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To cite this article: I Fernandez *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1193** 012084

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Investigation of ball burnishing process using vibration and acoustic emission sensors

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Abstract: In this paper, a ball burnishing tool mounted in a CNC lathe is characterized. This tool may work as vibration assisted ball-burnishing tool and in conventional way. The characterization consists of acoustic emission measurements in both burnishing processes, and vibration measurements with tri-axial accelerometers. The acoustic emission measurements permit to investigate if any kind of damage is produced in the material by the burnishing process. An operational deflection shape exercise has been performed with the vibration measurements. This permits to investigate the movement of the tool during the burnishing process and to evaluate the rigidity of the tool.

Keywords: Acoustic emission, Burnishing, Vibration assisted burnishing, Operating deflection shapes.

1. Introduction

The quality requirements of industrial products are increasing and mechanical components are not an exception [1]. Way back in 1920, the British scientist Griffith concluded that the strength of isotropic materials was much lower (between 10 and 20 times) than could be predicted theoretically, and this was due to the lack of continuity of the material, that is, to the existence of defects [2]. These defects occur in the process of obtaining the parts (metallurgical defects) or in the production process due to the details of the parts. The defects of the surface layers of the machine parts and components are especially dangerous. In these surface layers three properties are especially important: surface hardness, roughness and compressive residual stresses.

Ball burnishing is one of the best processes suitable to improve these properties [3]. This process consists of the plastic deformation of the target surface irregularities applying a controlled force by a sphere [4]. In recent years, we have witnessed to the birth of the so-called vibration-assisted ball burnishing (VABB). This “assistance” consists in that the ball that compresses the target surface is subjected to a high frequency vibration (between 20 and 40 kHz) which, in turn, is transmitted to the target surface. [5]. This vibration of the surface material produces a lowering of its yield limit. This phenomenon is called acustoplasticity [6]. As a result, the material plastic deformation is achieved with



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forces lower than those that would be necessary without vibration assistance. Consequently, vibration-assisted ball burnishing provides better results than conventional ball burnishing [7].

Different systems have been used to achieve the vibration assistance in burnishing processes (and in different machining processes) [1]. Most of them, as that is object of study in this paper, use a resonant system that produces a movement of low amplitude (between 3 and 30 μm) [8]. This system, that has been described by Jerez-Mesa et al (2018) in [9], consists in a piezoelectric stack where a high frequency electrical charge is applied and, consequently, it undergoes a deformation that transmits to the ball. This device is called sonotrode [10].

In this paper, the vibrating characterization of a burnishing tool mounted in a numerical control lathe is presented.

Acoustic emission are high frequency waves (in the ultrasonic frequency band) generated when any kind of damage (crack initiation, coalescence of voids, dislocation, etc) is produced in a solid material submitted to a high enough stress/strain state [11]. During fabrication processes different acoustic emission signals are usually emitted by the machined parts as consequence of the damage produced in them. In the burnishing processes presented in this paper the presence of acoustic emission produced by the burnishing process was explored.

The Materials and Methods Section presents a short description of the vibration assisted lathe burnishing tool and describes the performed tests. The Result Discussion Section explains the results obtained and discusses about them. The Conclusion Section summarizes the conclusions of these results.

2. Materials and Methods

2.1. Experimental setup

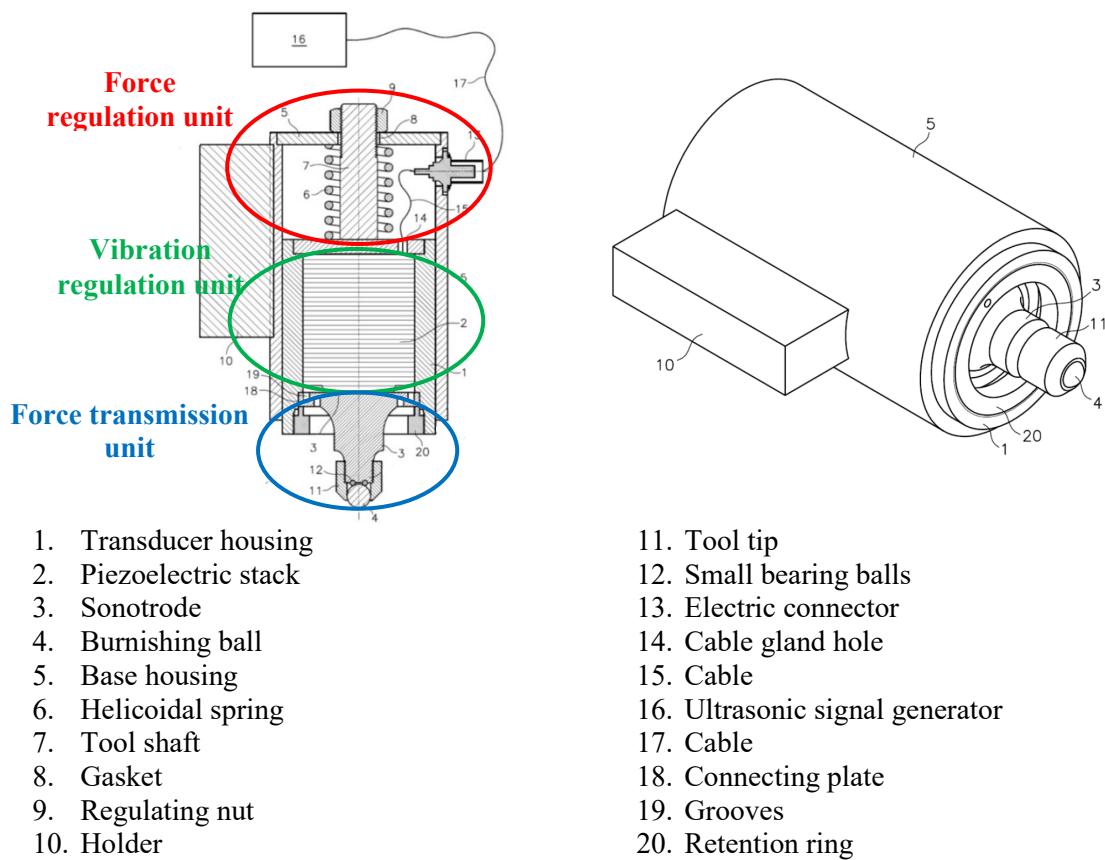
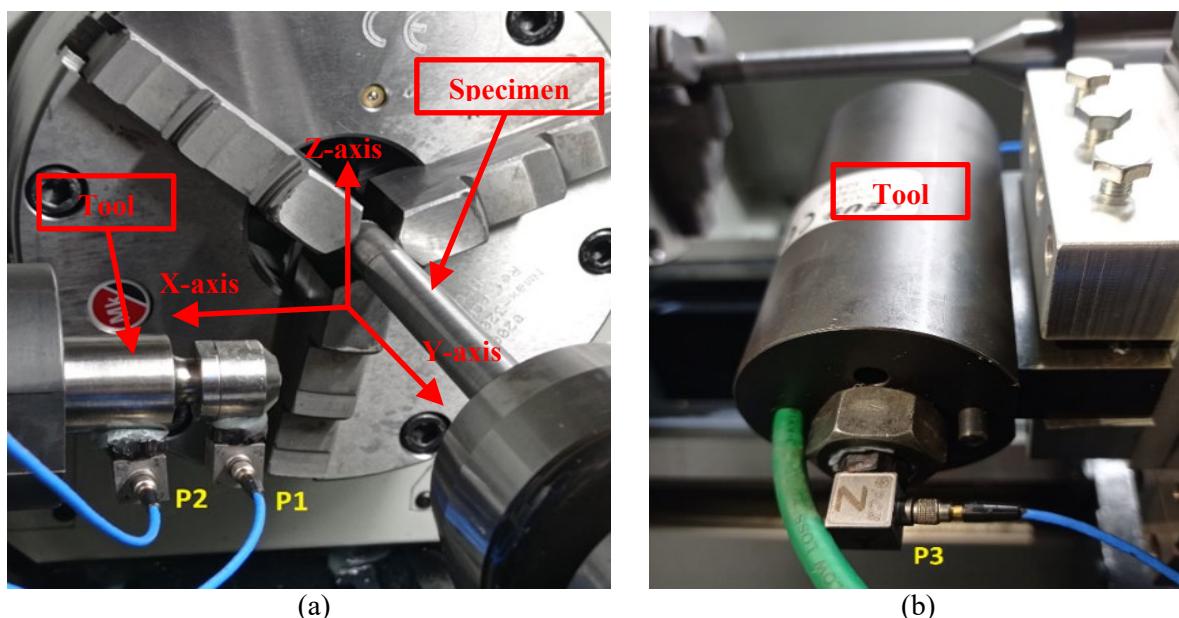
The used burnishing tool constitutes an innovative burnishing tool design that includes a piezoelectric vibration generator [12]. This tool is shown in figure 1. It consists of three parts:

- Force regulation unit. It controls the burnishing load by the compression of a spring. It also serves as the element to be clamped inside the tool holder to attach the tool to the machine.
- Vibration generation unit. It contains a piezoelectric stack that is feed by a high frequency harmonic signal and generates the assisting ultrasonic vibration. As explained before, this element called sonotrode.
- Force transmission unit. The function assigned to this module is to transmit the forces generated by the previous units (burnishing load and ultrasonic vibrating load) to the burnishing ball and, consequently, to the target surface. It incorporates an innovative system to support the burnishing ball that is composed by a set of small bearing balls embedded in the tool tip that supports the burnishing ball (figure 1, Position 12)).

This tool was mounted in a PINACHO CNC lathe SE 200 x 1000 mm. The specimen was fixed between the universal plate and the point. The material of the specimen was C45 steel (according to ISO-EN-36010). The specimen was previously machined (diameter passed from 15.0 mm to 14.8 mm). This machining cutting speed was 1500 rpm and the tool feed was 0.15 mm/rev.

Three tri-axial accelerometers PCB 356A32/NC6 were installed in the burnishing tool in order to study its vibrating behaviour. Two ones were mounted in the frontal part, near of the burnishing ball (P1 and P2 in figure 2A), and the other was mounted in the opposite part (P3 in figure 2B).

An acoustic emission sensor Vallen VS700-D was installed in the holder in order to explore the acoustic emission.

**Figure 1.** Used burnishing tool [12].**Figure 2.** Tri-axial accelerometers mounted in the tool and axis. **(a)** Frontal part (accelerometers P1 and P2 and axis). **(b)** Rear part (accelerometer P3).

2.2. Vibration and acoustic emission measurement during the burnishing processes

Vibrations were registered by the previously described accelerometers and an acquisition system Brüel&Kjaer 3053-B-120 (data transfer 24bit) during two burnishing processes. One measurement was performed without vibration assistance and the other was vibration assisted. The sampling frequency was 32768 Hz. The burnishing conditions were the following:

- Burnishing speed: 50 rpm, that with $d = 14.8$ mm, corresponds to 2.32 m/minute.
- Feed: 0.15 mm/revolution.
- Force: 90 N

Operating deflection shape is a vibration analysis tool that permits to get the knowing about the deflection of a component or structure in real operating conditions. Vibration time histories in different points are registered while the system is operating. By applying of the Fourier transform to these recordings, the vibration level versus frequency is known at the different points. Then a system's wire frame model can be animated in order to show the movement at each measured point and at each frequency [13]. An operation deflection shape analysis has been performed from the tool vibration measurements.

During both burnishing processes, the acoustic emission was registered in continuous mode.

3. Result discussion

3.1. Vibration measurements

A wire frame model was defined in the burnishing tool with the three measurement points defined, and then it was animated. The frequency of 300 Hz was selected because all points present a peak at this frequency in all directions. Figure 3 shows, as example, the spectrum corresponding to Point 1, X-axis.



Figure 3. Vibration spectrum of point 1, X-axis.

Figures 4 and 5 depict the animation at 300 Hz. Figure 4(a) shows the movement in vertical direction (Z-axis according to figure 2(a)): blue line shows the centre position and red lines show the extremum positions. A rotatory movement around the centre of the tool is clearly noticeable, with an amplitude of the extremes of about 0.05 μm. Figure 4(b) shows the horizontal movement in the direction of the lathe axis (Y-axis according to figure 2(a)). A translational movement of about 0.05 μm amplitude is also noticeable.

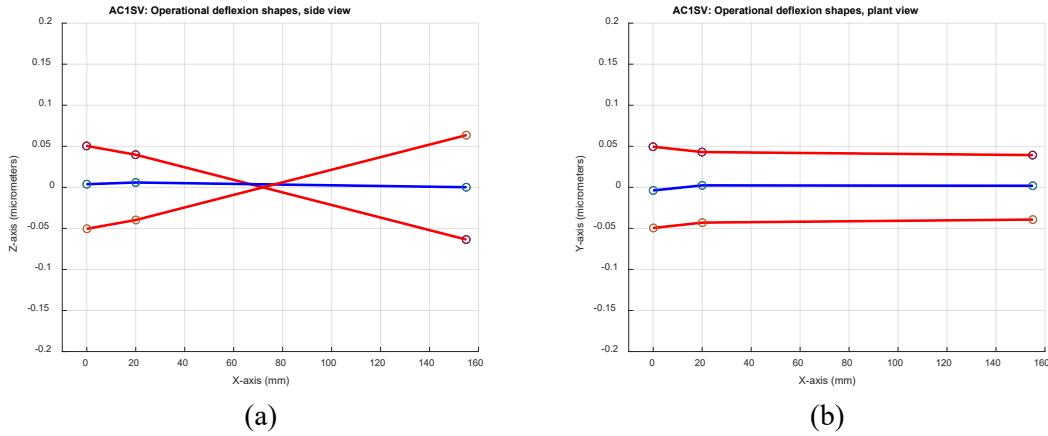


Figure 4. Tool's operating deflection shapes. The red continuous lines correspond to the extreme values and the dotted blue lines correspond to the medium values. **(a)** Left figure corresponds to the side view. **(b)** Right figure corresponds to the plant view

In order to know the movement in the tool axis (X-axis according to figure 2(a)), a zoom around its zero point is shown in figure 5. A displacement in the X direction is clearly noticeable and its amplitude is about $0.09 \mu\text{m}$.

After burnishing, the roughness profile was characterized. To do the surface texture analysis, a 1.5mm rectangle in the specimen radial direction per 2.5mm in the specimen axial direction was sampled. This measurement was made with a spacing of 2 μm in both directions. Measures were made by a STILL MICROMESURE2 profilometer. Then, with the MOUNTAINS software, the data collected were analysed, and the texture map and roughness profile are shown in figure 6. The values found on Y and Z axis where $R_{ay} = 0.135 \mu\text{m}$, in Y-direction and $R_{az} = 1.924 \mu\text{m}$, in Z-direction. Note that both R_a values are higher than vibratory amplitudes. Consequently, tool vibration does not affect to the final roughness.

A slight tool bending deformation is perceived in figure 4. This is compatible with the constructive arrangement of the sonotrode [9,12].

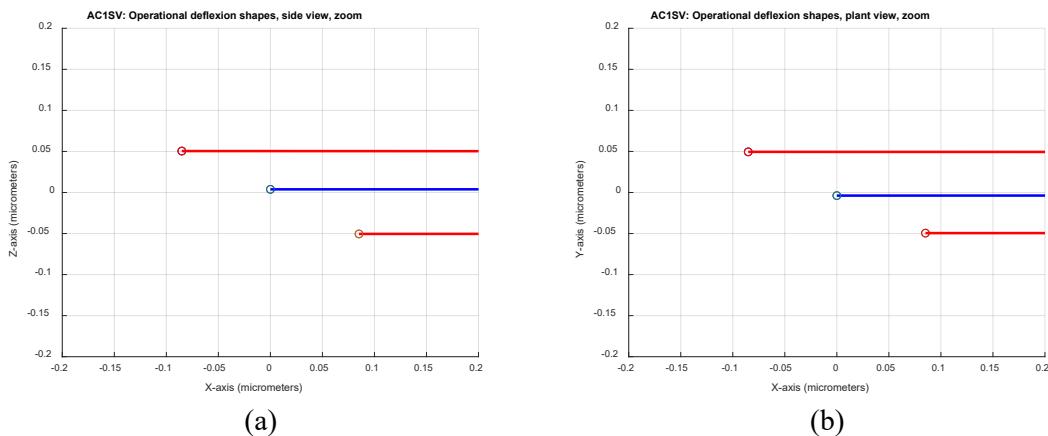


Figure 5. Zoom of the tool's operating deflection shape around the zero point of X-axis. The red lines correspond to the extreme values and the blue lines correspond to the medium values. **(a)** Left figure corresponds to the side view. **(b)** Right figure corresponds to the plant view.

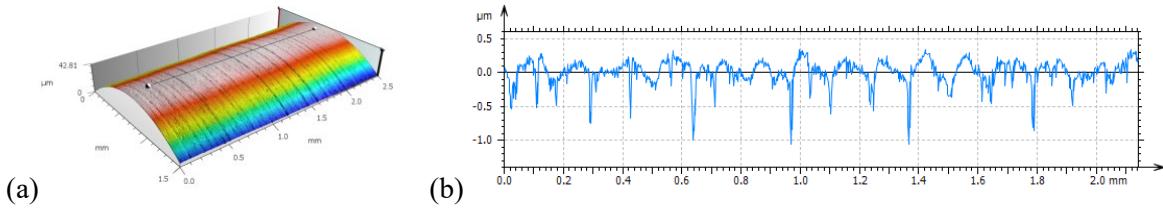


Figure 6. Roughness profile after burnishing. **(a)** Tri-dimensional profile **(b)** Longitudinal section.

3.2. Acoustic emission measurements

Figure 7 shows the acoustic emission time histories in different conditions. Figure 7(a) shows the background noise (signal corresponding to stopped lathe), figure 7(b) shows a burnishing process without vibration assistance and figure 7(c) shows a burnishing process with vibration assistance. Figures 7(a) and 7(b) are substantially the same, consequently, the burnishing process without vibration assistance does not produce acoustic emission. On the contrary, a clearly noticeable signal appears in the vibration assisted process because the sensor detects the assisting vibration (figure 7(c)).

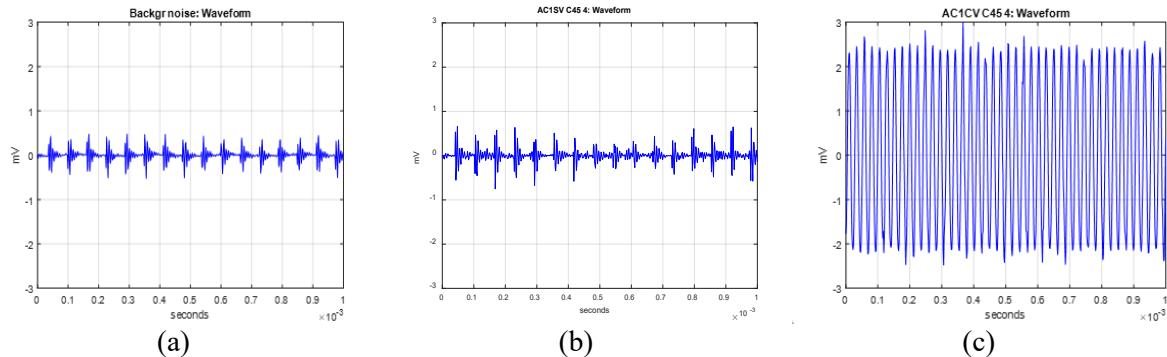


Figure 7. Acoustic emission time histories, corresponding to: **(a)** Background noise. **(b)** Burnishing without any vibration assistance. **(c)** Burnishing vibration assisted.

Figure 8 shows the frequency spectra corresponding to the same acoustic emission signals: figure 8(a) corresponding to background noise and figure 8(b) corresponding to burnishing without vibration assistance, are also the same. This confirms the absence of acoustic emission in a burnishing process without vibration assistance. In figure 8(c), an important peak at 41.8 kHz appears. This frequency corresponds to the ultrasonic vibration assistance and confirms that the assisting vibration is detected by the acoustic emission sensor. This is consistent with that reported by Jerez-Mesa et al [9] for vibration assisted burnishing in a milling machine.

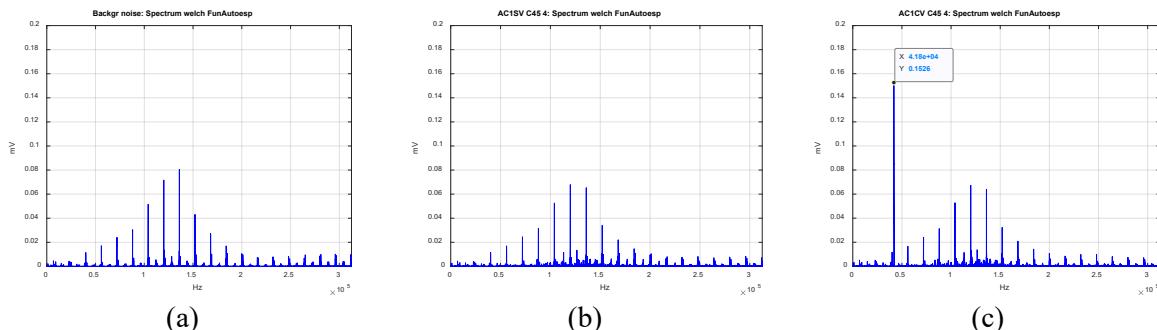


Figure 8. Acoustic emission spectra **(a)** Background noise. **(b)** Burnishing without any vibration assistance. **(c)** Burnishing vibration assisted.

In figure 8(c) can be noted that the measured level corresponding to the vibration assistance has an order of magnitude comparable with the background noise. It has to be taken account that the acoustic emission sensors do not have a flat frequency sensitivity throughout their frequency range. The sensor Vallen VS700-D used for the acquisition has a very low sensitivity around 40 kHz (figure 9), then the peak of 41.8 kHz is highly attenuated.

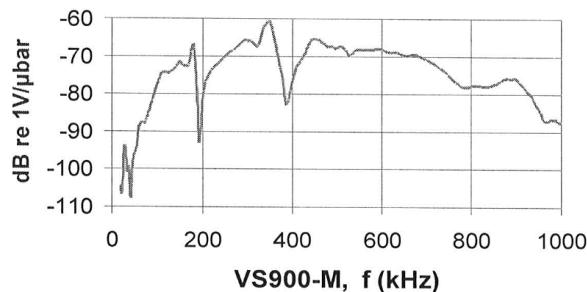


Figure 9. Frequency sensitivity of acoustic emission sensor VS700-D.

4. Conclusions

In this paper, a monitoring setup composed by three tri-axial accelerometers and an acoustic emission sensor is proposed to monitor and evaluate a burnishing tool mounted in a CNC lathe. The proposed structure has permitted the characterization of the system in the following way:

- An operating deflection shape analysis at the frequency of 300 Hz (where all points show its peak value) has shown a maximum displacement of 0.09 μm in the tool axis direction. Consequently, the rigidity of the system is good enough. In further work, this analysis will be performed with the vibration assisted process in order to evaluate the possible differences between both burnishing processes. Operational deflection shape is a good system to analyse the behaviour of the tool in any machining process.
- No acoustic emission appears during the burnishing process without vibration assistance. In vibration assisted burnishing process, the acoustic emission sensor detects the assisting vibration only. Consequently, no damage is detected in both ball burnishing processes on C45 steel. In further works, burnishing process on fragile materials will be explored.
- The operation of the tool is consistent with what was originally provided for in its original design.

Acknowledgements

Financial support for this study was provided by the Ministry of Science, Innovation and Universities of Spain (grant RTI2018-101653-B-I00) and Regional Government of Catalonia and FEDER funds for regional development (grant IU68-016744).

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