Preliminary study of the hardening effect and fatigue behaviour enhancement through vibration assisted ball burnishing on C45 Steel

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Abstract: The objective of this paper is to present a preliminary study of the effects of ball burnishing with vibration assistance on cycle fatigue endurance of cylindrical specimens subjected to bending stress and obtain the best input parameters. The specimens were burnished through 6 different combinations of preload force, number of passes and vibration assistance, finding that burnishing while applying a 90-N preload and 5 passes derives in the longest lifespan, being the vibration assistance not significant with this combination. In terms of roughness, it has been proved that the vibration assistance improves the finishing significatively, allowing to reduce the number of passes compared to NVABB and, as optimal ball-burnishing parameters, the 90-N preload and 5 passes combination derivates in a 93% improvement in terms of mean roughness of the surface. It is also been proved the hardening effect provoked by the ball-burnishing, being an improvement estimated around the 51% in the best case.

Keywords: Ball burnishing, Hardening, Fatigue, Vibration assistance.

1. Introduction
During the last decades there has been a lot of investigations related to the topological properties’ improvement due to the burnishing process application on them. In fact, the process allows reducing the superficial roughness, increase the hardness on the surface and the compressive residual stresses. In particular, the ball burnishing process consists on a cold plastic deformation of the surface by applying a controlled force, usually by a programmed routine in a CNC machine, in several passes [1].

The vibration assistance is applied to activate the acoustoplasticity phenomenon, which is described as the decrease of the quasi-static stress required to deform a material as result of the superimposition of a vibratory component on the deforming force. It has been also concluded that the vibration assistance could prevent the crack forming in workpieces due to the friction reduction in processes like press forming [2]. The vibration assisted ball burnishing (VABB) refers to the incorporation of a vibratory movement on the burnishing ball during the execution of the process and, as Travieso-Rodríguez mentions in his thesis [3], the cold-deformation process does not affect the bulk material but the surface irregularities are deformed by the effect of a rolling ball.

Furthermore, it is proved that vibration assisted ball burnishing (VABB) improves the fatigue life and hardness on AISI 1045 surfaces by an 83% on optimal burnishing conditions and a hardener
improvement around 14% [4]. Also, it was found that the ball-burnishing enhanced the fatigue limit of AISI 1045 cylindrical samples by a 21.25% when they were tested at high cycles, mainly due to the compressive residual stresses applied during the treatment [5]. Travieso-Rodríguez [6] found that the ball-burnishing process on AISI 1038, a material with similar characteristics to C45 steel cylindrical specimens, enhanced the hardness by a 41% and a fatigue lifespan by 77% improvement to non-burnished samples. It was also demonstrated that the input burnishing force and the number of passes are mutually substitutive in terms of fatigue resistance enhancement.

The aim of this paper is to perform a preliminary study of how a new model of ball burnishing tool assisted by vibrations developed by the research team implicated in it succeeds in modifying the surface texture and hardness of C45 cylindrical specimens, and in a second order, analyze how that modifies their fatigue life. Also, a comparison between conventional ball burnishing and vibration assisted ball burnishing is done, so that the influence of the vibration assistance can be assessed.

2. Materials and methods

2.1. Ball burnishing equipment

This paper shows the first results obtained with a new tool designed to execute the ball burnishing process assisted by vibrations on a lathe machine. It is based on burnishing force regulation through a calibrated spring lodged inside a cylindrical part (figure 1(a)). Consequently, the burnishing force depends on the compression length experimented by the spring and varies linearly according to Hooke’s Law. In addition, this tool is also able to perform the VABB, which will also be tested in this experiment.

To execute the VABB process, the burnishing force can be calculated as:

$$F_b = F_p + F_v + \eta$$  \hspace{1cm} (1)

where $F_b$ is the burnishing force, $F_p$ is the preload force given by the spring, $F_v$ is the ultrasonic vibratory force and $\eta$ are the low frequency force variations due to the surface irregularities during the feed movement of the tool. The tool is equipped with a hardened chromium steel AISI 52100 ball with a hardness value of approximately 57–66 HRC and a diameter of 10 mm.

![Schematic representation](image1(a).png)

![Real image](image1(b).png)

Figure 1. (a) Schematic representation of the ball burnishing tool used in this study. (b) Real image of the ball-burnishing tool.

Furthermore, a Kistler 5070 dynamometer will be used to acquire force and momentum data during the burnishing process and a custom vibration wave generator which will add a 40-kHz vibratory force to the ball burnishing tool.

2.2. Specimens

Fatigue specimens where manufactured from cold drawn C45 bars of 15-mm diameter (see table 1 and 2 to see, respectively, the chemical and the mechanical properties). The specimens were manufactured
with a CNC lathe, to obtain the geometry shown in figure 2, following the ASTM E606/E606M-12 standard.

**Table 1.** Chemical composition of the C45 steel.

| Steel       | C   | Si, ≤ | Mn | Si, ≤ | S, ≤ | Cr, ≤ | Ni, ≤ | Mo, ≤ | Cr + Mo +Ni, ≤ |
|-------------|-----|-------|----|-------|------|-------|-------|-------|---------------|
| C45(1.0503) | 0.42-0.50 | 0.40 | 0.50-0.80 | 0.045 | 0.045 | 0.40 | 0.40 | 0.10 | 0.63          |

**Table 2.** Mechanical properties of the C45 steel.

| Property                | Value | Units |
|-------------------------|-------|-------|
| Young’s modulus         | 200   | GPa   |
| Yield strength          | 350-550 | MPa |
| Tensile Strength        | 650-800 | MPa |
| Poisson coefficient     | 0.27-0.33 | -    |
| Elongation              | 8-25  | %     |
| Hardness                | 220-260 | HV   |

The manufacturing parameters used were fitted so that the surface average roughness (Ra) was around 1-1.5 μm, before the final ball burnishing process. The specimen’s length and diameter were defined according to the dimensional characteristics of the ISO 1143-2010 and tested according to the ASTM E606/E606M-12 standard. The transition surface between the initial section and the final one was solved by designing a new ball cover which allowed the spline interpolation calculated to ensure the same depth of penetration at any point of the trajectory followed with the aim of burnish the radial part with the same characteristics as the pure cylindrical part.

![Figure 2. Specimens drawings (dimensions in mm) extracted from the ISO 1143-2010 standard.](image)

2.3. Rotating bending fatigue machine

The tests were executed with an RFB-200-500 rotating bending machine. The force was put through a manual actuator with a pulley, which was holding a total load of 7 kgf. The specimen rotated during the test at a constant speed of 1500 min⁻¹, thus generating the alternative bending moment that accounts for the fatigue load. The speed was selected to avoid thermal fatigue and was fixed for all the tests carried. The normal stress applied, due to the bending stress, was fixed to 407 MPa, in other investigations [4] it was found that the fatigue limit was near 200 MPa, in order to reduce the testing time find the best burnishing parameters and compare the lifespan between all conditions at fixed fatigue conditions.

The relationship between the applied force and the maximum bending stress can be calculated through the Euler-Bernoulli expression particularized for a cantilever beam, point-loaded at the tip, with round section where $S_a$ is the maximum stress due to bending moment (eq. 2).

$$S_a = \frac{32FL}{\pi d^3}$$

(2)
where $F$ is the applied force, $L$ is the cantilever length, and $d$ is the beam minimum diameter.

2.4. Experimental design

Originally, the experimental design chosen was a screening design with two central points, obtaining a total of 14 samples. The levels of these parameters were chosen based on the results obtained by the research group in previous experimentation test on C45 steel. In order to ensure a different lifespan for the same fatigue stress, the force levels were set to 90-N, 180-N and 270-N, while the number of passes was set to 1, 3 and 5. The last analyzed factor was the effect of the vibration assistance on these conditions, that as the bibliography demonstrated in several previous references [7-9], enhances the fatigue lifespan, improves the topological characteristics and increase the hardness of the surface treated. The total number of test was limited and it has been analyzed the effect of the parameters in 3 pairs: the effect of the vibration assistance on two equal samples (in this case, the specimens selected were the samples 3 and 4), the effect of increasing the number of passes (in this case, the specimens selected were the samples 5 and 6) and a comparison between the vibration assistance and a higher number of passes (in this case, the specimens selected were the samples 1 and 2). The final specimen distribution is shown in table 3.

Table 3. Ball burnishing input parameters for all test samples.

| Sample | Force (N) | Nº passes | $A$ (%) | Aim of comparing these two tests |
|--------|-----------|-----------|---------|----------------------------------|
| 1      | 90        | 1         | 100     | Studying whether the assistance with vibrations can reduce the number of passes required to obtain the same results |
| 2      | 90        | 3         | 0       | Studying the actual influence of vibration assistance when the preload and number of passes are the same one |
| 3      | 90        | 5         | 0       | Studying the effect of applying a higher force and the difference between 3 and 5 passes |
| 4      | 90        | 5         | 100     |                                   |
| 5      | 180       | 3         | 100     |                                   |
| 6      | 180       | 5         | 100     |                                   |

As a result, the experimental design is thought as a preliminary study to analyze the effect of every combination and, therefore, use the results obtained in this paper in order to perform future complete fatigue test analysis with the optimal ball burnishing conditions. In fact, the preliminary results obtained in this study will be taken into account only as a very first step to answer the stated questions in future investigations consisting on extensive experimental applications.

2.5. Roughness analysis

With the aim of obtaining results in terms of roughness, the topology of the ball burnished cylindrical surfaces must be acquired. As the geometry of the specimens made it very complicated to register 2D roughness profiles with a contact profilometer or a 3D patch, the topological results were determined by defining 2D roughness profiles acquired with a and the radius of the burnished area through a STIL 3D micromeasurement station equipped with a chromatic sensor that makes it possible to acquire roughness without contact with the surface. The results obtained are collected at table 4 and shown in figure 3.

The roughness parameters analyzed in this investigation are the amplitude parameters, which represent statistical characteristics of the profile height, the extreme points and the height distribution of the sample. $Ra$ represents the arithmetical deviation of the roughness profile of the sampling length. $Rz$ represents the maximum height of the roughness profile (maximum value of profile peak height and the maximum value of profile valley depth). Skewness $Rsk$ and Kurtosis $Rku$ are the third and fourth moments of the height distribution histogram and are used to characterize the relative weight of negative and positive heights in the profile, thus enabling to describe its shape. More specifically, positive values of $Rsk$ profiles with prevailing valleys, whereas negatively skewed surfaces are mainly composed of positive heights. As for $Rku$, values higher than 3 represent abrupt profiles. On the contrary, values lower than 3 represent smoother profiles.
2.6. Hardness test procedure
Surface hardness represents the degree of plastic deformation caused on the specimen. It was measured through Vickers micro-indentations tests by applying a 1-N load. As the specimen surfaces are cylindrical, these measurements were corrected through numerical factors included in the ASTM E92-82 standard. For each specimen, 15 indentations were taken around the circumference next to the chamfer where the stress was concentrated, guaranteeing that the space between them was enough so that the results were not compromised.

2.7. Fatigue test procedure
The fatigue tests performed were done in the RFB-200-500 machine at a constant stress of 407 MPa and a speed of 1500 min⁻¹.

3. Results discussion

3.1. Roughness analysis
Table 4 shows the numerical results of the roughness measurements performed on the burnished surfaces.

| Group | Sample | Force (N) | Nº passes | A (%) | Ra (µm) | Δ Ra (µm) | Δ Ra / Ra (%) | Rz (µm) | Rsk | Rku |
|-------|--------|-----------|-----------|-------|---------|-----------|---------------|---------|-----|-----|
| 1     | 1      | 90        | 1         | 100   | 0.211   | 0.884     | 81            | 1.437   | -1.698 | 6.705 |
|       | 2      | 90        | 3         | 0     | 0.298   | 0.984     | 77            | 1.973   | -0.352 | 2.705 |
| 2     | 3      | 90        | 5         | 0     | 0.734   | 0.552     | 43            | 2.819   | -0.458 | 2.783 |
|       | 4      | 90        | 5         | 100   | 0.103   | 1.395     | 93            | 0.532   | -0.110 | 3.634 |
| 3     | 5      | 180       | 3         | 100   | 0.350   | 1.207     | 78            | 1.861   | 0.510  | 2.469 |
|       | 6      | 180       | 5         | 100   | 0.252   | 1.282     | 84            | 1.969   | -0.054 | 2.744 |

The results obtained show an impressive improvement in terms of the arithmetic height value in all samples tested, independently of the ball-burnishing inputs (see figure 3(a)). In the group 1 it is seen that the vibration assistance enhances the surface finishing more than performing a higher number of passes without vibration, while in the group 2 it is determined that the vibration assistance improves significantly the surface finishing when it is analyzed the effect of this vibration and, in the group 3, it is determined that when the vibration assistance is applied on both samples it is improving even more at high number of passes application. Of course, it should be needed to perform more repeatability in order to ensure that these assumptions are correct.

In fact, the best results obtained in terms of low roughness, Ra and Rz is the sample number 4 (90-N input force, 5 passes and vibration assistance), where it has experimented a 93% of Ra improvement from machined surface to ball-burnished surface. The kurtosis and skewness values are close to 0 and 3 (see figure 3(c)), respectively, which means, at sight of previous results, that the best topological enhancement has been achieved by the process [3]. Also, previous investigations have determined that there is a threshold pair of preload and number of passes that achieves the best result, being higher preloads and number of passes unadvised because they deform excessively the surface roughness of the specimens. In this case, for a 9,5-mm cylinder burnished with a 10-mm ball, it was determined that the optimal parameters were 90-N input force, 5 passes and vibration assistance (tested in sample 4). These results show a clear evidence of the geometric system result if we compare the burnishing parameters with those used in a milling machine, which are 270-N input force and 5 passes [10].
3.2. Hardness results

The results obtained from the Vickers micro-indentations hardness test (see figure 4 and table 5) revealed that, as was expected, the ball-burnishing hardening effect in all conditions tested when are compared to the machined C45 cold bar hardness of 220-240 HV. However, it seems that the soften effect occurred during the fatigue test (previous to hardness) due to the high stress selected for this study, which provoked thermal fatigue in some samples, and this may explain the dispersion in the results obtained.

Figure 3. (a) Comparison between the Ra before and after applying the ball burnishing procedure. (b) Evolution of the final Ra and Rz. (c) Skewness and Kurtosis evolution.

Figure 4. (a) Vickers hardness results for all samples, divided in study groups. (b) Fatigue lifespan results for all samples, divided in study groups.
Table 5. Results obtained from the hardness test.

| Group | Sample | Force (N) | Nº passes | A (%) | Hardness (HV) |
|-------|--------|-----------|-----------|-------|---------------|
| 1     | 1      | 90        | 1         | 100   | 289.7±17.9    |
| 2     | 2      | 90        | 3         | 0     | 321.5±28.1    |
|       | 3      | 90        | 5         | 0     | 275.4±14.1    |
| 1     | 4      | 90        | 5         | 100   | 266.7±16.0    |
| 3     | 5      | 180       | 3         | 100   | 302.2±24.9    |
| 6     | 18     | 0         | 5         | 100   | 331.9±17.5    |

3.3. Fatigue results

Once the results are obtained (see table 6), it is shown that the difference between the samples from a same group are not significant, but some conclusions can be extracted when the groups are compared between them. The group 3 show low-cycle results compared to what was expected from the beginning, showing that during the ball-burnishing process at high force provoked severe plastic deformation, which reduced significatively the fatigue lifespan of the samples tested. Regarding the vibration assistance, it is seen that enhances the fatigue lifespan when a few number of passes is applied, losing its improvement as far as the number of passes is increased, as it is shown in the results obtained in the group 2, where the results are almost identical. Therefore, the combination of 90-N force and 5 passes is the most significant combination in terms of fatigue life enhancement.

Table 6. Results obtained from the fatigue test.

| Group | Sample | Force (N) | Nº passes | A (%) | Nº cycles |
|-------|--------|-----------|-----------|-------|-----------|
| 1     | 1      | 90        | 1         | 100   | 74825     |
| 2     | 2      | 90        | 3         | 0     | 73390     |
|       | 3      | 90        | 5         | 0     | 104013    |
|       | 4      | 90        | 5         | 100   | 100332    |
| 3     | 5      | 180       | 3         | 100   | 83015     |
| 6     | 18     | 0         | 5         | 100   | 74249     |

4. Conclusions

Once that all tests are performed and, analysing the results obtained, it can be concluded that:

- The ball-burnishing improves the topological properties of the C45 cylindrical surfaces.
- The number of passes is the most significant parameter in terms of topological properties improvement.
- Performing the ball burnishing operation with a 10-mm ball of hardened chromium steel and the combination of 90 N, 5 passes and vibration assistance is the most suitable in terms of fatigue enhancement and a good surface finishing.
- It is needed to do more iterations to find a relation between the hardening effect and the fatigue lifespan increase due to the ball-burnishing process.

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