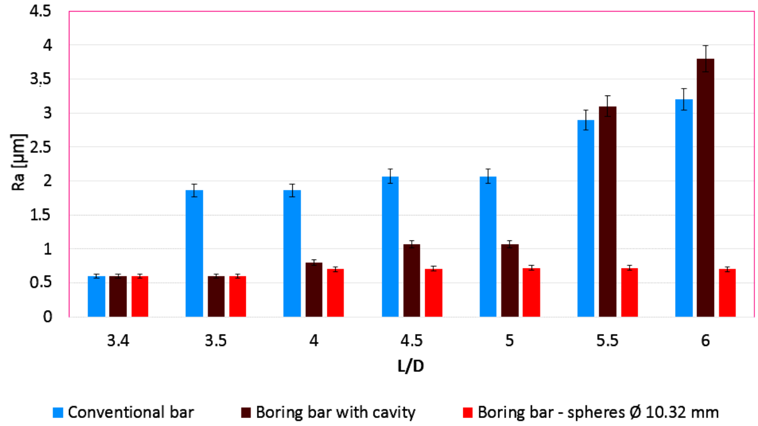
may be seen, too, that for boring bar filled with 9 and 10 mm diameter spheres, the surface roughnesses of the test specimens increases drastically from L/D values equal to 4, while that, for boring bar filled with 10.32 mm spheres, the roughness varies little. Figure 4 (b) presents the average RMS acceleration values of the tool during the turning operations. It is noticed that, as expected, they behave similarly to the surface roughness.

The tool holders filed with 9 and 10 mm spheres got into an unstable mode for L/Ds equal to or greater than 4, where it can be noted that the acceleration signal, that is, the tool vibration, grows exponentially as the tool overhang increases. When the boring bar filled with 10.32 mm spheres, both the surface roughness and the acceleration presented reasonable values until an L/D equal to 6. This result indicates that the mass of the particles in the cavity may have a greater effect on the damping than the value of the clearance between the particles and the cavity wall, once that, as the particle diameter increased, and thus its mass, the spacing between the particles and the cavity's wall decreased.

Then, the boring bar with a cavity filled with 10.32 mm diameter spheres, which had the best performance among the boring bar filled with spheres, had its performance compared to the ones of the conventional boring bar and of the boring bar with an empty cavity. Figure 5 (b) enables comparing the tool accelerations when each configuration of the boring bar is employed. It is seen that the acceleration of the boring bar filled with Ø 10.32 mm diameter spheres remained practically constant for all tested overhangs and, correspondingly, both the surface roughness and the geometric profile of the machined surface did not deteriorate within the test limits, as shown in figure 5 (a). As for the conventional boring bar, it vibrated significantly at L/D equal to and greater than 3.4. Therefore, it is possible to use a boring



(a)



(b)

Figure 5. (a) Acceleration values and (b) average surface roughness (Ra) obtained with the conventional bar, the boring bar with a cavity and the boring bar filled with Ø 10.32 mm steel spheres.

bar with a sphere filled cavity at L/D values up to 6, whereas for the conventional boring bar it is not advisable to exceed the L/D value of 3.4. This indicates that it is possible to perform internal turning operations using 20 mm diameter boring bar filled with spheres with overhangs up to 120 mm – and not 68 mm, which is the stablished conventional limit for this system.

The tests showed essentially that, as may be seen in figures 5 (a) and (b), the steel boring bar can exceed a L/D equal to 4 recommended by some tool makers [8, 21-23] with a gain above 50 % when a particle impact damper is used. This greater overhang equals the overhang limit for cemented carbide boring bars, which is around a L/D value of 6 – That allows of replacing cemented carbide boring bar with steel boring bar filled with spheres. By making a cavity inside the steel tool holder, that substitution is rendered possible, reducing costs and increasing efficiency. It is convenient to note that it was not possible to verify whether a boring bar with a PID may attain the performance of an anti-vibration one, which allows for a L/D equal to 10 [8]. The length of the boring bar employed did not render that test possible, because of the constraint that, to guarantee a rigid fixation, the length of the boring bar fixed inside the machine turret should be at least four-times its diameter.

The main points to be highlighted based on the results shown are:

- Tool vibration remained almost constant with the increase of the tool overhang up to the point it suddenly increased in a certain value of tool overhang (called limit value for stable cutting). Small changes in the tool overhang close to the limit region generated this sudden variation, indicating that the tool bar is very sensitive to the rigidity change in this range of overhang;

- the use of internal turning tool bars with impact damper caused an increase of the limit value for stable cutting and, consequently, made possible the turning of deep holes;
- As the diameter of the spheres increased, the limit value for stable cutting also increased, indicating that the damping effect is higher when the mass of the spheres is higher and the gap between the spheres and the cavity wall is lower, which cause, the increase of the impact momentum transfer.
- when the sphere diameter used in the impact damper was 10.32 mm it was not possible to determine the limit value for stable cutting in terms of tool vibration, because it was possible to cut up to a L/D value of 6 without sudden increase in the acceleration signal. We could not go higher with the L/D value in these experiments, since, above this tool overhang, it was not possible anymore to hold the bar in the lathe turret in a safe way.

Based on these results it can be stated that the vibration energy dissipation (damping effect) caused by the impact of the spheres against the cavity wall is higher when the spheres have higher mass associated to the decrease of the gap between spheres and the cavity wall. The impact of these spheres against the wall transfers a high amount of linear momentum from the tool bar containing the cavity to the spheres. The damping effect depends on the variation of the linear momentum during the impact of the sphere, which, in turn, depends on the sphere material, mass, the speed of the sphere at the impact moments and the restitution coefficient of the impact. Since this last parameter was the same for all bar configurations (the materials of the spheres and of the tool bar were the same for all types of bars), the linear momentum depends on the spheres mass (which increased a lot with a little increase of the sphere diameter), the sphere speed at the moment of contact between the sphere and the wall and the number of collisions between these elements (collisions with wall speed in opposite sense to the sphere speed). What the results of the experiments showed is that the increase of sphere mass (or sphere diameter) and the decrease of the gap (which may have increased the number and frequency of impacts between the elements) caused a higher damping effect of the sphere impacts against the cavity wall. Therefore, the impact damper, which used the biggest spheres, was the one, which caused the highest damping effect and, consequently was able to cut with the longest tool overhang.

Another important point to evaluate the damping capacity of the impact damper is the mass ratio between the spheres inside the cavity and the mass of the vibrating body (the tool bar). As the sphere masses increased, this ratio also increased and, consequently, increased the amount of material to cause the damping effect of the toolbar.

It can be observed in figure 6 that the peak excitation frequencies of the tool during the machining process, obtained by applying the Fast

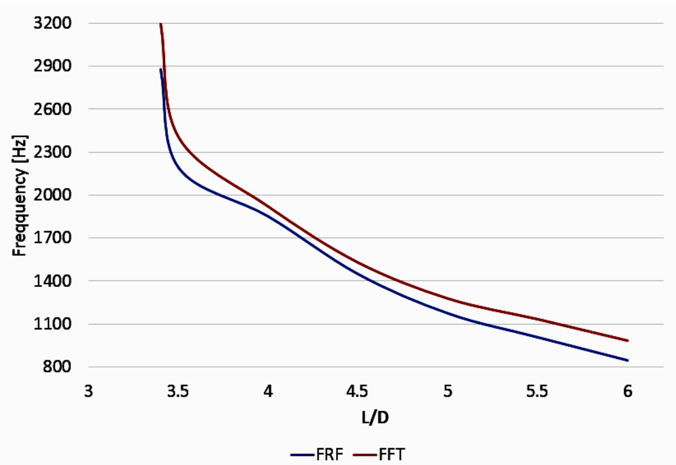


Figure 6. Comparison between the FRF and the FFT of the boring bar with the best performance (boring bar filled with Ø 10.32 mm spheres).

Fourier Transform (FFT) to the tool vibration signals obtained during the machining operation with the boring bar filled with 10.32 mm spheres, are very much similar to the natural frequency of the tool (FRF) obtained from the impact tests. Both decrease as the tool overhang increases. Therefore, as the tool overhang increases, the deflexion caused by the cutting forces also increases and, consequently, both the excitation and natural frequencies decrease. However, as it may be seen in figures 4 and 5 (b), that vibration increases little, probably due to the damping caused by the spheres impacting against the cavity's walls. Consequently, the surface roughness obtained when using this boring bar also remains in an adequate level.

5. CONCLUSIONS

Based on the results that were exposed and discussed in this work, it may be concluded that, in the internal turning of hardened steel with conventional boring bar and boring bar with impact dampers:

- The damping capacity of the damper used in this work is such that it allows of using boring bar L/Ds way greater than the ones recommended for conventional boring bar, thus making the internal turning of deeper holes possible;
- The L/D of the boring bar can be increased when using spheres whose diameter is a little less than the diameter of the cavity in the damped tool holder, when compared to the boring bar filled with smaller spheres;
- The impact damper is able to compensate the mass loss of the boring bar with a cavity and, consequently, its loss of stiffness and change in natural frequency. That makes obtaining good surface finishes of the machined parts possible, while using grater L/Ds than the ones recommended for conventional boring bar.

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