Analysis of the influence of the hydrostatic ball burnishing pressure in the surface hardness and roughness of medium carbon steels

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Abstract. Standing sectors in the industry such as railroad or plastic injection moulds present many challenges for manufacturing complex components in terms of finishing requirements and mechanical properties. Because of that, hydrostatic ball burnishing is considered an optimal solution since it reduces surface roughness and generates hardened surfaces and compressive residual stresses, increasing the performance and lifespan of this parts in terms of resistance and mechanical fatigue. Additionally, this technology could be integrated directly into the machining centres, what reduces times and dimensional errors arising from mooring changes. Therefore, lead times and production costs can be drastically reduced in comparison with other finishing techniques. The aim of this project is to analyse the use of the ball burnishing process to improve the final quality of medium carbon steel surfaces, minimizing surface roughness and improving hardness. In order to achieve significant results, different working pressures are analysed in terms of surface roughness and hardness in AISI 1045 and AISI P20 steels. The results showed a reduction in roughness parameters of more than 89% for both materials using a pressure of 10 MPa. Moreover, at a pressure of 30 MPa, the surface hardness has been increased by 15% and 34% respectively.

1. Introduction

With the aim of maintaining competitiveness in a globalized world, the different industrial sectors are forced to be in a permanent development, even the most traditional sectors such as the steel industry. In fact, the European Union has developed different plans in many different sectors to enhance this objective. This is the case of the railroad industry or the plastic injection moulds sector, among others.

Many of the components of these industries must withstand high cyclical working loads during their lifespan, for example railway axles (according to the UNE-EN 13103-1:2019). Indeed, high geometrical precision and roughness adjustments are required to ensure the adequate functions of the components. Therefore, many of them are considered critical from very high-added value parts.

Hence, to achieve these demanding requirements, different superfinishing techniques are used. Some of them are the hydrostatic ball burnishing and the polishing. In fact, within the superfinishing technologies, hydrostatic ball burnishing offers greater advantages over the rest. Firstly,
this technique can be applied directly on the same machine where the finishing process is performed. This implies a reduction in workpiece transportation times and, in a more important manner it removes positioning and fixing errors in multi-machine processes, something that is essential in components with restrictive geometrical requirements. Furthermore, it is a process that consists on material deformation, avoiding cutting. It is based on rolling a hard metal or ceramic ball under pressure on a surface. However, the main limitation of this process is geometrical. Due to the geometry of the tool, the angle between the normal direction of the burnished surface and the tool axis must be between ±28º. In figure 1 it can be seen a scheme of the transmitting force to the burnished surface. In this operation, the speed of the tool in relation to the surface can reach the maximum allowed by the machine.

![Scheme of the transmitting force](image)

**Figure 1.** Scheme of the transmitting force [1].

By means of this plastic deformation, a displacement of the material in cold is produced, causing peaks of roughness to fill the hollows of the valleys, thus reducing the surface roughness [2]. The main characteristic of this technique lies on the fact that, in addition to improving the quality of the surface, it also generates compressive residual stresses, what increase performance and service life. This implies an improvement of the mechanical fatigue resistance, being very beneficial for components that are subjected to high loads during many work cycles [3].

In fact, Travieso-Rodríguez et al. [4] concluded that, when applying ball burnishing to AISI 1038 steel, the surface hardness of the workpiece is enhanced. Moreover, this improvement resulted in improving mechanical fatigue resistance to failure. In this sense, Hua et al. [5] claim that a 15% increase in the surface hardness in Inconel® 718 means an 83% improvement in mechanical fatigue failure.

The key to the correct implementation of hydrostatic ball burnishing lies in the influence of the process parameters on the workpiece and the appropriate choice according to the desired result. In line with this, Saldaña-Robles et al. [6] concluded that, using the right ball burnishing parameters, AISI 1045 steel surface roughness can be improved in more than an 80%. However, changing those burnishing parameters, the surface hardness can be optimized up to a 14%. In the literature, researchers agree that, in the case of obtaining an improvement in surface roughness and hardness, the most relevant parameters are burnishing pressure and force, ball diameter and burnishing speed.

The burnishing pressure corresponds to the pressure exerted by the fluid inside the tool and it is the responsible of controlling the burnishing force applied to the workpiece. An increase in the pressure means a significantly increase of the reached depth by the ball, although there is a limit beyond which there is no appreciable improvement [1].

Related to the roughness values, researchers establish different points of view. On the one hand, the study by Luca et al. [7] points out that the pressure is not excessively relevant for roughness values. On the other hand, El-Taweel and El-Axir [8] and Swirad and Wdowik [9] established that a higher burnishing force reduces the surface roughness, provided that a limit is not exceeded beyond which the
roughness increases again. Since higher pressure also means higher burnishing force and vice versa, it is not clear the level of influence of this parameter on the final roughness. However, researchers agree that the greater the burnishing pressure is, the greater the surface hardness up to a limit.

Furthermore, the diameter of the burnishing ball affects to the forces generated in burnishing, the larger the ball diameter is defined, the greater the area of ball-surface contact is obtained and, thus, the greater the force appears for the same pressure. This results in a higher surface hardness and, consequently, higher residual stresses, but with bigger ball trucks on the final surface. Hence, a compromise should be reached.

Finally, the increase in burnishing speed enhances surface hardness and minimizes the roughness up to a limit beyond which the surface finish deteriorates. Nonetheless, due to the fact that the optimal speed range is elevated, it is not as relevant as the burnishing pressure or force. Furthermore, it affects directly in the machining process [10].

Thereby, in this study, an analysis of the influence of pressure during the hydrostatic ball burnishing process on the surface roughness and hardness is performed for two different medium carbon steels, AISI 1045 and AISI P20, commonly used in railways axles and plastic injection moulds respectively. In the following table the main properties and the chemical composition of both materials are shown.

| Table 1. Chemical composition and mechanical and physical properties. |
|---------------------------------------------------------------|
| **Chemical Composition (%)**                                  |
| Material          | C    | Mn    | P    | S    | Cr  | Mo  | Si  | Fe |
| AISI 1045         | 0.45 | 0.73  | 0.04 | 0.05 | -   | -   | -   | Balanced |
| AISI P20          | 0.40 | 1.50  | 0.01 | 0.01 | 1.90 | 0.20 | 0.30 | Balanced |
| **Mechanical and physical properties**                        |
| Material          | Hardness | Young’s Modulus | Tensile Strength | Density | Poisson’s Component |
| AISI 1045         | 212 HB    | 200 GPa         | 413 MPa          | 7.85 g/cm³ | 0.29          |
| AISI P20          | 290 HB    | 207 GPa         | 862 MPa          | 7.86 g/cm³ | 0.30          |

2. Experimental set up
The tests were carried out in a KONDIA® HS1000 machine centre with 18 kW of power in which both milling and hydrostatic ball burnishing were made on prismatic geometry test pieces of 20×20×10 millimetres.

In order to see the influence of the ball burnishing process, the surface of the workpieces was milled and used as a reference for the measurements. For this operation, a PPH 1600-CL1 quality 2003 was used and the cutting parameters can be seen in table 1. This cutting parameters are commonly used for finishing operations in medium carbon steels.

| Table 2. Milling cutting parameters. |
|-------------------------------------|
| Diameter [mm] | z [-] | vc [m/min] | fz [mm/(r*z)] | ap [mm] | ae [mm] |
|------------|-----|---------|-------------|------|------|
| 16         | 2   | 250     | 0.05        | 0.20 | 0.20 |

For the hydrostatic ball burnishing process, a special burnishing tool was used with a 6 mm diameter ceramic ball (HG6-19E90-ZS20-X) as well as a hydraulic pump HGP 6.5 Ecoroll. Both, the tool and the hydraulic pump, were from the same manufacturer. The burnishing speed was established in 2000 mm/min for both steels and the feed direction was perpendicular to the milled direction in order to minimize the surface roughness. The tested burnishing pressures were 10 and 30 MPa.
3. Results and Discussion

Topographies of all the workpieces were obtained. Furthermore, surface roughness and hardness for each material was measured and compared with the reference milled ones.

3.1. Surface roughness

Workpiece surface topographies were obtained with a confocal optical microscope Leica DCM3D with a resolution of 0.1 nm. From those topographies, three random profiles were analysed obtaining, according with the ISO 4287:1997, $R_a$ and $R_z$ parameters.

In figure 2 the topographies of AISI 1045 steel are shown.

![Figure 2. Topographies of the AISI 1045 surfaces. (a) Reference, (b) 10 MPa burnishing and (c) 30 MPa burnishing.](image)

It can be seen that, with the application of hydrostatic ball burnishing, the peaks resulting from the milling operation are notably reduced with both pressures. However, between them the appreciation is not as clear. In fact, due to the higher waves that can be seen, it seems that the burnished surface with 30 MPa has exceeded the pressure threshold that optimizes the surface roughness.

In figure 3 it can be seen the surface topographies of AISI P20 steel. As in the case of AISI 1045, it can appreciate a great improvement in the surface quality.

![Figure 3. Topographies of the AISI P20 surfaces. (a) Reference, (b) 10 MPa burnishing and (c) 30 MPa burnishing.](image)

The high peaks left by the milling operation almost disappeared after the hydrostatic ball burnishing process, leaving small waves in the tested surface. Moreover, as has been the case with AISI 1045, the smaller pressure left a smoother surface than the one left by burnishing with a pressure of 30 MPa. Figure 4 shows the comparison between the reference surface and the burnished surfaces at 10 and 30 MPa of the roughness parameters, $R_a$ and $R_z$. It can be seen that the hydrostatic ball burnishing process decrease both parameters significantly in both AISI 1045 and AISI P20.
In AISI 1045 steel, the hydrostatic ball burnishing at a pressure of 10 MPa reduce in more than a 90% and 85% the roughness parameters $R_a$ and $R_z$ respectively. However, when the pressure was of 30 MPa, that reduction was not as huge as in the previous case (84% and 80% respectively). Therefore, ball burnishing process in this steel at a pressure of 30 MPa has exceeded the threshold that optimizes the surface roughness.

Similar thing happened with AISI P20 steel. Nonetheless, in this case the reduction percentage for both pressures and parameters was a little bit higher. While $R_a$ parameter was reduced in a 92% and 85% at pressures of 10 and 30 MPa respectively, $R_z$ parameter decreased in a 90% and 81% respectively. Thus, for this material the pressure of 30 MPa also went over the roughness optimized threshold and in a mayor proportion than in AISI 1045 steel.

3.2. Surface hardness

The hardness measurements were obtained with a Future-Tech hardness tester. To make the comparison, five measures were carried out in each tested workpiece. In figure 5 can be seen the average of those measures.

As it can be seen, AISI P20 steel is harder than AISI 1045 from the milling stage. However, higher increases in hardness have been obtained in AISI 1045. While in AISI P20 the increase in hardness reached 8% and 15% using 10 and 30 MPa respectively, in AISI 1045 those percentages have improved a 22% and 34% respectively. It should be noticed that, in contrast with what occurred with the surface roughness, the more the pressure is applied the greater the hardness obtained in both steels. Hence, in the case of surface hardness it has not reached the threshold from which the hardness does not increase. Furthermore, this results agree with what Saldaña-Robles et al. [6] said: different combinations of hydrostatic ball burnishing parameters optimize different surface quality parameters.
4. Conclusions
In this work an analysis of the influence of hydrostatic ball burnishing pressure in different surface quality parameters has been made. After carrying out the tests and the different measurements, the following conclusions have been reached:

- In AISI 1045 steel there has been obtained an improvement in Rₐ and Rₚ roughness parameters of 92% and 89% respectively with a pressure of 10 MPa. In the case of AISI P20 steel, that improvement has overcome 90% in both parameters using a pressure of 10 MPa.
- In both materials, using a pressure of 30 MPa resulted in an exceeding of the surface roughness optimized threshold.
- Using a pressure of 30 MPa increases the surface hardness of both steels. The increase in AISI 1045 was 15% and in AISI P20 was 34%.
- Different combinations of the process parameters can optimize different surface quality parameters. Thus, the choice of hydrostatic ball burnishing parameters should be according to the desired result in the final component.

5. References
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