An experimental evaluation of particle impact dampers applied on the tool for milling of hardened steel complex surface

Victor Rossi Saciotto1 · Anselmo Eduardo Diniz1

Received: 2 September 2021 / Accepted: 18 January 2022 / Published online: 26 January 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
In the manufacturing of dies and molds, vibrations may represent serious problems, since the finishing tool used is usually slender (high length/diameter ratio) in order to machine deep cavities with complex geometries, typical of these products. Vibration is an undesirable phenomenon in any machining operation as it can lead to poor surface finish, low material removal rate, and high tool wear rate. Impact dampers have been put into the tools as a method for reducing vibration in machining processes. Damping occurs through energy dissipation and linear momentum exchange during intermittent collisions between the main structure (in this case the milling tool) and a free mass (spheres or cylinders placed within a tool cavity). Although efficient, these types of dampers are highly nonlinear. Thus, the aim of this work is to analyze the effect of different materials and geometries (steel spheres, tungsten spheres and steel cylinders) acting as impact damper elements inside a ball nose end milling tool. To perform this task, a comparison of commercial tool holders and dampened tool holders was done in the milling of a convex D6 steel surface, comparing commercial tool holders with dampened ones. The results showed that the tools with impact dampers generated lower values of roughness in the workpiece (around 30% of the value observed in the conventional steel tool holder for the case of steel cylinders and around 40% for both spheres) and presented lower levels of vibration when compared to the same tool without the impact damper, mainly in the machining of workpiece regions where radial and tangential forces are predominant. The tool which used tungsten spheres as damper elements generated roughness surfaces similar to those obtained with steel spheres, while the tool which used steel cylinders only generated lower roughness in the regions where the axial force component is not predominant, which shows that its performance is highly dependent on the resulting force direction.

Keywords Milling · Damper · Impact · Tool vibration

1 Introduction
With the increasing use of high speed machining techniques, vibrations may represent serious problems, since due to the high speeds involved, the local modes of the spindle-toolholder-tool subsystem are excited, impairing the achievement of tight tolerances and low surface finish of the workpiece and causing tool breakage and damage to the machine structure [1]. When it comes to the milling of molds and dies, in addition to the high speeds involved in the process, another aggravating factor for the occurrence of excessive vibrations is the fact that the tool is quite slender, since it needs to copy complex forms, often with small radii and usually in deep cavities, what creates the necessity of using long tools.

During the milling of dies and molds with 3-axis machines, due to the circular shape of the tool, the angle formed between the tool axis and the workpiece surface changes according to the inclination of both [2]. This angle has a strong influence on the components of the machining force. When the tool axis is parallel to the surface of the workpiece, only the tangential and radial force components are present; the axial component is close to zero. As this angle decreases, the radial component value decreases and the axial component value increases. In ball nose end mills, the radial direction of the tool is not very rigid, as only the tool body resists deflection [3]. Thus, one of the main problems in machining using slender tools occurs near vertical
walls, where the radial force is greater and the tool deflection and its consequent vibration affect the surface quality and dimensional accuracy of the workpiece [4].

Machining processes may generate three different types of mechanical vibrations. They are known as free vibrations, forced vibrations, and self-excited vibrations [5–7]. Free vibrations occur when the system is displaced from its equilibrium with no external forces causing the motion. In machining operations, free vibrations appear, for example, as a result of the collision between the tool and workpiece [5]. Forced vibrations occur due to external excitations and are those that occur due to dynamic forces applied to a stable system, for example: cutting forces variation; interrupted cutting processes, such as milling; internal sources, such as unbalanced rotating elements; and external disturbances, transmitted from the floor to the machine tool [8]. Self-excited vibrations originate in the system itself and extract energy to start and grow from the alternated force produced by the interaction between the tool and the workpiece during the machining process. This type of vibration raises the instability of the system and is the most undesirable and least controllable one [6, 7].

The occurrence of vibrations can be minimized either through the modeling of the system and subsequent appropriate choice of machining parameters, or through the addition of dampers in order to maintain a high rate of chip removal [5]. Dampers used in machining operations can be divided into active or passive systems. Active systems have the ability to monitor the dynamic state of the machine tool-part system, diagnose a given occurrence, and actively execute decisions that changes, if necessary, the system to a more suitable condition [9]. An active system is implemented using actuators, controllers, and sensors to control the vibration in the machining process [10, 11].

Passive dampers, despite not being able to modify their operation according to a system response, are preferred, as they are simpler and cheaper to build. The principle of passive damping is to convert mechanical energy into other forms, for example, heat. To perform this task, it includes strategies based on the modification of certain elements of the structure, in order to modify the behavior of the system [8].

An example of passive damper used in machining is the TMD (Tuned-Mass Damper), whose working principle is an inertial mass added to a structure. The added mass absorbs part of the vibration acting on the main structure and generates the damping [12]. A TMD used in machining, which is commercially available, is the Silent Tools™ line, from Sandvik Coromant. In this system, inside the tool holder, there is a preset passive dampening mechanism, in which a mass in contact with a rubber acts as a damper [13]. Despite the efficiency in reducing vibrations, this type of tool has a very high cost when compared to simpler systems. Furthermore, the TMD performs satisfactorily in a limited frequency range [14], which makes each tool holder suitable for a particular operation and for a specific range of machining parameters.

Another type of passive damper is the impact damper, which is one of the most effective passive control methods for minimizing vibrations. The advantages of this type of damper are that they are cheap, simple to manufacture, and provide good performance under a wide range of accelerations and frequencies [15]. They are composed of either one or multiple masses placed inside a cavity connected to a vibrating structure. In this way, the energy is dissipated through the impact and friction of the added masses with the structure to be damped [16]. They are highly non-linear since the damping is derived from a combination of energy loss through friction and partially inelastic collisions with the structure and the particles themselves. There is also a linear momentum exchange mechanism, in which the momentum is transferred from the structure to the particles. This energy is then stored in the particles in terms of kinetic energy and deformation [9, 10].

In order to understand the highly nonlinear behavior of the impact dampers, Albuquerque [17] modeled and experimented an impact damper. Forced vibrations were performed, and it was found that a specific gap value between the particle and the structure provides an optimum damping efficiency. The vibration attenuation depends, first, on the collision between the particles and the structure moving against each other. The greatest attenuation is obtained when, at the instant of the contact, the impact mass and the structure have opposite velocity direction. When a very small gap is used, there is a reduction in the efficiency of the impact damper, since part of the impacts occurs when the velocities are in the same direction. When the gap is too large, there will be no collision between particles and structure. Thus, the gap must be adequately designed for greater efficiency. It should be noted, however, that a gap is only considered small or large when it is related to the system vibration amplitude and frequency [17].

Sims et al. [18] experimented a particle impact damper during a milling operation, in which the element of greatest instability was the workpiece. In this way, the damper was attached to the body of the workpiece. With the use of the dampers, the maximum depth of cut was increased from 0.2 to 7 mm, maintaining the surface roughness. Also, according to the same authors, when compared to other damping techniques, such as TMDs, the impact damper is effective for a wider frequency range, with a smaller size and lower damper mass.

One of the first works to use the impact damping system inside cutting tools was that of Suyama et al. [19], who performed tests for the internal turning of hardened steel SAE 4340 with tool holders of steel, carbide, and steel with several small steel spheres acting as particle dampers. The use
of particle dampers increased the maximum tool overhang from 68 to 80 mm in comparison to the conventional steel tool holder, maintaining the stability of the cut.

Diniz et al. [20] evaluated the use of impact dampers in the internal turning of hardened steel SAE 4340. For this purpose, they drilled an 8.32-mm diameter hole in the axial direction of the tool holder. Steel spheres with diameters slightly smaller than the hole (5, 6.5, and 8 mm) were inserted in the cavity. The tool with 8 mm spheres showed the best results and allowed the increase of the maximum overhang of the conventional tool from 70 mm \( (L/D = 4.375) \) to 128 mm \( (L/D = 8) \), maintaining the same roughness values and without chatter occurrence. Based on these results, it was inferred that the damping caused by the impact of the spheres is greater when they have greater mass, associated with a smaller gap between spheres and cavity, since the damping effect depends on the exchange of linear momentum between the spheres and the tool, which is related to the sphere mass, impact velocity, and number of collisions [20].

Galarza et al. [21] evaluated the impact damper effectiveness during a ball nose end milling of a convex D6 steel surface with 60 HRc hardness. In order to apply the damping system, they drilled a 6-mm diameter and 130-mm length hole in the tool axial direction. Then, the hole was filled with spheres of 5.9, 5.5, and 5 mm diameter. The results showed that the lowest surface roughness values were obtained for the tool with the largest sphere (5.9 mm). Therefore, it was again proved that the best results were obtained for smaller gaps and higher sphere mass.

However, the application of impact dampers in rotating tools has not been widely studied. The aim of this work is to reduce the tool vibration level during the milling of convex surfaces through the application of an impact damper constructed with the addition of either steel or tungsten spheres or steel cylinders into the tool holder, in order to determine the best damping element material and geometry to reduce the vibration level of a slender milling tool. Aiming this goal, the average roughness of the workpiece at the beginning and end of tool life, tool life, and the force variation during machining will be analyzed.

2 Materials and methods

All the milling experiments were done in a Mori Seiki SV40 three-axis vertical machining center with 22 kW, maximum speed of 12,000 rpm, and GE Fanuc MSC-518 computer numerical control. In order to obtain the milling forces in the \( X \), \( Y \), and \( Z \) directions during machining, a KISTLER 9295B piezoelectric dynamometer was used, connected to a KISTLER 5019B signal conditioner fixed on the machine worktable, which transmits the force signals through an A/D National Instruments PCI-6025E acquisition plate, for a computer with LabVIEW 2011 software. A low pass filter was used in the conditioner with a cutoff frequency of 5 kHz, an acquisition rate of 10 kHz, and a conversion rate of 400 N/V. Subsequently, a digital bandpass filter between 150 and 2000 Hz was applied, eliminating network noise in the 60 Hz frequency and its first harmonic. The frequency was limited to 2000 Hz, since the highest frequencies found in the signal were in the order of 1500 Hz. The fixation of the dynamometer and the workpiece is shown in Fig. 1.

To measure the tool flank wear, a Quimis Q714ZT2 optical microscope was used, connected to a 1.3 megapixel Motic digital camera, with a maximum zoom of 80 times. Image acquisition and processing were performed using the Motic Image Plus software. The wear was measured each time the tool had cut a full machining area of the workpiece (one quarter of the circle with 40 mm thickness — see Fig. 5). This procedure was repeated until the tool maximum flank wear \( (V_{B_{max}}) \) reached 0.2 mm. This value was used based on the work of [20] and [21], since in finishing operations, flank wear may not reach high values; otherwise, it could harm the workpiece surface finish. To obtain the mean roughness \( (R_a) \), a portable Mitutoyo Surftest SJ-210 roughness tester was used, with a cut-off \( (\lambda_c) \) of 0.8 mm [22], connected to a computer containing the SurfTest® SJ210 software. The roughness measurement was executed in the direction perpendicular to the tool feed.

![Fig. 1 Workpiece and dynamometer fixation](image-url)
An AISI D6 steel specimen, quenched and tempered presenting hardness of 60HRc, was used as workpiece, which dimensions may be observed in Fig. 2.

Commercial steel tool holders R216F-12A16S-085, one original and another with a 6.1-mm diameter axial hole, were used, as well as a R216F-12A16C-085 carbide tool holder, all from Sandvik Coromant. The carbide tool holder tends to have much lower vibration levels, since it has an elastic modulus about three times greater than that of steel, which contributes to the reduction of vibration amplitudes. For all the cases studied, inserts with a circular edge of 12 mm diameter ISO code R216F-12 30 E-L 1010 made of ISO H10 carbide with PVD coating of TiAlN, also from Sandvik Coromant, were used.

The impact dampers were inserted into the tool holder as shown in Fig. 3. First, a 6-mm diameter hole was drilled in the axial direction of the tool along its central axis. Subsequently, a reamer was used in order to obtain a final hole diameter of 6.1 mm. Both, the spheres and the cylinders, used as damper elements had a diameter equal to 6 mm. Thus, a maximum diametrical clearance of 0.1 mm was maintained. To adjust the axial clearance between the spheres, an M8 × 1.5 thread with 15 mm length was made, adjusted with an internal hexagonal screw; thus, the clearance in the axial direction remained constant for all tested configurations. The tool overhang used (distance between the tool fixation and the tool tip) was 85 mm (Fig. 3). The choice of diameter for spheres and cylinders was based on the Galarza et al. [21] work. These authors carried out a

![Fig. 2 Schematic drawing of the workpiece](image1)

![Fig. 3 Schematic drawing of the tool holder with cylinders (a) and spheres (b)](image2)
study with the same steel tool holder, with steel spheres of different diameters acting as dampers, concluding that the greatest damping was observed for smaller gaps (0.1 mm) between the structure and the spheres, that is, spheres with larger diameters. Thus, maintaining a maximum gap of 0.1 mm, tests were performed varying the material and geometry of the damper.

As the impact damping principle uses the linear moment exchange which occurs during intermittent collisions, it was decided, in addition to steel spheres, to use a material with higher density in order to increase the damper mass and, thus, obtain greater attenuation of vibration during each impact. The highest density material commercially available was tungsten, which has density of 14.95 g/cm³, about 1.9 times greater than steel density. Still aiming to increase the damper mass, but this time without changing the damper material, it was also decided to use steel cylinders. Therefore, to carry out the tests, five different tool configurations were used, as shown in Table 1.

The area of the workpiece machined during the tests corresponds to a circular surface with a radius of 30 mm (Fig. 2), on which milling was performed with 3 programmable axes, that is, always keeping the tool in the vertical direction. Thus, when the tool is cutting region 3 (Fig. 4), the radial force components will be quite significant. This is the most critical region during the operation, with the tendency to increase vibrations, since the radial direction of the tool is not very rigid, as only the tool body, which has a high L/D ratio, resists deflection.

During the tests, milling was performed using down milling and in a concordant descending path, with feed direction from regions 1 to 3 (Figs. 4 and 5a), since the tests carried out by Kull Neto et al. [23] and Galarza et al. [21] showed that, during copy milling, this strategy generates a better surface finish. All the measurements were performed considering a lead angle of 5° for region 1, 45° for region 2, and 85° for region 3, as illustrated by the blue areas highlighted in Fig. 4.

The machining parameters used to carry out the experiments are shown in Table 2.

Firstly, tests were carried out with the carbide and steel commercial tool holders, without the addition of dampers, until the tool reached a maximum tool flank wear $V_{B_{\text{max}}}$ of 0.2 mm (tool life tests). The tool wear was always measured in the region with the largest diameter of the insert, since it is the region that experiences the highest cutting speeds. Force levels in the $X$, $Y$, and $Z$ directions were acquired 5 times during each pass (the pass corresponds to the machined surface across the entire width of the workpiece; see Fig. 5b). In each acquisition, 5 tool cycles were measured (each cycle corresponds to an entry and an exit of the tool in the workpiece; see Fig. 5a), totaling 25 measured cycles per pass. This procedure was carried out during all passes. The average roughness of the workpiece was measured 4 times in the direction of the width of cut (perpendicularly to the feed direction) in each of the 3 regions, also in all passes. In region 1, the roughness was always measured for a 5° lead angle, in region 2 for a 45° lead angle, and in region 3 for a 85° lead angle.

Three replicas of the experiment were made with the carbide tool holder and two with the steel tool holder, analyzing tool wear, roughness, and force signal. Subsequently, using two inserts with 0.2 mm of flank wear, 2 replicas were performed to measure the average roughness and forces, this time for the steel tool holder with steel spheres, tungsten spheres, and steel cylinders. In order not to encourage wear greater than 0.2 mm, in each of these tests, only 1/3 of the part width was machined, and after each pass, it was checked if the wear remained constant.

Then, a new tool life test was carried out with tungsten spheres, this time using a new insert as in the first two tests (tests with conventional tools), analyzing all passes in order to obtain the wear, forces, and roughness results along tool life. In this case, 2 replicas were also made. The tool life tests were just performed for the commercial tool holders and the steel tool holder with tungsten spheres, as

---

Table 1 Configurations for each test

| Number | Tool holder type     | Damper              |
|--------|----------------------|---------------------|
| 1      | Solid Steel          | No damper           |
| 2      | Solid Carbide        | No damper           |
| 3      | Steel with Ø 6.1 mm hole | Steel spheres Ø 6 mm |
| 4      | Steel with Ø 6.1 mm hole | Tungsten spheres Ø 6 mm |
| 5      | Steel with Ø 6.1 mm hole | Steel cylinders Ø 6 mm |
it was the situation in which better results were expected according to previous simulations with impact dampers [24]. Therefore, it was decided to analyze the life of both conventional tools (solid carbide and steel) compared to the tool with tungsten spheres. In Table 3, all tested configurations are summarized.

3 Results and discussion

Figure 6 shows the roughness measurements at the end of tool life, that is, when the tool flank wear was 0.2 mm. Roughness measurements were performed in regions 1, 2, and 3 of the workpiece, with four measurements for each region in each of the replicas performed.

It could be noted that in region 1, where forces are predominantly oriented in the axial direction of the tool, there is no significant variation in roughness between the tested tools. This happens because the axial direction of the tool is quite rigid no matter the tool holder material, since the tool clamp and the machine head are the responsible elements to resist the compression caused by the axial force. Therefore, the particles (spheres or cylinders) did not experience the required vibration levels in the radial and tangential directions to perform considerable damping, what was also reported by Galarza et al. [21].

In region 3, where the forces in the radial and tangential directions of the tool were more distinguished, there was a significantly greater roughness generated by the conventional steel tool holder, which was expected, since the forces acted toward the direction of lowest rigidity of the tool. The use of impact dampers in this case had great efficiency, since in this region, the force is oriented toward the impact between the sphere/cylinder and the tool holder wall. The average roughness values were reduced to around 30% of the value observed in the conventional steel tool holder for the case of steel cylinders and around 40% for both spheres. In this case, the gap between the particles and the tool holder was enough for the damping to occur in an ideal condition, corroborating the theory proposed by Albuquerque [17].

Tool holders with both steel and tungsten spheres generated similar levels of roughness, which indicates that for the conditions tested in region 3, there was no significant difference between the use of steel and tungsten spheres. On the other hand, the use of steel cylinders generated slightly smaller roughness. This shows that the 90% increase in mass caused by the use of tungsten balls did not contribute to the reduction of tool vibration. On the other hand, the 50% increase in mass associated with geometry modification, caused by the use of the cylinder, showed better results, which indicates that there is an optimal mass ratio between the structure and the damper. Moreover, it is important to remember the geometric influence, since for the cylinder dampers the impact of the element against the hole wall

Table 2  Machining parameters used

| Spindle Speed (RPM) | \( f_z \) (mm) | \( a_p \) (mm) | \( a_e \) (mm) |
|---------------------|----------------|----------------|----------------|
| 11,000              | 0.1            | 0.2            | 0.3            |

Fig. 5  Representation of one cycle (a) and one pass (b)
occurs in a line and not in a single point, as in the case of spheres.

In region 2, where axial and radial force components are significant, the steel cylinders did not show a good result, maintaining the roughness levels far above the steel and tungsten sphere configurations. With respect to steel and tungsten spheres, the performance in region 2 was also similar between the two configurations.

The carbide tool holder, even without the use of dampers, due to its rigidity about 3 times greater than that of the steel tool holder, provided roughness values much lower than the other configurations in regions 2 and 3, which indicates that the magnitude and the variation of forces were not enough to cause excessive vibrations of the tool. The results shown in Fig. 6 prove that the dampers used in this work made the tool to be more efficient than the usual steel tool holder, but not more efficient than the carbide holder. However, it is important to remember that this kind of damper does not significantly increase the price of the tool holder (at least when steel spheres and cylinders are used as dampers). Thus, it continues to be cheaper than the carbide tool holder.

Figure 7 shows the average roughness levels in the first pass of the tool, that is, with a fresh tool. Roughness tests with fresh tools were carried out for the commercial tool holders made of steel and carbide and for the tool holder with tungsten spheres. These tests were just performed with tungsten spheres acting as impact dampers, as it was the situation in which better results were expected according to previous simulations [24]. These authors modeled a simplified impact damper, considering two degrees of freedom, and by using a non-linear contact model, the greatest damping occurred using tungsten spheres, mainly due to the greater mass of the spheres, which generates greater energy dissipation per impact.

The roughness levels for the steel holder were much lower at the beginning of tool life than at the end of life (compare Fig. 6 with Fig. 7), with averages for Ra between 0.6 and 0.8 µm (Fig. 7). This shows that wear directly contributed to the increase in roughness, which was due to the increase in force levels as $V_{\text{bmax}}$ increased. The tool with tungsten spheres generated slightly higher levels of roughness when compared to the conventional steel tool holder, but it still maintained the roughness at levels considered low, with an average value of Ra of 0.8 µm. In this case (fresh tool), as the acting forces were smaller, the effect of the impact damper was not observed as it was for worn tools (Fig. 6). Therefore, when the insert wear was not significant, the use of tungsten spheres did not bring benefits to the surface finish of the workpiece. As wear levels increased, a significant rise in workpiece roughness levels occurred when machining with commercial steel tool holder, which greatly reduced tool life when compared with the damped one. At this moment (milling with worn tool) the vibration acting on the tool is sufficient to generate an adequate momentum exchange between

![Fig. 6 Roughness generated at the end of tool life ($V_{\text{bmax}} = 0.2$ mm) in the 3 regions studied](image)
the particles (spheres or cylinders) and the tool holder, then the damped tool holder presents a better result when compared with the commercial one, as shown in Fig. 6.

The carbide tool holder, in all 3 regions, generated the lowest roughness levels in the workpiece (less than 0.4 µm), which again can be explained by its static stiffness, about 3 times greater than that of the steel tool holder. In this case, even when the force levels were lower, it can be noted that the carbide tool holder is better than the other two tool configurations.

Figure 8a shows the tool maximum flank wear along all passes. The straight lines with the same colors correspond to the replicas tested. Tool wear was observed using an optical microscope to measure flank wear and observe any possible tool damage.

Note that the wear rate varied significantly after the first pass, ranging from 0.060 to 0.140 mm. For the carbide tool, the highest initial wear value was obtained in two tests, even generating a low level of roughness. Therefore, the high variation of wear in the first pass may be due to an inherent position error of the insert fixation on the tool holder. From the second pass onward, the wear rate was similar for all tools, except for one of the tests in the carbide tool holder, which showed a higher wear rate. Therefore, it was decided to carry out another replica for this configuration, totaling three tool life tests with the carbide tool holder. Figure 8b shows tool flank wear measurements for carbide (i), steel (ii), and steel with tungsten spheres (iii) tools when tool wear had reached $V_{f_{\text{max}}} = 0.2$ mm. The maximum flank wear always occurred close to the maximum insert diameter, since this is the region where the highest cutting speeds occurred. In addition, this part of the tool touched the workpiece in region 3, where the greatest radial force and the greatest vibration occurred. For a better understanding of the data, Fig. 9 shows tool life in terms of the volume of chip removed, considering a $V_{f_{\text{max}}} = 0.2$ mm.

By analyzing the graph, considering the dispersions, it can be seen that tool life was not influenced by the tool holder material (steel or carbide) or by the addition of tungsten spheres. In Fig. 8b, it can be seen that there were no tool wear damages, such as cracks and chippings, which indicates that the insert presented adequate toughness to withstand these levels of vibration, even on the situations where its level was higher. Thus, in this case, the use of impact dampers and the use of the carbide tool provided lower levels of roughness, but not longer tool lives, which indicates that the vibration experienced by the tool with the steel tool holder was not enough to compromise tool life even in the worst case scenario. Vibration would influence tool life if it had caused damages such as cracks and chippings on the edge. Since these occurrences were not present due to the suitable tool toughness, tool lives were similar for all the tool holders tried.

Figure 10 shows the force signals in the X, Y, and Z directions obtained by the dynamometer during the first pass with carbide, steel, and steel with tungsten spheres tool holders. This figure shows the force raw signal, just filtered according to what was cited in Sect. 2, with the intention to show the force variation along all the tool trajectory. Later in this work, when the purpose will be to analyze the vibration of the tool in regions 2 and 3, the signal will be processed in order to obtain just the variation of the force peak values in each of these regions. Note that, at the beginning of the cut, in region 1, the axial force (Z axis) was predominant, reaching more than 150 N for steel tools and 200 N for carbide tools. The large efforts in Z in region 1 were mainly due to the small effective contact diameter of the tool, which generated a lot of plastic deformation of the material being cut and friction in the contact region [25]. As the tool moved to region 2, there was a significant decrease in the Z forces; at the end of the cut, in region 3, the amplitude of forces in X tended to increase, acting more significantly for the carbide tool, surpassing the values obtained for the force in Z. Region 3 is considered the most critical for the occurrence of vibrations, since it is the region where the efforts in X and Y, which are oriented in the direction of less rigidity of the tool, tend to be greater.
As already shown, the roughness levels at the beginning of the tool life were much lower than those obtained at the end of life, with little difference between the tool with and without impact dampers, which shows that the addition of tungsten spheres did not work in this case. This can be explained mainly due to the low force values obtained. As wear increased, forces, particularly at $X$, also increased. From that moment on, the impact damper started to have the desired effect, since the wear promoted higher vibration amplitude of the tool holder, which approximated the gap to the ideal condition, improving the damping performance due to a higher exchange of linear momentum between the particles and the tool holder.

Figure 11 shows the force signal in $X$, $Y$, and $Z$ directions at the end of tool life, that is, with a maximum flank wear of 0.2 mm. A significant increase in efforts in $X$ and $Z$ can be seen for steel and carbide tool holders in region 3, which shows that tool wear contributed significantly to the force increase. The addition of dampers contributed to a reduction of efforts in region 3. While for the conventional steel tool holder the force in $X$ was around 50 N, the tool with steel cylinders generated 37 N in the same direction and the tools with steel and tungsten spheres about 20 N. This shows that part of the cutting energy that was applied to the process by the force on the tool was absorbed by the damping particles. To better understand the effects caused by force on the
roughness of the workpiece, it is necessary to observe how the effort variation occurred during cutting.

Figure 12 shows for 2 tool cycles how the cutting force varied in the $X$ axis, which is the most significant for the occurrence of vibrations on the tool, since the force in the $Z$ axis occurs in the most rigid direction of the tool, and the $Y$ axis force was low, since the tool contact angle was small.

---

**Fig. 9** Tool life by chip volume produced in mm$^3$

**Fig. 10** Force signals in $X$, $Y$, and $Z$ directions during the first pass of the tool
Analyzing Fig. 12, a more accentuated instability can be seen in the highlighted regions in the cases of solid steel tool holder and the tool holder with steel cylinders. For a better understanding of the phenomena that occurred in the regions of interest, the analyzed region should be further expanded. To perform this task, firstly, the force signal for the carbide

Fig. 11 Force signals in X, Y, and Z directions during the first pass of the tool at the end of tool life
tool holder, which has reached the lowest levels of roughness, was analyzed. The regions of interest were 2 and 3, where a greater tendency for excessive vibrations occurs.

For better visualization of the force signals, the representation is done in the form of a polar diagram, with $X$, $Y$, and $Z$ axes represented. The signal was processed in order to show the peak values of the force signal in ten tool revolutions for the carbide tool holder (Fig. 13). This polar diagram shows the maximum force each edge performs in each tool revolution and, consequently, there are two points in the diagram per revolution. Therefore, each point indicates the amount of material that a specific edge removed in each revolution. The force variation between two successive points indicates that the tool is deflected, and each edge removes a different portion of material. The variation of peak forces in each revolution indicates the displacement of the tool from one revolution to the other and, consequently, indicates tool vibration. Moreover, when in one revolution a given edge removes a different amount of material it had removed in the prior (or in the next) revolution, the workpiece surface roughness is directly affected. The radius of the circle represents the force value in Newtons. The closer the polygon is to the circular shape, the lower the tool vibration.

As the tool has 2 cutting edges, there are 20 points for every 10 revolutions of the tool. It is observed that even for the carbide tool, in which the average roughness levels were always in the order of 0.4 µm, there was a significant difference in forces between one edge and the other, with this difference being practically constant, which indicates that one edge cuts a larger portion of material than the other one. One hypothesis for this occurrence is that, when fixing the insert in the tool holder, there was a positioning error, inherent to the process, since the fixation was done by a screw, which may have caused one of the edges to be placed
a little more externally in relation to the other. The roughness of the workpiece will result from the action of the edge that removed more material, since only this edge removes the deepest layer of material. Thus, in order to understand the force variation that occurred in the tool, we decided to analyze the peak of forces during 10 revolutions only for the edge that removed the greatest amount of material (Fig. 14).

In this case, a behavior much closer to the ideal (polar diagram with a circular shape) is observed, which occurs when there is no variation in efforts. Lower variation in force levels indicates that the tool in each revolution removed the same portion of material from the workpiece and experienced less vibration. The carbide tool holder experienced small levels of vibration, and, consequently, smaller average roughness results. This shows that it is not the force magnitude that increases roughness, but its variation, that is, vibration.

Figure 15 represents the force variation which occurred for all strategies tested during the machining of region 2.

The use of the solid steel tool holder and the tool holder with steel cylinders showed the greatest deviation from an ideal circle, which shows that these configurations experienced higher levels of vibration during the machining of region 2, which confirms the higher average roughness values and shows that the damping effect was not satisfactory for the steel cylinders during the cutting in region 2.

As for tools with steel and tungsten spheres, there is a significant improvement in relation to the conventional steel tool (figure closer to a circle), which shows that there was a beneficial effect caused by the impact damping. Even so, the carbide tool holder had a more regular response, both for X and Z forces, which shows that its rigidity, about 3
Fig. 15  Peaks of force signal in one edge — Region 2
times greater than that of steel, contributed to avoid excessive vibrations.

Figure 16 represents the force variation which occurred in the tool for all strategies tested during the machining of region 3. The Y forces, in this case, were not represented in the diagram for steel tool holders, as they have very low values, which could be confounded with signal noise.

Once again, the carbide tool presented the polar diagram closest to a circle. The solid steel tool holder presented the greatest variation of efforts, that is, the highest levels of vibration, which justifies the high values of average roughness obtained with this configuration in region 3.

Among the impact damper configurations, steel and tungsten spheres showed similar performance, better than the initial condition (solid steel tool holder), but still did not achieve the performance of the carbide tool holder. Note that the magnitude of forces is much smaller for the tool with spheres when compared to the conventional steel tool holder. Thus, the variation of forces observed in Fig. 16 is much smaller for tools with dampers.

For the tested conditions, the tungsten spheres presented similar results both for workpiece roughness and for tool vibration levels when compared to the steel spheres. This shows that the increase in mass with the use of tungsten (1.9 × greater than steel) did not significantly contribute to improve the system’ damping. One possible explanation for this occurrence is that the increase in the sphere mass made the impact velocity between the tool body and the sphere smaller, since the exchange of movement amount between the bodies is directly proportional to its mass and velocity. Furthermore, the restitution coefficients of tungsten and steel are different, which makes the speed and number of impacts different as well.

The tool with steel cylinders, on the other hand, had the best performance among the dampers in region 3, mainly considering the variation of efforts in the X direction which, as already mentioned, is the direction in which the vibration occurs, contrary to what occurred in region 2. This indicates that the orientation of forces has a great influence when using cylinders as impact dampers. This result explains the roughness behavior, which had a high value in region 2 when using a damper with steel cylinders, but a much lower value when this same tool cut region 3 (see Fig. 6).

One hypothesis that may explain why this configuration has not been effective in region 2 is the way in which the impact between the cylinder and the tool cavity occurred. The ideal contact occurs when the cylinder wall collides with the cavity, forming a contact line. As in region 2, there is a composition of Z and X efforts; as shown in Fig. 17, the cylinders tended to suffer a greater inclination, impairing the contact with the cavity wall. In other words, the contact did not occur between the cylinder body (damping element) and the cavity wall, but between its edge and the wall. In addition, the axial direction efforts affected the radial movement of the cylinder, since there was friction between the contact surfaces among the cylinders (friction between a cylinder and the cylinders below and above it), causing a reduction in the efficiency of the impact damper.

In region 3, as shown in Fig. 18, the axial forces were still significant, but with a reduction of more than 50% of their magnitude, which made the contacts to occur in less unfavorable conditions for the cylinders. Comparing the composition of the forces on the tool in regions 2 and 3 (Figs. 17 and 18), it can be seen that the $F_{XZ}$ component was much more inclined towards X in region 3 (51.21° of inclination against 12.99° in region 2) and with much smaller magnitude (21.60 N in region 3 and 96.04 N in region 2). Therefore, for cylinders to be effective in the damping task, the forces must be predominantly in the plane perpendicular to the tool axis, in such a way to make the cylinder-wall collisions actually occur in a line (or close to it). When spheres were used as damping elements, this did not occur, as the sphere-wall collisions will always occur at one point.

The use of cylinders as damping particles proved to be more effective when the axial force/radial force ratio is not excessive. However, for dies and mold surfaces with complex trajectories and high axial force ratio, the use of cylinders is not recommended. Steel and tungsten spheres, despite having shown higher roughness in region 3 when compared to cylinders, are recommended, as they maintain more constant roughness levels throughout the workpiece, reaching maximum roughness always lower than 1.2 µm. This value represents a significant improvement over steel conventional tool holder, especially in region 3, where the conventional tool reached an average roughness greater than 2 µm. Among the steel tool holders, it is recommended to use steel spheres, which guarantee similar performance when compared to tungsten ones and have a much lower cost.

The use of impact dampers in regions 2 and 3 proved to be effective (except for the use of cylinders in region 2) in reducing vibration and roughness levels when compared with the commercial steel tool holder. This happened because in these regions the vibration acting on the tool was sufficient to generate an adequate momentum exchange between the particles (spheres or cylinders) and the tool holder. In region 1, this did not happen, because the particles did not experience the required vibration levels to perform considerable damping. This corroborates the theory proposed by Albuquerque [17], which states that, depending on the system vibration amplitude and frequency, there is a distinct ideal gap between dampers and hole wall. In regions 2 and 3, the gap was ideal for the damping to occur. In region 1, the gap was too large to cause any momentum exchange between the tool holder and the particles. This phenomenon was also observed in Diniz et al.’s [20] and Galarza et al.’s [21] work. In their case, the use of larger spheres provided
Fig. 16 Peaks of force signal in one edge — Region 3
a higher damping to the system, which occurred due to the gap reduction that allowed a higher frequency of impacts between the tool holder and the particles. This fact, associated with a larger mass, contributed to a greater momentum exchange between the spheres and the tool holder and, consequently, higher damping. Moreover, in region 1, the main movement of the spheres was in the vertical direction (Z direction) due to the high value of the $F_Z$ component in this region. These movements did not stimulate the impacts between spheres and wall and, consequently, did not stimulate the damping phenomenon.

Despite the improvement in tool performance with the use of impact dampers, the carbide tool holders still presented the best results, with an average roughness of less than 0.6 µm for all regions. This fact occurred due to its greater rigidity, which contributed to a much smaller displacement level of the tool when compared to conventional steel tool holders. However, this type of tool has a much higher cost. According to the supplier, the carbide tool holder costs US$697.00; meanwhile, the steel tool holder costs US$298.00. The cost of the impact dampers used to fill the steel tool holder was US$3.40 (steel spheres), US$68.40
(tungsten spheres), and US$5.10 (steel cylinders). Thus, even when tungsten spheres are used, the most expensive damper tested, the cost of the steel tool holder is 47% lower when compared with the carbide one. Therefore, in some cases, there is a greater benefit/cost ratio with the use of impact dampers.

4 Conclusions

The results of this work on the development of a slender milling tool with impact dampers allows us to conclude, for hardened steel milling in conditions similar to those experienced in this work, that:

- The use of steel cylinders acting as impact dampers is not recommended for situations where the axial force is considerable. On the other hand, in region 3, where the radial forces are predominant, the dampers made of steel cylinders presented the lowest vibration among the dampers used (lowest variation between the peak forces from one revolution to the next one) and, consequently, the lowest surface roughness, what did not occur in region 2. This fact indicates that the orientation of forces has a great influence when using cylinders as impact dampers.
- The carbide tool holder presented the best performance in terms of reducing vibrations and obtaining lower levels of average roughness when compared to all tested steel tools. Even with the damping generated by the impact dampers, the fact that the carbide tool holder has a rigidity about 3 times greater than the steel tool holder allowed the achievement of better results.
- The vibration experienced by the tool, even in the worst case, did not influence either the tool life or its wear rate.
- In region 3 of the workpiece, the tungsten spheres presented similar results both for workpiece roughness and for tool vibration levels (measured by the peak force variation in the polar diagram) when compared to the steel spheres. This shows that the increase in mass with the use of tungsten (1.9 × greater than steel) did not significantly contribute to improve the system’s damping.

Future studies are required to determine if tungsten spheres are more effective when compared to steel spheres in situations where the tool has greater amplitudes of vibration.

Acknowledgements The authors would like to thank the “Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq” for providing the scholarship; “Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP” and DEMM-FEM/UNICAMP.

Funding The research leading to these results received funding from “Conselho Nacional de Desenvolvimento Científico e Tecnológico—CNPq” under Grant Agreement No 131984/2018–7 and “Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP” (2013/00551–7).

Declarations

Ethics approval Not applicable.
Consent to participate Not applicable.
Consent for publication Not applicable.
Competing interests The authors declare no competing interests.
References

1. Quintana G, de Ciurana J, Campa EJ (2009) Machine tool spindles. In: Lamikiz A (ed) López de Lacalle LN. Machine tools for high performance machining. Springer, London, pp 75–128
2. Scandiffo I, Diniz AE, de Souza AF (2016) Evaluating surface roughness, tool life, and machining force when milling free-form shapes on hardened AISI D6 steel. Int J Adv Manuf Technol 82:2075–2086. https://doi.org/10.1007/s00170-015-7525-0
3. De Oliveira AJ, Diniz AE (2009) Tool life and tool wear in the semi-finish milling of inclined surfaces. J Mater Process Technol 209:5448–5455. https://doi.org/10.1016/j.jmatprotec.2009.04.022
4. Neto KH, Diniz AE, Pederiva R (2016) Influence of tooth passing frequency, feed direction, and tool overhang on the surface roughness of curved surfaces of hardened steel. Int J Adv Manuf Technol 82:753–764. https://doi.org/10.1007/s00170-015-7419-1
5. Quintana G, de Ciurana J (2011) Chatter in machining processes: a review. Int J Mach Tools Manuf 51:363–376. https://doi.org/10.1016/j.ijmachtools.2011.01.001
6. Altintas Y (2012) Manufacturing automation: metal cutting mechanics, machine tool vibrations, and CNC design. Cambridge University Press, New York
7. Yue C, Gao H, Liu X, Liang SY, Wang L (2019) A review of chatter vibration research in milling. Chinese J Aeronaut 32:215–242. https://doi.org/10.1007/s10163-018-11007
8. Waydande S, Mahajan DA, Gajjal SY (2014) A review on vibration attenuation of boring bar by using passive dampers. Int J Emerg Technol Adv Eng 4:117–122
9. Fei J, Lin B, Yan S, Ding M, Xiao J, Zhang J, Zhang X, Ji C, Sui T (2017) Chatter mitigation using moving damper. J Sound Vib 410:49–63. https://doi.org/10.1016/j.jsv.2017.08.033
10. Yang Y, Dai W, Liu Q (2015) Design and implementation of two-degree-of-freedom tuned mass damper in milling vibration mitigation. J Sound Vib 355:78–88. https://doi.org/10.1016/j.jsv.2014.09.032
11. Madoliat R, Hayati S, Ghasemi Ghalehabahan A (2011) Investigation of chatter suppression in slender endmill via a frictional damper. Sci Iran 18:1069–1077. https://doi.org/10.1016/j.sci.2011.08.008
12. Munoz J, Beudaert X, Dombovari Z, Altintas Y, Budak E, Brecher C, Stepán G (2016) Chatter suppression techniques in metal cutting. CIRP Ann 65:785–808. https://doi.org/10.1016/j.cirp.2016.06.004
13. Cormont S (2017) Silent tools. Sandvik, Sandviken
14. Wong CX, Daniel MC, Rongong JA (2009) Energy dissipation prediction of particle dampers. J Sound Vib 319:91–118. https://doi.org/10.1016/j.jsv.2008.06.027
15. Djemal F, Chaari R, Gafsi W, Chaari F, Haddar M (2019) Passive vibration suppression using ball impact damper absorber. Appl Acoust 147:72–76. https://doi.org/10.1016/j.apacoust.2017.09.011
16. Paul PS, Raja P, Aruldhas P, Pringle S, Shaji E (2018) Effectiveness of particle and mass impact damping on tool vibration during hard turning process. Proc Inst Mech Eng Part B J Eng Manuf 232:776–786. https://doi.org/10.1177/095440541660995
17. Albuquerque MV (2016) Modelagem e análise dinâmica de um absorvedor de vibrações por efeito de impacto. Dissertation. University of Campinas
18. Sims ND, Amarasinghe A, Ridgway K (2005) Particle dampers for workpiece chatter mitigation. Proceedings of the ASME 2005 International Mechanical Engineering Congress and Exposition 825–832. https://doi.org/10.1115/IMECE2005-82687
19. Suyama DI, Diniz AE, Pederiva R (2016) The use of carbide and particle-damped bars to increase tool overhang in the internal turning of hardened steel. Int J Adv Manuf Technol 86:2083–2092. https://doi.org/10.1007/s00170-015-8328-z
20. Diniz AE, da Silva WTA, Suyama DI, Pederiva R, Albuquerque MV (2019) Evaluating the use of a new type of impact damper for internal turning tool bar in deep holes. Int J Adv Manuf Technol 101:1375–1390. https://doi.org/10.1007/s00170-018-3039-x
21. Galarza FAM, Albuquerque MV, Antoniali AIS, Pederiva R, Diniz AE (2020) Design and experimental evaluation of an impact damper to be used in a slender end mill tool in the machining of hardened steel. Int J Adv Manuf Technol 106:2553–2567. https://doi.org/10.1007/s00170-019-04786-9
22. ISO (1996) Geometrical Product Specifications (GPS) - Surface texture: Profile method - Nominal characteristics of contact (stylus) instruments. ISO 3274:1996
23. Kull Neto H, Diniz AE, Pederiva R (2016) The influence of cutting forces on surface roughness in the milling of curved hardened steel surfaces. Int J Adv Manuf Technol 84:1209–1218. https://doi.org/10.1007/s00170-015-7811-x
24. Saciotto VR, Diniz AE, Albuquerque MV, Pederiva R (2019) Simulação do amortecimento de ferramenta de usinagem usando cilíndro de aço, esferas de aço e de tungstênio. Anais do XXIII Colóquio de Usinagem 74–78
25. Kull Neto H, Diniz AE, Pederiva R (2016) Tool life and surface roughness in the milling of curved hardened-steel surfaces. Int J Adv Manuf Technol 87:2983–2995. https://doi.org/10.1007/s00170-016-8640-2

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.