Ball Burnishing effects on hardness and residual stresses in UDIMET 720 pieces

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Abstract: Ball burnishing can be used to increase superficial hardness in treated materials. The aim of this paper is to study its influence over a nickel-based superalloy, UDIMET 720. To do this, the specimens where burnished and their hardness is analyzed, before and after the process, in the micro and nanometric scales. To corroborate findings, residual stresses are measured by the X-ray diffraction technique. This process has been found to be able to increase superficial hardness values up to 31% in the superalloy. Results also show that the hardness differential between the micro and nanometric scale is around 13%. An increase in compressive stress has been measured after the procedure, which can help explain this increase in hardness.

Keywords: Ball burnishing, Vibration assistance, Micro-hardness, Nano-Hardness, Residual stress.

1. Introduction

Ball burnishing consists of plastically deforming the irregularities of a surface using a tool that applies a regulated force through passes adjacent to each other, all of this controlled by a routine programmed in CNC [1]. With this process, the material located in the peaks is compressed, reducing the surface roughness of the material, and inducing residual stresses.

During the last decades, numerous investigations have been carried out to confirm the improvement that burnishing supposes to certain mechanical properties of a piece. Specifically, the process allows for simultaneously reducing the surface roughness, increasing the hardness of the surface layers of the part and increasing the compressive residual stresses of the manufactured materials.

One of the main issues found by researchers in this field is the abundance of possible parameters subject to study. Some of the most relevant are the burnishing force [2], feed, original texture of the machined surface [3], among others.

It has been demonstrated that ball burnishing can induce residual compressive stresses in the material [4]. For this, the most significant burnishing parameter is the applied force. The higher the force is, the more residual stress is induced. Various authors have corroborated that residual stress has an influence on surface hardness measurements [5,6]
Regarding surface hardness, Travieso-Rodríguez et al. [7] investigated the effect of ball burnishing on various materials and explained how varying input parameters for burnishing affect the final surface hardness. From there, it has been concluded that applied force and the number of passes are the most influential parameters in the case of hardness. According to Saldaña-Robles et al, [8] the surface hardness of a material can be increased from 16% to 60% after burnishing. This variation depends on the parameters used in the process. However, applied force is one of the most influential parameters.

Ball burnishing effects have been studied in polymeric materials too. In this paper, Janczewski et al, [9] studied the change in surface properties that burnishing causes in low-density polymers (LDPA). In this, it has been discovered that the improvement of roughness obtained by burnishing is significantly lower than in the case of metals. In addition, in the same paper, it is discovered that the hardness values for the material remain the same as before the operation. However, they deduce that the operation makes sense in this type of material, as it significantly reduces its wear. Apparently, this is due to changes in the conformation of LDPA chains.

Furthermore, assisting burnishing with a vibration can help to enhance the changes in hardness found after the application of the process. Teimouri et al [10] conducted a study to evaluate surface properties, by performing a roughness analysis, a hardness analysis by using Vickers micro indentation, and residual stresses of Aluminum AA-6061. In this paper, they discovered that the increase in vibration amplitude during the process increases the hardness of the material. However, surface roughness does not present linear behavior.

Another method used to determine the hardness of the material after burnishing is nano indentation. This technique allows the user to measure the changes caused by the burnishing process much closer to the surface than micro indentation. Luo et al [11] performed one of such tests. In their findings, the maximum value of hardness is found at a penetration depth of 2 μm, and the hardening film is over 4 μm. Both of them are penetration depths too small to use conventional micro indentation.

Ball burnishing and its effects have been studied on a large number of materials. In the vast majority of them, an increase in surface hardness has been observed after treatment, in addition to an improvement in its surface roughness. The most influential parameters, in most cases, are the burnishing force and the number of passes applied [12].

Assisting the burnishing process with vibrations, significantly improves the properties of the manufactured pieces. It can be also observed that normally the values of surface hardness increase with respect to the obtained when the process is used without the vibration assistance [13].

This paper studies the effect of burnishing with vibration assistance in a nickel-based alloy, UDIMET 720. To evaluate the effect of the process on the piece material, micro and nano indentations were done on the workpieces. A comparison between both techniques is also present. The residuals stresses were also measured in order to establish a relation with the hardness acquired by the material.

The results presented in this paper are important to continue adding information to the study of burnishing process and the effects obtained in the pieces that are treated with this process. At the end, the industry demands pieces with good properties to withstand the performance to which they are subjected, and, in this case, the burnishing process helps in this regard.

2. Materials and methods

2.1. Ball Burnishing tool

The ball burnishing process is carried out in a CNC milling machine. To do this, a tool characterized by Jerez-Mesa [14] was used. This tool, as shown in figure 1, is composed by three modules. A spring, inside the force control module, allows regulating the force exerted on the material, in a way proportional to Hooke’s Law. The intermediate module contains a piezoelectric material, which excited by an electric current, produces a vibration of 40 kHz frequency. An external signal generator can control this electric current. Finally, the force transmission module consists of a ball, which makes contact with the treated material, and bearing spheres to reduce the friction between the ball and the tool.
The material studied is a nickel-based alloy with aeronautical applications, UDIMET 720.

### 2.2. UDIMET Specimens

The raw material is a Ø117 mm cylindrical block of UDIMET 720. The mechanical properties and the chemical composition of this material are shown in tables 1 and 2 respectively.

#### Table 1. Mechanical properties of UDIMET 720.

| Property              | Units | 25 °C | 875 °C |
|-----------------------|-------|-------|--------|
| Elongation            | %     | 4     | 17     |
| Yield Strength (0.2%) | MPa   | 950   | 540    |
| Tensile Strength      | MPa   | 1100  | 665    |
| Density               | g cm⁻³|       | 8.08   |
| Coefficient of Expansion | µm m⁻¹°C⁻¹ | 12.24 |

#### Table 2. Chemical composition of UDIMET 720.

| Ni  | Cr  | Co  | Ti  | Mo  | Al  | W   | Zr  | C   | B   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| *   | 15.5-| 14.0-| 4.75-| 2.75-| 2.25-| 1.0-| 0.025-| 0.01-| 0.01-|
| 16.5 | 15.5 | 5.25 | 3.25 | 2.75 | 1.5 | 0.05 | 0.02 | 0.02 |

Before burnishing, the studied surface is machined by a Ø10 mm ball end mill, to obtain an initial Ra of around 3.5 μm. Then, the pieces will be burnished at 450 N in force, 5 burnishing passes, with the assistance of vibration. These passes follow a perpendicular trajectory to those described by the previous milling. The used ball has a diameter of 10 mm, and the feed rate is 300 mm/min. Finally, the lateral pass step is 0.3 mm. In order to have enough surface to make all the measurements, an area of 10 × 10 mm has been treated with this process. After the burnishing process, the Arithmetical mean height (Sa) was reduced to 0.9 μm. Those conditions were selected based on a previous study [15]. Finally, this specimen is cut from the raw material block using a cutting machine.
2.3. Response indicators

2.3.1. Micro Hardness. The hardening effect of the process has been studied by Vickers micro indentation tests according to UNE EN ISO 6507-1. For this test’s purposes, a load of 10N was selected. Five repetitions were carried out, and hardness are reported as the average value and their error. This technique was used because it is the cheapest and easiest way to find the values of hardness. A more sophisticated technique that allows one to do the same measurements, but in a more precise way is nano indentation.

2.3.2. Nano hardness. Nano indentation is a technique that allows us to make hardness measurements very near the surface of the material. Theoretically, this should be the part most affected by the burnishing process. This technique has several advantages over micro indentation. One of them is the ability to fully automate the process, being able to perform several hundreds of indentations in just a few minutes. A byproduct of this automation is the ability to create maps, which can serve as a visual representation of the hardness state of the material in interesting zones. In addition, the measurements done can appreciate the hardness changes in the nano parts of the material. Therefore, it could be appreciated if the burnishing changes the material hardness at that scale in the same magnitude that it does at microscale.

To do this comparison with the micro indentation measurement done on the superficial of the specimens, a nano indentation test has been also carried out in UDIMET specimens, using iNano equipment (Nanomechanics, Inc., Oak Ridge, TN, USA). A map of 20×20 indentations, with a separation of 1.5 μm between them, has been created with a maximum penetration applied load of 3 mN. This way, the indented area is 30×30 μm, which is a 0.3% of the total burnished area. The results obtained from this measurement are represented graphically in a hardness map of the material surface, and they can be averaged to obtain the hardness value of the measured zone of the material.

2.3.3. Residual stresses. The hardness of a material is directly correlated to the residual stresses present in it. It has been demonstrated that the higher the residual stress of a piece is, the higher the hardness of the material is [16].

For this reason, residual stresses have been measured in the UDIMET piece using the x-ray diffraction technique. With this technique, the deformation of the crystal structure is measured, and the stress is determined from the elastic constants of diffraction. The x-rays strike an area on the surface of the sample, which typically encompasses a large number of crystalline grains (depending on the beam geometry and the grain size of the material). Furthermore, they penetrate a certain distance into the material, which depends on the wavelength of the incident radiation, the material, and the angle of incidence.

For this particular study, the anode used to generate the radiation is Mn alpha. Thirteen different tilt positions have been measured, with an exposition time of 60s for each of them. With Bragg’s law, the diffraction angle has been found to be 149.825°.

3. Results

3.1. Hardness in UDIMET 720

Micro hardness. Hardness in the UDIMET sample has been studied using Vickers micro indentation with 10N-load, both in the base material and in the burnished specimen. Five indentation tests are carried out for each studied condition, and the average and error have been reported.

Again, as seen in figure 2, in this material the mean measured hardness increases with the application of burnishing process. With this condition, an increase from 4.45 GPa to 5.82 GPa with the burnishing process can be observed. This change is around a 30.02%.
3.1.1. Nano hardness. The nano indentation maps show also an increase on hardness on the top layer of the material (figure 3). The purple zones in the maps are caused by the irregularities of the material, since this technique is very susceptible to the roughness of the studied zone of the material. This problem is clearly visible in the burnished specimen map (figure 3 (b)).

![Nano hardness results](image)

**Figure 2.** Micro Hardness results for UDIMET 720.

![Nano hardness results](image)

**Figure 3.** (a) Nano hardness results for the base specimen. (b) Nano hardness results for the burnished specimen.

As it can be seen in table 3, hardness values augmented substantially when applying the burnishing process. This change represents a 31.2% of increment. However, these values, both in the base and the burnished specimen are lower than those found by micro indentation. In case of the base specimen, the difference is 13.09%, and in the burnished specimen, the difference is 12.61%. This could be because at nano scale, the surface cannot be considered locally flat, and the material’s volume affected by the plasticity ball is underestimated. It means that measuring the hardness by both methods there are some differences. These differences can be caused by the indentation size effect, which occurs when indentations are made at very low loads, as it was observed by Broitman [17] before. Due to the cost difference between both methods and the difficulties to obtain correct measurements using the nano indentation technique, it would be advisable to revise the use of nano indentation for future projects.
Table 3. Nano hardness results for UDIMET 720.

| Specimen  | Nanohardness (GPa) | Standard deviation |
|-----------|---------------------|--------------------|
| Base      | 3.87                | 1.73               |
| Burnished | 5.08                | 1.39               |

3.2. Residual Stress

To corroborate the influence of burnishing over the material mechanical properties, compressive residual stress measurements have been done in the UDIMET specimen both in the burnished and milled zones. This measurement has been done by the X-ray diffraction technique.

![Residual Stress](image)

Figure 4. Residual Stress results for UDIMET 720.

As it can be seen in figure 4, although the error in the measurements is quite large, with the error bars of both measures overlapping themselves a big difference in residual stress can be found.

Table 4. Residual Stresses results for UDIMET 720.

| Specimen  | Residual Stress (MPa) | Standard deviation |
|-----------|-----------------------|--------------------|
| Base      | -234                  | 163                |
| Burnished | -417                  | 217                |

In this case, as seen in table 4, an increment of 78% in residual stresses has been found. However, this value is not very reliable, because of the big errors in the measurements. These errors can be caused because the chosen measurement technique may be inappropriate for this material. To corroborate this, more test has to be done, also using another kind of technique such as, the hole drilling method, Focus Ion beam (FIB), etc.

4. Conclusions

After the experimental process developed in this paper, the following items can be concluded:

- The burnishing parameters selected in this study proved to be adequate and generated changes in the mechanical properties of UDIMET 720.
• Ball burnishing affects the hardness of the material, increasing it over the raw material in the order of 31%.
• Ball burnishing has been found to increase compressive residual stress on UDIMET 720, in the order of 78%.
• The increase of hardness has been found to be proportional in both the nanometric and micrometric scales, with a difference in the order of 13% between both measurements, and to the increase of residual stress values.

Acknowledgements
Financial support for this study was provided by the Ministry of Science, Innovation and Universities of Spain, through grant RTI2018-101653-B-I00, which is greatly appreciated. Additionally, by the regional government of Catalonia and FEDER funds for regional development through grant IU68-016744.

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