Characterization of ball-burnishing vibration-assisted process

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Resumen
Este trabajo está dirigido al estudio del proceso de bruñido con bola asistido por una vibración. Se parte de considerar que dicha vibración ayudará al proceso, facilitando la deformación que se produce sobre la superficie de trabajo. Dado que no existe una herramienta similar en el mercado, con el fin de realizar el estudio, ha sido necesario diseñar, caracterizar y fabricar una herramienta capaz de realizar el proceso de bruñido con bola asistido, teniendo en cuenta los componentes fundamentales que intervienen en dicho diseño y el modelo físico que caracteriza la operación. Bajo estos criterios, la caracterización de la operación de la herramienta también se realiza mediante la evaluación de la rugosidad de la superficie que queda después de que ocurre el proceso. Para la validación experimental se han utilizado piezas de trabajo de aluminio y de acero. Estos resultados se compararon con los obtenidos por la misma herramienta sin utilizar vibraciones. Los resultados de rugosidad que resultan del bruñido con bola asistido, mejoran con respecto a los obtenidos utilizando el proceso sin asistencia, en ambos materiales ensayados.

Palabras Clave: Bruñido con bola, deformación plástica, vibraciones, acusto-plasticidad, rugosidad superficial

Abstract
First of all, this work refers to the study of the ball-burnishing process assisted by a vibration. It starts by considering that this vibration helps to make the development of this finishing process easier, because it helps to deform the workpiece material more easily. Since there is no similar tool on the market, in order to conduct the study, it has been necessary to design, characterize and manufacture a tool that can perform the process, taking into account the critical components that are involved in the design, and the physical model characterizing the operation. Under these criteria, the characterization of the tool operation is also done by evaluating the surface roughness that remains after the process occurs. For experimental validation have been used workpieces of aluminium and steel. These results are compared to those obtained by the same tool without using vibration. Roughness results obtained using the ball-burnishing vibration-assisted process improves with respect to those obtained using the process without assistance, in both materials tested.

Keywords: Ball-burnishing, plastic deformation, vibrations, acousto-plasticity, surface roughness.

1. Introduction

Nowadays, in the industry, there are a lot of mechanical components for machine tools, automobiles, planes, trains, boats, molds, forming dies, and many other pieces, which should have a good surface roughness, a geometric tolerance level, a surface hardness with a high degree and significant mechanical strength values to be able to work even in hard conditions. Many traditional processes are being studied to improve and adapt them to new difficulties found in the industry. Furthermore, parallel researches provide novel solutions for longer life cycles of many components that undergo, for example, daily high rates of wear or the effect of cyclical forces.

In recent years, the amount of research associated with the different processes allowing to produce these pieces with the right features, so that they meet these benefits, has grown markedly.

There is a process that solves all these requirements: ball-burnishing. It could meet many of these needs with wide lead over other processes. This process also has its limitations in terms of what materials can be burnished, and how their properties vary.

Ball-burnishing is defined as a technological operation consisting in plastically deforming surface irregularities, by the action of the force exerted by a ball [1].

This process could be performed with a conventional tool [2], or assisted by vibration, as it is presented in this study. Through the vibration-assisted process, a greater dislocation movement of the material workpiece is achieved. This allows us to work on harder materials with less force, and even improve the results of the process [3].

Today in the market there is no tool that uses the assistance of a vibration, to make a ball-burnishing process. This is the reason why a prototype tool capable of performing the above process has been designed and manufactured. This is the main contribution of this work.

Then, this paper aims to study the behavior of a ball-burnishing vibration-assisted tool. To do that, firstly the design of the tool through the study of its fundamental parts is described. Analysis of the elements which provide the vibration via a physical model is made. This is why they are the essential elements for the tool operation.

Subsequently the model will be experimentally verified. Finally, practical tests will be performed to determine the surface roughness values obtained with the developed tool. The practical tests are carried out in workpieces of aluminum A92017 and steel G10380.

In the absence of such a tool nowadays in the industry, its implementation could be of great importance, because it fulfills significant demands, such as obtaining parts with good mechanical properties and hard surfaces, by using lower strength. This would lead to a lower energy consumption, which is very relevant today.

The use of vibration as a method of assisting the conventional manufacturing process is widely used in the modern industry and it has been referenced by several authors [4, 5, 6], as a method to improve the surface quality of workpieces.

2. Development study

2.1. Schematic functional description

The first consideration defined before developing the tool components that affect the study of ball-burnishing process was how to introduce in it the vibrations. In the current industry, the vibration generators most widely used are the piezoelectric transducers. However, in this case, vibrations are generated by an electromagnetic transducer which is used to convert alternating current into a variable magnetic field. This field produces an attractive cyclical force on the metal plates M_1 and M_2, with thickness h1 and h2, deforming them and causing a vibration which frequency is determined by the magnetic field (Figure 1).

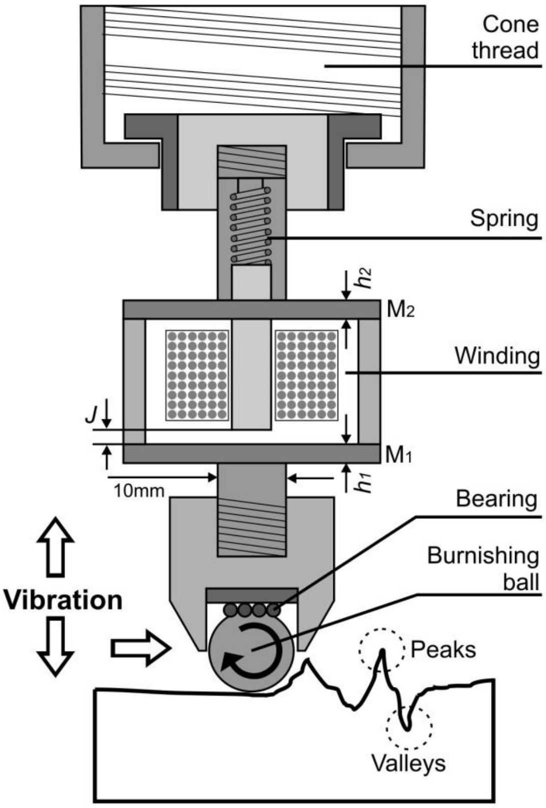


Figure 1. *Functional diagram of the vibration system.* M_1*- Plate attached to the burnishing ball,* M_2*: Plate attached to the spring,* h_1*:* M_1 *plate thickness,* h_2*:* M_2 *plate thickness, J: Gap.*

Figure 1 show how the tool can be easily installed using an ISO cone in the same CNC machine where the piece has been prior machining. The thread cone is fixed to the tool body, which comprises a cylinder that has a spring housed inside it. This spring is able to deform by the effect of the vibration, but it ensures the maintenance of a constant force throughout the process. It is solidary with a rod that is in contact with the coil core. The coil is inside a cylinder closed on both faces using two plates M_1 and M_2. These plates are coupled, and vibrating to a predetermined working frequency, transmitting this vibration to the bottom part of the tool where the ball burnishing is placed. The ball is in contact with a bearing, which facilitates it free rotational movement. The bearing is composed by several spheres of 2mm of diameter, and it is the responsible for transmitting the vibration generated by the coil.

Plastic deformation of the workpiece is produced by the effect of a hard ball of 10mm of diameter, which comes into contact with it, acting under the action of a constant and normal force, high enough to modify the surface topography treated.

2.2. Significant design criteria

Starting from these premises, from the standpoint of design, it is important to monitor certain parameters which will determine the correct functioning of the tool, as specified in the scheme of Figure 1. These elements of special interest are:

- The thickness of plates M_1 and M_2
- The interrelationship that is established between them
- The *J* gap; defined as the distance between the coil core and the center of the M_1 plate.

Conceptually, this distance must be greater than the maximum relative plate deflection between M_1-M_2, that is experienced during operation of the tool.

Therefore, this paper seeks the maximum relative deflection between M_1-M_2 plates in order to estimate the optimum value of the gap. With this optimized value, there is not a significant decrease in the magnetic field strength, which is then transferred to the vibration plates, and in turn to the ball-burnishing process.

From here, it is useful to study the behavior of the deflection, when both plates are working (M1 and M2). Moreover, this deflection value will also depend on the thickness of the two plates. This is the reason why throughout the study, various thicknesses were evaluated in order to determine which one is right.

To characterize this tool, the following assumptions were made:

- The amplitude and frequency of the vibration that is directly generated by the magnetic attraction force generated by the coil.
- The deformations of the plates are in an elastic regime, therefore, the material properties such as Young's modulus and Poisson's ratio are considered constant.
- The tool should work in a resonant mode whose frequency must be estimated.

The plate considered in this study is a rigid thin plate [7], because: the plate diameter *D* is 53mm, the plate thickness h is less than 5mm and the maximum plate deflection w is less than 0.08mm. With these values the aspect ratio *D/h* and the ratio *w/h* is reduced to:

$$\frac{D}{h} > 10 \quad \text{y} \quad \frac{w}{h} < 0{,}2 \qquad (1)$$

The model developed in this study is based on the classical theory of Kirchhoff [8]. Therefore, assuming that the deformations in solids to be considered are infinitesimal, the relationship between the stress components and the strain components depends on the solid compound material. In the case of an elastic and isotropic solid, the constitutive equations take the form of Hooke's generalized law [7].

The assumption of isotropic material is suitable to define the behavior of the C-45K steel (according to standard EN 10083-2), which will be used to manufacture the vibrating plates and whose characterization is specified in Table 1.

Table 1. *Characterization criteria for C-45K steel.* [2]

Material designation	C-45K Steel
Density, ρ	0,00784 gr/mm^3
Young's modulus, *E*	211795 N/mm^2
Poisson's ratio, *v*	0,2866
Self-hardening coefficient, *n*	0,190
Tensile Strength Yield, *y*	416 N/mm^2

The equations relating the stress components to the deformation components are often called constitutive equations. Hooke's law for a reference system in polar coordinates with axial symmetry are used [7].

2.3. Model of the coupled plates

In the global behavior of the plates of the tool under consideration, in addition to the influence of the vibration generator, other elements are present with equal importance. When it begins to apply a force on the burnishing tool, the M_1 and M_2 plates are deformed depending on the direction of force, but in opposite directions to each other. The deformation produces a resulting deflection between the two plates. It must be studied how the deformations of the plates are coupled.

In order to obtain these results, it is necessary to make a series of successive steps that will allow a drill-down analysis of the elements to establish the functioning of the entire system.

From the deduction of the equations of all theories considered, the differential equations 2 and 3 are obtained. They predict the w deflection of each of the circular plates, depending on the *r* radius and *t* time. These equations are the basis of the model to be developed.

$$\frac{\partial^4 w}{\partial r^4}+\frac{2}{\mathrm{r}}\frac{\partial^3 w}{\partial r^3}-\frac{1}{r^2}\frac{\partial^2 w}{\partial r^2}+\frac{1}{\mathrm{r}^3}\frac{\partial w}{\partial r}-\frac{P}{K}=\frac{\rho}{K}\frac{\partial^2 w}{\partial t^2} \qquad (2)$$

$$\frac{\partial^4 w}{\partial r^4}-\frac{2}{\mathrm{r}}\frac{\partial^3 w}{\partial r^3}+\frac{1}{r^2}\frac{\partial^2 w}{\partial r^2}-\frac{1}{\mathrm{r}^3}\frac{\partial w}{\partial r}+\frac{P}{K}=\frac{\rho}{K}\frac{\partial^2 w}{\partial t^2} \qquad (3)$$

The boundary conditions are defined on 4.

$$w(r=R)=0 \qquad \frac{\partial w}{\partial r}(r=0)=0 \qquad (4)$$

P is the vertical load distribution, and is defined by Equation 5. The value of the forcing function is constant.

$$P=P_0\,sen\,2\pi f \qquad (5)$$

P_0 being the initial value of the power system load. It is constant and resulting from spring compression and f, driving frequency of the coil that generates the varying magnetic field, which also generates the deflection variable force.

Furthermore, the flexural modulus of the rigidity plate K, defined in [7], is as shown in equation 6.

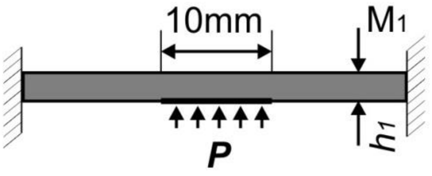
$$K=\frac{E\mathrm{h}^3}{12(1-v^2)} \qquad (6)$$

2.4. Solution to the static problem

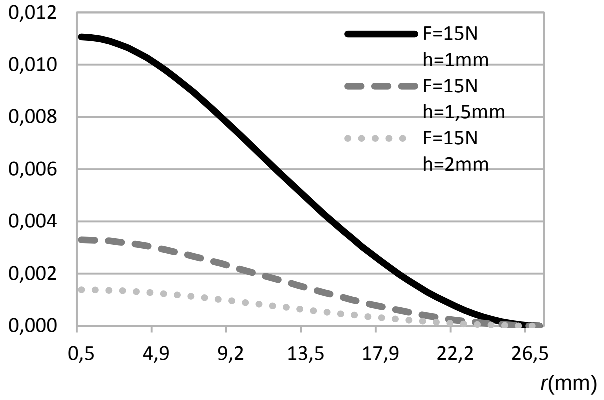
It solves the static problem with the purpose of assessing the resulting deflection of the plates, as a result of a constant burnishing force. This problem does not consider the force due to superimposed vibration. The static deflection of the plates is a condition that affects the tool design. The burnishing force must produce a resulting deflection value lower than the J gap.

To perform this analysis, we implement the Lazarus language software which leads to a solution that has been obtained through the finite difference method. We used 50 nodes with a 0,000002s integration step.

Using such software, we performed a comparative study of the maximum deflection of the M1 plate, evaluated for three h thicknesses (1mm, 1.5mm and 2mm) and three different *F* burnishing forces (15N, 30N and 50N). The values of these burnishing forces are taken from previous studies [2].



(a)



(b)

Figure 2. *Representation of M_1 plate deformation for different thickness conditions.*

The load is applied as shown in Figure 2(a). For example, it is known that when the force increases, the plates are deformed in relation to the increase. Likewise, when the thicknesses are smaller, the plates are deflected more. Figure 2(b) shows the graphs of the simulation in which the differences in the h-F relations for the smallest of all the forces used can be observed. When studying the behavior of the other plate (M_2), a symmetrical deflection of M_1 was observed, but with the opposite sign.

By way of summary, one can say that for these conditions, any thickness under study may be valid, since even a 2mm plate has a relative deflection that is sufficient to modify the surface roughness of the workpiece to be burnished. Of the three cases, the thickness of 2mm presents less complexity for the manufacturing of the plate.

2.5. Numerical solution to the stationary problem

The problem under study is truly dynamic, since forces involved change over time as you go through the process. In this case, the maximum deflection reached by the tool plates can be found for each of the conditions stated in the study which are derived from the analysis of the static behavior.
It is necessary to analyze the resulting vibration of the vibration coupling of the two plates. The analysis is performed for the following cases:

- M_1=1mm and M_2=1mm
- M_1=1mm and M_2=2mm
- M_1=2mm and M_2=1mm.

It starts by considering that there is a forced vibration introduced by a vibration generator into the tool. In this case, the resonance frequencies can be estimated (first vibration mode). We used this first vibration mode to do the first test, and also because is easy to arrive it using the vibration generator made. For this, the developed software was used once again in order to the resulting relative deflection values obtained when coupling the two vibration plates for the first mode of vibration.

The behavior of the relative deflection is greater in the case in which the two plates have a thickness of 1mm, as it might be expected. When the plates have a thickness of 2mm, there is a smaller deflection compared to the first case. The behavior of the plates was analyzed for a frequency sweep between 50Hz and 10000Hz. Anyway, we decide to use plates of 2 mm because is easier to manufacture them. Figure 3 show the results for the choose case ($h_1=h_2=2mm$).

2.6. Experimental check of the plate deflection

To check the actual relative deflection, the M_1 plate was studied when the tool was subjected to the influence of the sinusoidal driver. A displacement digital electronic display unit produced by MARPOSS was used. The sensor is placed on the central point of the tool shank, which is the maximum displacement area, to take the appropriate reading at the moment in which M1 is vibrating at 2600 Hz (Figure 3). This frequency is taken from the simulation results of the deflection of M_1=2mm.

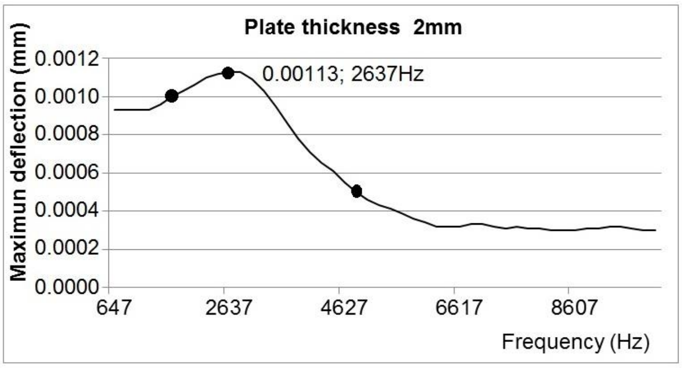


Figure 3. *Sweeping the sinusoidal excitation frequency of the M_1 plate, contrasted with the experimentally measured values at 2600Hz.*

It has been experimentally determined that the plate designed for the tool, under the terms of the theoretical study, has a maximum relative deflection of 0.0012 mm at 2600 Hz, as seen in Figure 3. This value corresponds with what is shown in the graph, where the maximum deflection (0.0013 mm) is obtained at 2637 Hz. These three points are indicated on the graph of Figure 3.

In order to obtain various experimental values, the deflection mode resonance measurements were taken at various frequencies. It was possible to obtain a reading of 0.0010 mm at 2200 Hz, and another from 0.0005 mm at 4,800 Hz. Both results corroborate the behavior of the curve obtained in the simulation.

Figure 4 show the prototype tool manufactured, taking into account all the design criteria described before.

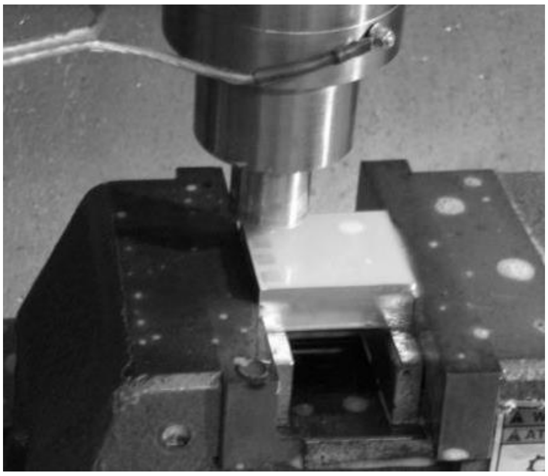


Figure 4. *Prototype of the ball-burnishing vibration-assisted tool.*

2.7. Preliminary experiments to characterize the tool operation

In order to evaluate the behavior of the prototype tool that was designed, burnishing tests on two pieces of aluminum A92017 and two pieces of steel G10380, were developed (Figure 5). The dimensions of said workpieces were 54 x 44 x 15.5mm. One of the aspects of these pieces was milled using a hard metal spherical cutter measuring 8mm in diameter, rotating at 3000 min-1 with a feed rate of 330mm/min, with a depth of pass of 0.5mm and a lateral swath width of 0.5mm. To perform the burnishing process the prototype tool was placed at the head of the CNC Lagun MC600 milling machine.

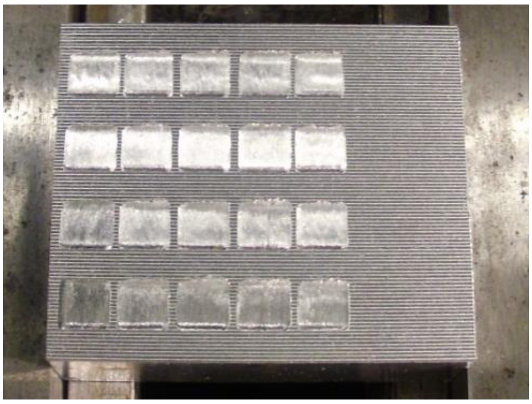


Figure 5. *Workpieces used, after ball-burnishing*

A comparative study was performed between conventional burnishing and vibration-assisted burnishing, made with the same prototype tool. The process parameters used (shown in Table 2), were taken in relation to those obtained by Travieso-Rodriguez J.A. et al [1]. To obtain the vibration, the tool is coupled to a vibration generator with coupled plates vibrating at a frequency of 2500Hz (the sinusoidal excitation frequency that produces the resonance of the plate), which is defined in the simulation, for these conditions of h thicknesses (Figure 3).

Table 2. *Burnishing parameters used*

Parameter	**Valor 1**	**Valor 2**
Feed-rate (mm/min), *f*	500	750
Ball penetration depth (mm), *p*	0,75	1
Side step width (mm), *b*	0,08	0,115

After performing both burnishing processes on the workpieces, the resulting surface roughness measurements of the burnished specimens were found. Indicators measured the average surface roughness (Ra) and the maximum roughness total evaluation length (Rz) in two directions that were parallel and perpendicular to the advancement direction of the prior milling operation. Subsequently a comparison between the values was obtained. Some examples of the results of these measurements and comparisons between them can be seen in Tables 3 and 4.

As shown in the above results, the surface roughness values obtained with the vibration-assisted tool on the burnished surfaces are better than those of the tool without vibration. For Ra// by 37%, for Rz// by 21%, for Ra⊥ by 21%, and for Rz⊥ by 24% on average across the experiments performed in aluminium workpieces. In case of steel workpieces, for Ra// by 38%, for Rz// by 35%, for Ra⊥ by 33%, and for Rz⊥ by 42% on average.

More experiments must be conducted to further evaluate the behavior of the tool under different working conditions, on other materials and at other frequencies as those found in the theoretical development, before being synthesized. There is also a proposal to make measurements of other parameters that help to check the burnishing results, such as hardness and residual stresses. Anyway with these results the preliminary evaluation of the tool can be done.

Table 3. *Results of surface roughness indicators measured for conventional burnishing (specimen 1) and vibration-assisted burnishing (specimen 2), in aluminium A92017 workpieces*

Lateral pass width (mm)	**Depth of burnishing (mm)**	**Feed-rate of burnishing (mm/min)**	**Specimen 1**				**Specimen 2**			
			Ra//	**Rz//**	**Ra⊥**	**Rz⊥**	**Ra//**	**Rz//**	**Ra⊥**	**Rz⊥**

0,08	1	500	0,809	4,939	0,454	2,35	0,587	4,754	0,385	2,035
0,08	1	500	1,937	10,862	0,562	3,952	1,212	6,620	0,475	2,969
0,08	1	500	1,269	8,055	0,705	3,546	0,587	7,754	0,385	2,035
0,115	0,75	750	1,280	8,567	0,541	3,670	0,826	5,185	0,467	2,611
0,115	0,75	750	1,484	8,463	1,695	7,724	1,020	6,830	1,454	6,907

Table 4. *Results of surface roughness indicators measured for conventional burnishing (specimen 3) and vibration-assisted burnishing (specimen 4), in steel G10380 workpieces*

Lateral pass width (mm)	**Depth of burnishing (mm)**	**Feed-rate of burnishing (mm/min)**	**Specimen 3**				**Specimen 4**			
			Ra//	**Rz//**	**Ra⊥**	**Rz⊥**	**Ra//**	**Rz//**	**Ra⊥**	**Rz⊥**
0,08	1	500	3,070	15,005	0,141	0,825	1,673	8,788	0,481	3,781
0,08	1	500	2,854	12,057	0,155	0,745	1,934	9,417	0,791	4,334
0,08	1	500	3,739	15,742	0,148	0,740	2,219	10,131	0,297	3,133
0,115	0,75	750	2,610	13,582	0,158	0,857	0,914	5,139	0,695	3,765
0,115	0,75	750	2,824	13,590	0,144	0,910	2,759	11,971	0,295	2,347

3. Conclusions

1. The ball-burnishing vibration-assisted process has been studied. The changes of surface roughness results obtained when using the vibrations to assist the process, compared to when performing the process without being assisted has been also analyzed.

2. A method to characterize the plates involved in the design of a tool to be used in the ball-burnishing vibration-assisted process has been successfully developed.

3. Reliable numerical solutions have been obtained to predict the plate deflection values that can be used to optimize the different basic design parameters: the thickness of the plates, the gap and the working frequency of the vibration generator.

4. It is designed, characterized and manufactured a completely new tool for market and the first experimental results show improvements compared to the conventional burnishing process, for the surface roughness parameters evaluated.

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