Article

Combination of Acoustic Emission and Vibratory Measurements to Characterize an Ultrasonic Vibration Assisted Ball Burnishing Tool for a Lathe

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Abstract: In this paper, a resonant system that produces a movement of low amplitude and ultrasonic frequency is used to achieve the vibration assistance in a ball-burnishing process. A full vibration characterization of this process performed in a lathe was done. It is carried out by a new tool designed in the research group of the authors. Its purpose is to demonstrate that the machine and the tool do not have any resonance problem during the process and to prevent possible failures. The analysis of this dynamic behaviour permits to validate the suitability of the tool when it is anchored to a numerical control lathe. This is very important for its future industrial implementation. It is also intended to confirm that the system adequately transmits vibrations through the material. To do this, a methodology to validate the dynamic tool behaviour was developed. Several techniques that combine the usual and ultrasonic vibration ranges through static and dynamic measurements were merged: vibration and acoustic emission measurements. An operational deflection shape (ODS) exercise has been also performed. Results show the suitability of the tool used to transmit the assistance vibrations, and that no damage is produced in the material in any case.

Keywords: accelerometer; process monitoring; natural frequencies; ball burnishing; ultrasonic; piezoelectric; acoustic emission; operational deflection shape.

1. Introduction

The quality requirements of industrial products are increasing more and more and the machined components are not an exception [1]. Back in 1920, the British scientist Griffith concluded that the strength of the materials with isotropic properties was much lower (between 10 and 20 times) than could be predicted theoretically, and this is 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 components (metallurgical defects) or in the production process due to geometric details. The defects of the surface layers of the machined components are especially dangerous. In these surface layers, three properties are especially important: surface hardness, roughness and compressive residual stresses.

Ball burnishing is one the most suitable processes to improve these properties [3]. It consists of the plastic deformation of the target surface irregularities applying a controlled force by a sphere [4]. In recent years, the technical world has 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 acoustoplasticity [6]. As a result, the material plastic deformation is achieved with forces lower than those that would be necessary without vibration assistance. Consequently, VABB provides better results than conventional or non-vibration assistance ball burnishing (NVABB) [7].

Different systems have been used to achieve the vibration assistance in burnishing process (and also 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 is described by Jerez-Mesa [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, a full vibration characterization of a ball burnishing process performed in a lathe is presented. This ball burnishing process is carried out by a tool designed in the research group to which the authors belong [11]. Its purpose is to demonstrate that the machine and the tool do not have any resonance problem during the process and to prevent possible failures. The analysis of this dynamic behaviour permits to validate the suitability of the tool when it is anchored to a numerical control lathe. This is very important for its future industrial implementation. It is particularly intended for the application in industries that manufacture elements with revolution symmetry that have to be subjected to high-cycle fatigue or an important wear has to be prevented. It is also intended to confirm that the system adequately transmits vibrations through the material.

In this way, it is intended to develop a methodology to validate the dynamic tool behaviour merging several techniques that combine the usual and ultrasonic vibration ranges through static and dynamic measurements. In the static measurements, the frequency response functions of the tool are measured and consequently the natural frequencies are known [12]; the dynamic measurements allow to characterize the burnishing process (vibration assisted or not) in operating conditions. In this case, acoustic emission is used to detect possible damage in the material during the VABB process. When any possible damage is produced during the material machining (crack start, coalescence of voids, dislocations, etc.), a high frequency wave is generated and transmitted along the material, this wave is called acoustic emission [13].

This perspective of analysis of the burnishing problem combining different vibration and signal measurement techniques has been used in the past for the detection of failures in different manufacturing areas [14]. Maia et al. (2015) [15] describe that the acoustic emission is related to the wear mechanisms of the cutting tool. Pandiyan & Tjahjowidodo (2019) [16] applied dynamic measurements to establish the fault thresholds in grinding wheels at different conditions. About the burnishing, there are only few references where the application is so direct. Dornfeld & Liu (1999) [17] concluded that acoustic emission (AE) helps revealing information about the frictional behaviour of the ball burnishing process, as it has a strong correlation with the kinetic friction coefficient and the texture surface profile. Their works also concluded that AE shows that the burnishing process can be divided in 4 stages from a dynamic point of view. Only in the first two ones positive results during burnishing can be obtained. Strömbergsson et al. (2017) [18] observed that using an AE technique during a burnishing process is very positive to monitor and to confirm that the operation has performed its function. For example, an AE signal in Root Mean Squared (RMS) representation for 5 minutes shows that the decrease of the coefficient of friction (COF) stagnates after a time, and that the tribological behaviour is not stable in time. Therefore, it can help investigators to be warned of excessive wear of the

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burnishing ball that could affect the finishing results. Salahshoor & Guo (2011) [19] used AE to monitor the burnishing process on a magnesium-calcium alloy.

Although the few references about the application of AE to the burnishing, there are some studies in which this technique is used to diagnose possible faults in contacts between solid bodies in relative motion, a case to which burnishing is easily assimilable due to the way it takes place, and which is therefore considered relevant as an antecedent for this paper [20]. Tandon et al. (1999) [21] highlighted the effectiveness to detect failures in contacts between ball bearings, and they concluded that AE can detect the transfer of particles from the wear of two surfaces in contact. They also concluded that AE is more effective than the analysis of vibrations because it can detect before the errors. Hase et al. (2012) [23] concluded that the frequency spectra of the AE signals measured during the tribological tests permit to distinguish the wear mechanism between the contact surfaces. Geng et al. (2019) [23] concluded that the AE signals acquired at highest sampling frequencies are more sensitive to detect the friction mechanisms between two contact surfaces tan the evolution of the friction coefficient that characterizes this contact.

The analysis included in previous paragraphs allows to perceive a fundamental importance in the application of traditional techniques of static and dynamic vibration analysis applied to the VABB process that this paper deal with. Thus, the dynamic results derived from the VABB applied to two different ferric alloys are described, in order to evaluate different magnitudes in different burning conditions: two burnishing forces (90 N and 270 N) and considering the vibration assistance (yes or not). The measured magnitudes are burnishing force, vibrations and acoustic emission. This will permit to characterize the process itself, the suitability of the tool used to transmit the assistance vibrations, and to detect possible damage in the specimen produced by this process. From the vibration measurements, an operational deflection shape (ODS) exercise has been also performed.

2. Materials and Methods

2.1. Experimental setup

In order to characterize the dynamic behaviour of the machine-tool-part set two kinds of tests were performed: impact tests in static condition, and vibrations, forces and acoustic emission monitoring in running (dynamic) condition of the burnishing system. The used ball-burnishing tool has the possibility to perform NVABB and VABB processes. The frequency of this ultrasonic vibration is 40 kHz. All tests were performed in a PINACHO SE 200x1000 mm CNC lathe. The specimens were fixed between a self-centering three-jaw chuck plate and the point.

Different burnishing parameters were taken into account in this study: specimen material (C45 steel according to EN 10020:2000 and GJL250 grey cast iron according to EN 1560:2011), burnishing force (90 N and 270 N) and ultrasonic vibration assistance (yes or not). The specimens were previously machined. Table 1 shows their initial and final dimensions, the cutting parameters and the measured roughness. No cutting fluids were used in the machining.

Table 1. Cutting parameters and specimen dimensions (initial and final)

Material	Initial dimensions		Cutting parameters			Final dimensions		
	D [mm]	L [mm]	Cutting speed [m/min]	Feed [mm/rev]	Cutting depth [mm]	D [mm]	L [mm]	Roughness Ra [µm]
C45	15	133	70.7	0.15	0.2	14.8	133	1.187
GJL250	30	185	Max: 56.5	0.3	0.8	14.0	185	2.310

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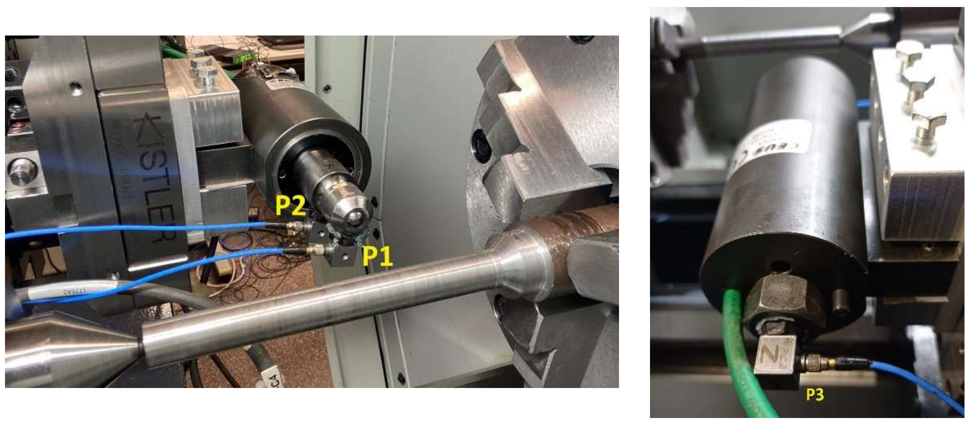
Min: 29.4	0.15	0.4

Different accelerometers were used. Three tri-axial accelerometers 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 (Positions P1 and P2 of Figure 1(a)), and the other was mounted in the opposite part (Position P3 of Figure 1(b)). The characteristics of these accelerometers are shown in Table 2. The measurement directions of the accelerometers correspond to the burnishing feed (X), vertical direction (Y) and direction of the burnishing force (Z).

Table 2. Accelerometers used for the measurements

Measurement position	Accelerometer	Frequency range [Hz]
Tool (P1, P2 y P3)	PCB 356A32/NC	1 ÷ 4 000
Lathe bed, directions A, V y H	KISTLER Type 8752A50	0.5 ÷ 5 000



(a) (b)

Figure 1. Triaxial accelerometers installed in the tool: (a) frontal view; (b) rear view.

Three mono-axial accelerometers were installed in the lathe bed, in order to know the vibrational transmissibility from the machine, in the burnishing process. Figure 2 shows these accelerometers and their measurement directions: A (axial according to the specimen rotation), V (vertical) and H (horizontal). The characteristics of these accelerometers are also shown in Table 2.

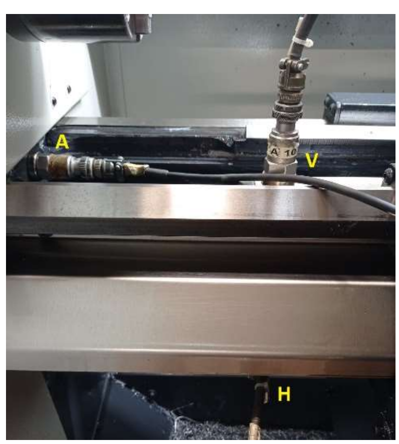


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Figure 2. Accelerometers mounted on the lathe bed.

2.2. Burnishing force monitoring

The compressive deformation of the spring installed inside the tool-holder is linearly related to the force transmitted by the burnishing tool to the target surface [9], and in turning processes; this is linearly related to the penetration of the tool in the direction of the depth of the pass. The nominal burnishing forces of the tests were 90 N and 270 N for the steel specimen and only 90 N for the grey cast iron, because 270 N is excessive load for this material.

The force is monitored by a KITSLER 9129AA dynamometer, adapted to the lathe holder where the tool is mounted, Figure 1(a). The force signal is conditioned by a KITSLER 5070A12100 amplifier. Burnishing forces were acquired in impact tests in static condition and in measurements in operating conditions of the burnishing system (Figure 3).

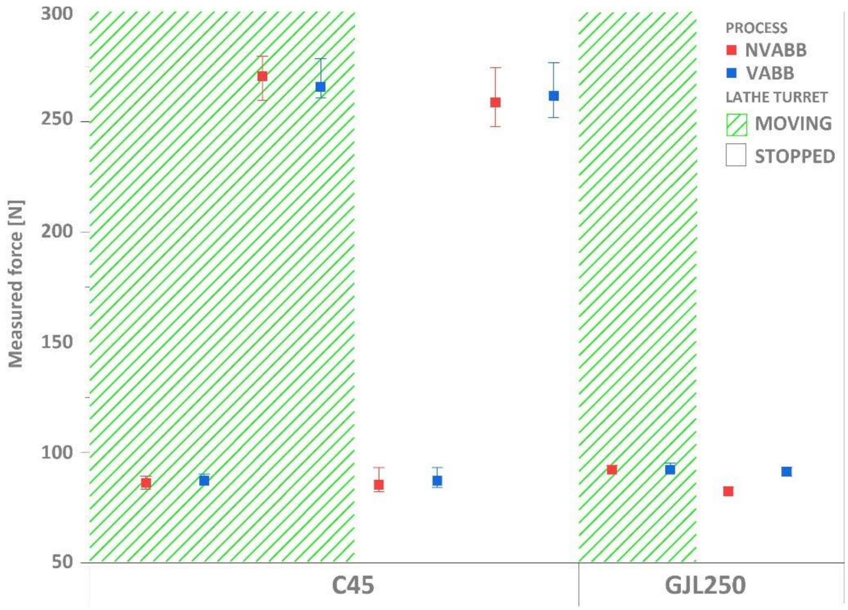

Figure 3. . Average, maximum and minimum forces recorded during the tests.

2.3. Impact tests

Impulse excitation was used to determine the natural frequencies of the tool on different conditions. Impacts were carried out with an impact hammer (KISTLER 9722A2000) with steel tip (9902A). Its maximum frequency is 9.3 kHz and its maximum force is 11 kN. These characteristics were suitable because, according to previous works [24], in which natural frequencies of a similar tool were lower than 5 kHz.

Impacts were performed at three tool points in vertical direction (points I1, I2 and I3) and vibrations were measured at three points (P1, P2 and P3) in three directions, shown in Figure 4. The conditions in which the impacts were carried out are the following:

- Tool installed it its holder without any contact with the specimen (free tool).
- Tool in contact with the specimen and forces between them of 90 N and 270 N with the steel specimen and force of 90 N with the green cast iron. These conditions were repeated with the tool in two positions, one near of the plate and the other near of the point.

In total 15 impact tests were performed. The vibration assistance was not activated during the impact tests because in a previous work [24] was demonstrated that the ultrasonic vibration of the assistance does not affect to the tool natural frequencies.

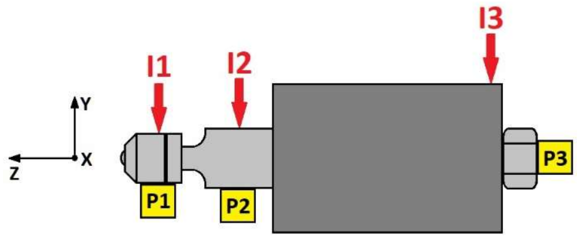

Figure 4. Lateral view of the impact points on the tool

The acquisition and further analysis of the vibration signals were performed with an analyser Brüel&Kjær 3053-B-120 y el software PULSE Reflex respectively. Ten channels were defined, three for each tri-axial accelerometer and the other for the impact hammer.

2.4. Vibration monitoring during the burnishing process

Different burnishing tests with different forces were performed in order to characterize the machine-tool-specimen set in the burnishing process. The used burnishing forces were 90 N and 270 N for the C45 steel and 90 N for the GLJ250 grey cast iron. The second variable was the ultrasonic vibration assistance that could be present (VABB) or not (NVABB) in the tool. The burnishing speed was 2.33 m/min and the feed was 0.15 mm/revolution. The burnished length of each test was 10 mm, except for some tests that were carried out without feed for 3 minutes.

The layout of these tests are shown in Figure 5, for C45 and GJL250 specimens.

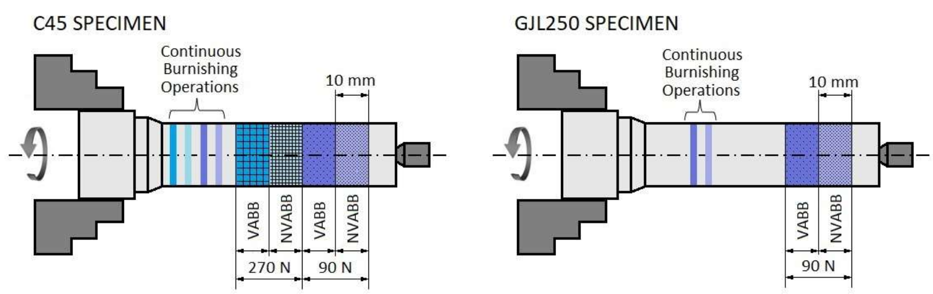

Figure 5. Burnishing test areas

From these measurements, an operation deflexion shape (ODS) of the tool has been obtained. ODS 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 are recorded in operating conditions. By applying 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 [25].

2.5. Acoustic emission measurements during the burnishing process

As explained before, acoustic emission waves are high frequency waves (in the ultrasonic frequency band) generated when any kind of damage is produced in a material. During manufacturing processes, different acoustic emission signals are usually emitted by the machined parts as consequence of the damage produced in them. For the burnishing process presented in this paper, the eventual presence of acoustic emission events resulting from it were explored because, as was indicated in the introduction, previous results of other authors have validated the application of this this technique to the characterization of the process itself.

To this aim, an acoustic emission sensor Vallen, model VS700-D, was installed in the tool holder. A Vallen preamplifier, model AEP4, a Vallen AMSY5 acoustic emission system and Vallen acquisition software were used for conditioning and recording the acoustic emission signals. The sampling frequency of the acquisition was 625 000 samples/s.

3. Results and discussion

3.1. Impact tests

Impacts performed at point I3 (Figure 4) does not provide any valid information because the base housing is disconnected from the tool in order that the ultrasonic vibrations are transmitted to the lathe [11].

According to the impact position, the best responses correspond always to the vertical direction (Y) that is the impact direction. Frequency Response Functions (FRF) of the point P3 show bad coherence between excitation and response.

The signals measured at points P1 and P2, corresponding to the tests performed without contact between tool and specimen show a natural frequency around 1.5 kHz. Figure 6 shows the FRF and the coherence function corresponding to the response at point P1 with excitation at I2. Some low peaks appear also around 500 Hz and 900 Hz. The band between 2 and 3 kHz is also noticeable but its coherence is not gut.

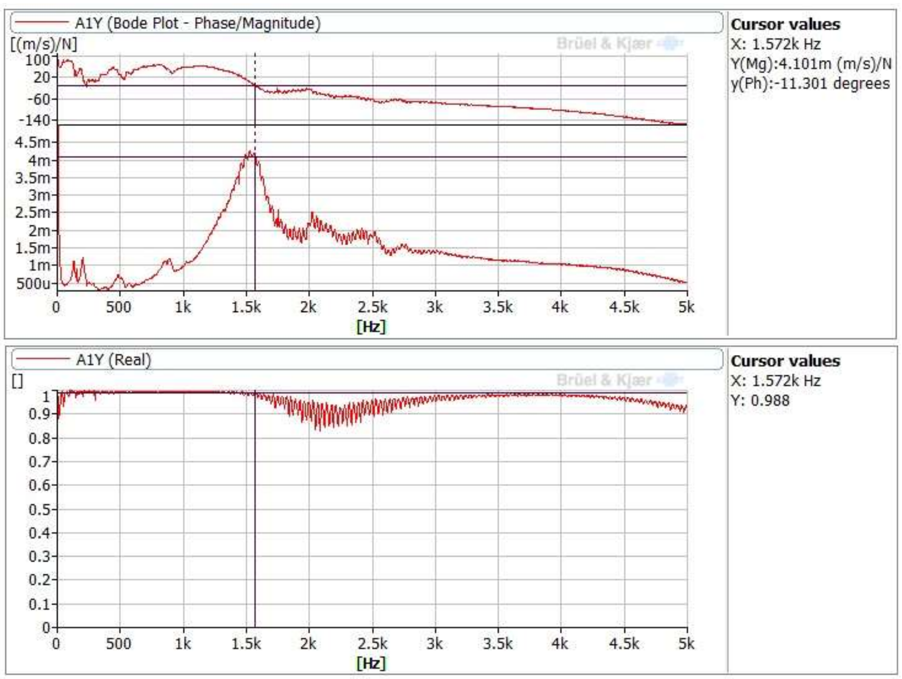

Figure 6. FRF obtained at P1 with impact at I2.

In the tests performed with contact between tool and specimen there are no differences between the different test conditions (force and tool position). Consequently, the load and the tool position does not affect to the results. In these cases, natural frequencies in signals measured at point P3 are noticeable. New components in the band between 1.2 and 2.8 kHz appear. The amplitudes are lower than those obtained in measurements without contact tool-specimen. Figure 7 shows FRF and coherence corresponding to response at P1 and impact at I1, in position near of lathe point and with a load of 90 N.

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Natural frequencies are always much lower than the assisting frequency that is 40 kHz constituting the 5% of this magnitude.

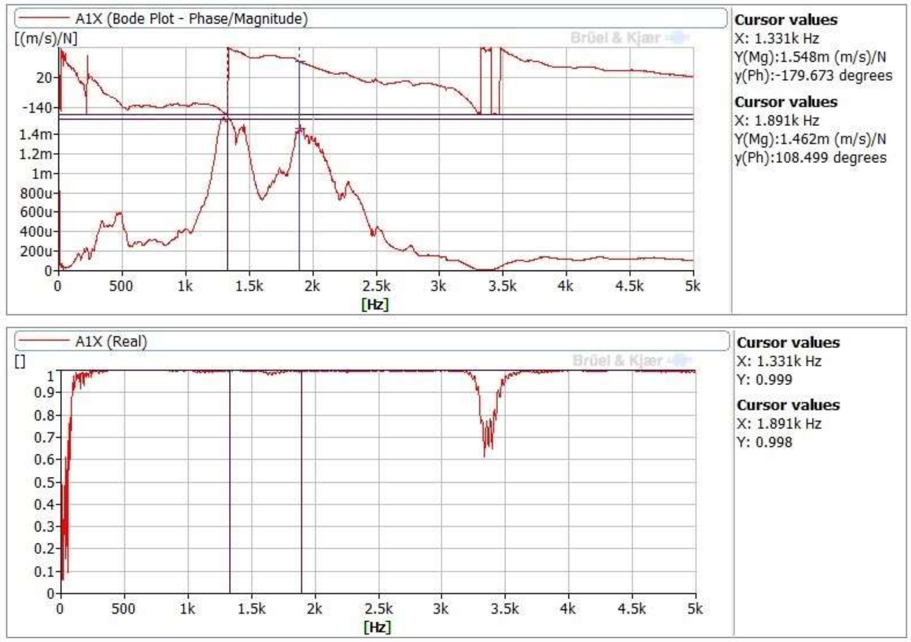

Figure 7. FRF obtained at P1 with impact at I1, with a load of 270 N

3.2. Vibration monitoring during the burnishing process

Measurement signals acquired by tool accelerometers (Figure 1) and test bed accelerometers (Figure 2) during burnishing processes were processed and analysed in time and frequency domains. The maximum analysis frequency was 4 kHz. Spectra are shown in some cases up to 2 kHz because no components appear at higher frequencies.

The vibration behaviour of the tool during the burnishing process is similar for both materials in all burnishing conditions. In burnishing of C45 components at 15.8 Hz and 32.1 Hz are noticeable, while in burnishing of GJL250 are noticeable components at 17 Hz and 34.2 Hz. This difference is due to the burnishing speeds are slightly different and these components are related with mechanical and electrical operation of the lathe. In all cases, the components are very small, about μm/s RMS. According to the ISO 20816 [26] for vibrations in machines, the highest allowable vibration level is 0.28 mm/s RMS and all the measured levels are considerably lower. Figure 8 shows the spectra in Z direction (direction of burnishing force) for both materials with a burnishing force of 90 N and without vibration assistance.

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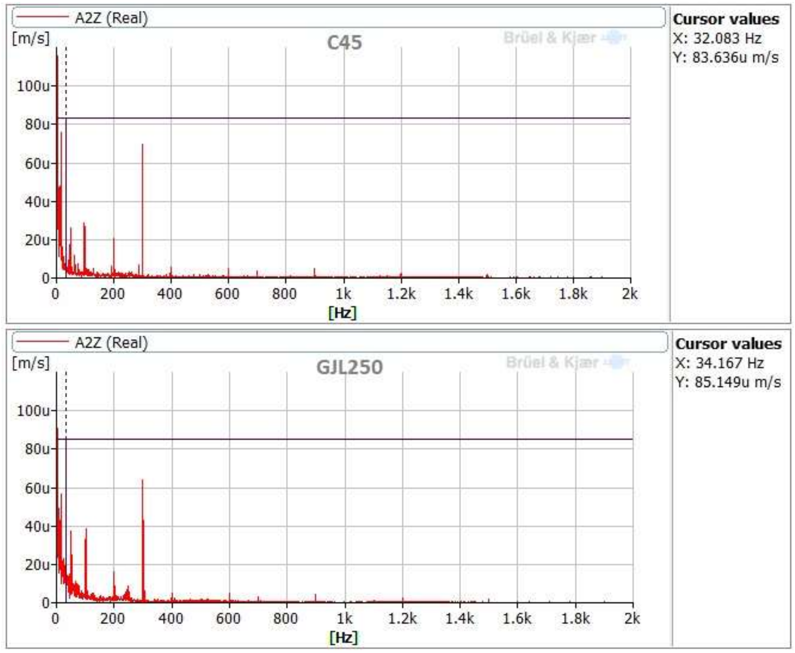

Figure 8. Vibration spectra measured at point 2, in Z direction (direction of the burnishing force), with a NVABB force of 90 N

In tests without vibration assistance, the amplitudes corresponding to points P1 and P2 in burnishing force direction (Z), are higher than amplitudes corresponding to the other two directions: burnishing feed direction (X) and vertical direction (Y). This can be justified because these points are at the end of the tool and they receive all the effort of the burnishing operation. In the case of C45, the amplitudes at point P3 are greater than at points P1 and P2, while in GJL250 the amplitudes at the three points are similar. At the point P3, the highest amplitude is in Y (vertical) direction, which may be due to at the time of burnishing; point P3 is in the distal part of the tool, as shown in Figure 1(b).

Figure 9 compares the spectra, measured with a burnishing force of 90 N of both materials, with and without vibration assistance, at point P3. This figure shows Y-axis only because all directions show the same frequency peaks with very similar amplitudes. Additionally, signals measured without vibration assistance have a similar behaviour to the vibration-assisted ones.

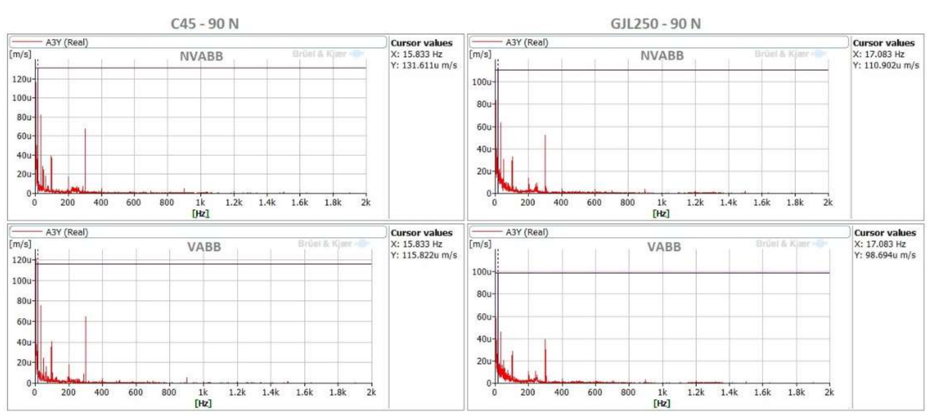

Figure 9. Comparison of spectra of both materials, using VABB and NVABB, measured at Point P3, in Y (vertical) direction and with a burnishing force of 90 N

Two burnishing forces were used in tests with C45 steel. No differences between the signals monitored in both conditions were noted. As example of this, Figure 10 shows the spectra corresponding to different points and measurement directions. All these spectra correspond to measurements without vibration assistance.

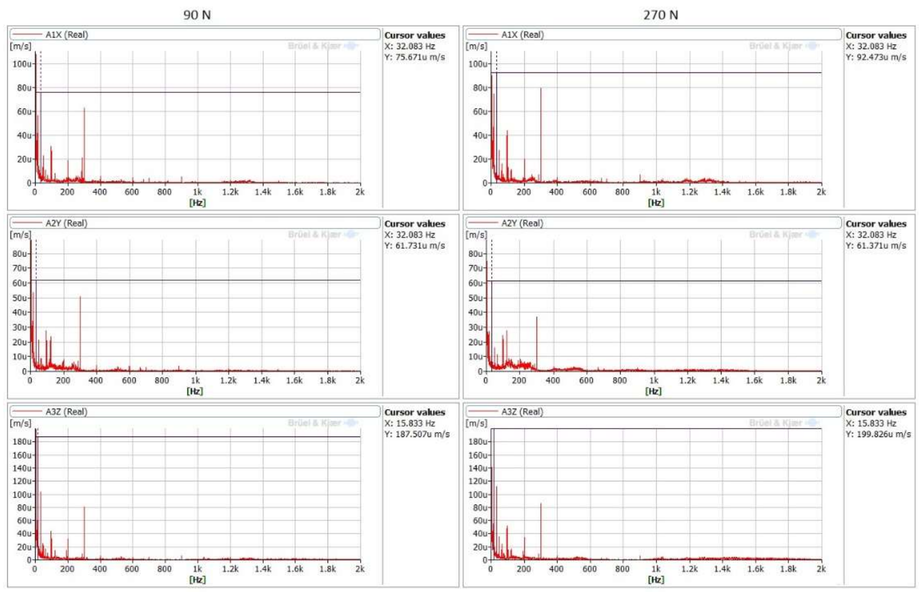

Figure 10. Comparison of spectra of C45 with burnishing forces of 90 N and 270 N, without vibration assistance

Additionally, measurements without burnishing feed were carried out with both materials, with the same conditions before specified. The duration of each one of these measurements was 3 minutes. The analysis of these tests shows similar results to the ones obtained with burnishing feed. The same frequency peaks appear, with very small amplitudes. The only difference is the possible excitation of natural frequencies in the range between 800 Hz and 1400 Hz, but with very low amplitudes. Figure 11 shows an example of these signals.

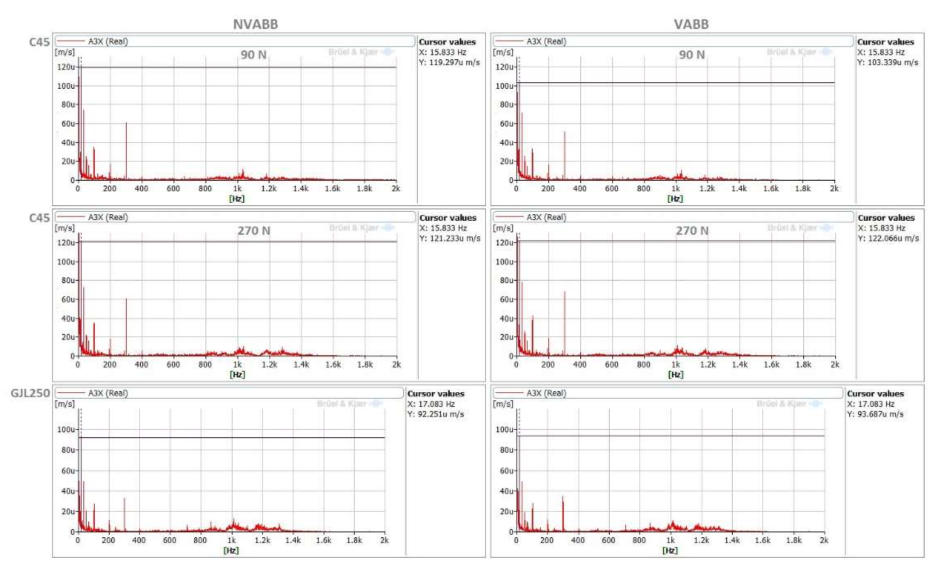

Figure 11. Measurements in burnishing without feed

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The vibration measurements in the lathe test bed show a normal behaviour of the machine. Components that interfere with those obtained in the tool are not noted, but a possible excitation of the natural frequencies between 800 Hz and 1400 Hz is noticeable, but with very low amplitudes.

Figure 12 shows some signals measured in the lathe test bed during the burnishing of the steel specimen. Comparing the signals measured with vibration assistance in the horizontal (H), vertical (V) and axial (A) measurement positions, a very similar behaviour between them is noticeable and the amplitudes are very low. Looking at the not assisted vibration spectra measured in horizontal direction at burnishing forces of 90 N and 270 N (Figure 12) no differences appear between them, consequently the burnishing force does not affect to the horizontal vibrations of the lathe test bed. Additionally, no differences appear between horizontal spectra with and without vibration assistance with both burnishing forces in Figure 12, then there is no influence of the vibrating assistance in the lathe test bed. This is expected according to the tool design, lathe rigidity and the test bed points where the measurements have been performed.

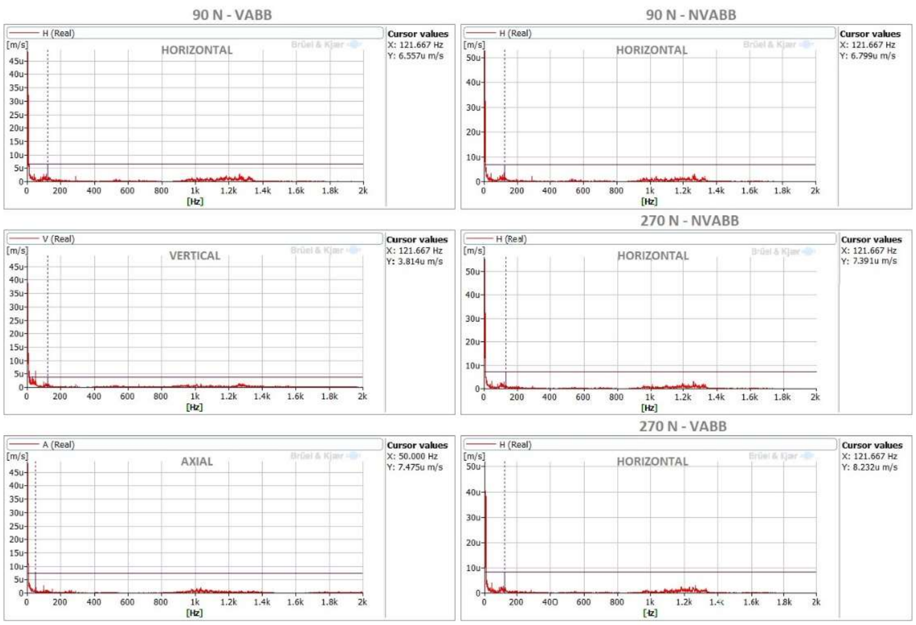

Figure 12. Spectra measured in lathe test bed at different loads and different measurement positions

3.3. Acoustic emission monitoring during the burnishing process

Figure 13 shows acoustic emission time histories in different processes. Figure 13(a) shows the background noise. Figure 13(b) shows the acoustic emission signal during the burnishing process of the C45 steel specimen, with a burnishing force of 90 N, without vibration assistance. Finally, Figure 13(c) shows the C45 burnishing, with a burnishing force of 90 N, with vibration assistance. Figures 13(a) and 13(b) are very similar, then, burnishing process without vibration assistance does not produce any acoustic emission. On the contrary, a clearly noticeable signal appears in Figure 13(c), corresponding to the vibration assisted burnishing process. This is due to the acoustic emission sensor detects the assisting vibration signal. No acoustic emission different from that produced by the vibration assistance appears, consequently, ball burnishing process does not produce any damage in the material.

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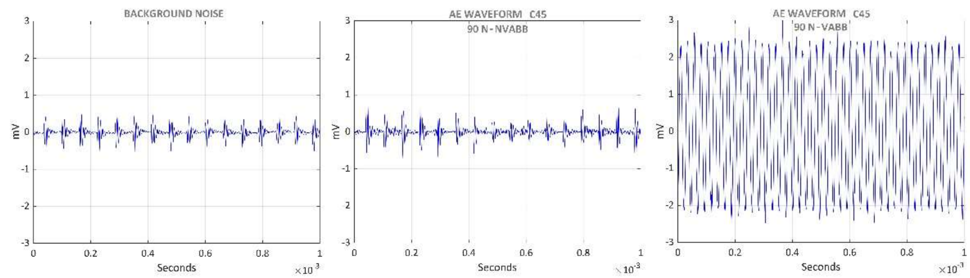
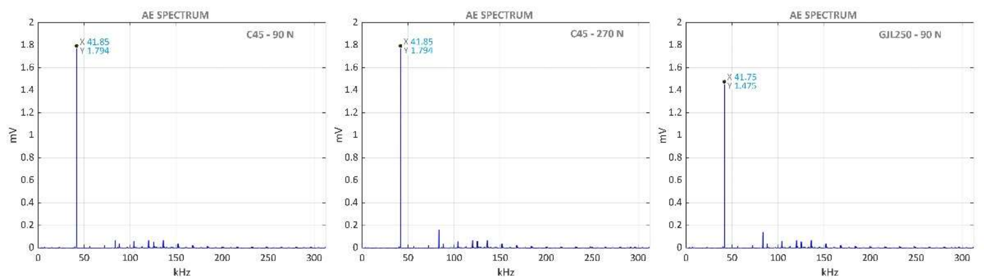


(a) (b) (c)

Figure 13. AE time histories of C45 during different conditions: (a) background noise; (b) NVABB; (c) VABB

Figure 14 shows the AE spectra corresponding to the VABB of both materials, burnished with different forces: (a) C45 steel specimen with 90 N, (b) C45 steel specimen with 270 N, and (c) GJL250 grey cast iron specimen with 90 N. In all figures, the frequency corresponding to the vibration assistance is the only noticeable peak. This is consistent with what was found in a previous work [9].



(a) (b) (c)

Figure 14. AE spectra corresponding to different VABB (a) C45 steel with 90 N; (b) C45 steel with 270 N; (c) GJL250 cast iron with 90 N

The vibration assisting frequency is very stable. Its variation is 100 Hz that corresponds to 0.25 % of the frequency. The level is the same in both VABB for C45 steel then the burnishing force does not influence it. The vibration level in case of GJL250 VABB is lower that the C45 ones, due to the high GJL250 internal damping [27].

3.4. Operating Deflection Shape

An ODS of the tool in the burnishing process of C45, force of 90 N and without vibration assistance has been performed. The frequency of 32 Hz was selected because it has a noticeable displacement and an acceptable background noise. Figure 15 shows the ODS. Figure 15(a) is a lateral view and shows the movement in vertical direction. Red lines correspond to extreme positions and blue lines correspond to the mean position. A rotatory movement around of the centre of the tool is clearly noticeable; with an amplitude of the extremes around 0.6 μm. Figure 15(b) shows the plant view. A translation movement in the burnishing feed direction of about 0.5 μm amplitude is also noticeable. In order to knowing the movement in the axis tool direction, a zoom around the zero point has been performed (Figure 15(c)). A displacement of about 0.9 μm is noticeable.

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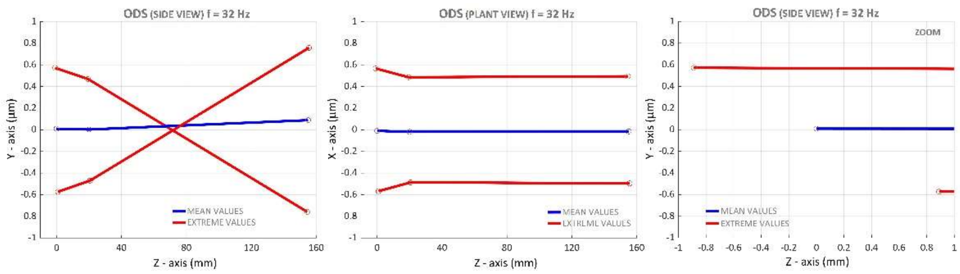

(a) (b) (c)

Figure 15. ODS of the tool at 32 Hz. (a) Lateral view. (b) Plant view. (c) Zoom of lateral view.

4. Conclusions

Impact tests performed in the tool have permitted to determine its natural frequencies. Signals were measured and processed up to 5 kHz due to measurement system limitations, but no natural frequencies higher than 2 kHz were noted. Consequently, it can be said that the high frequency that appears in the process is what the tool provides.

Results of the impact tests with load between specimen and tool show that this load affects to the system rigidity and consequently, to its natural frequency. However, there is no significant differences between responses with different loads. The values of the natural frequencies measured in the tool are about 5 % of 40 kHz that is the vibration assisting frequency.

Referring to the vibration measurements in operating conditions, no differences between burnishing of both materials (C45 and GJL250) appear, except in the frequencies related to the rotation speed during the burnishing. The components that are related with the mechanical and electrical operation of the lathe show very low amplitudes, lower than ones that the standard consider suitable for a new machine. There are no differences between VABB and NVABB processes in the vibration measurement results in any case.

Comparing the vibration levels in the different directions in NVABB tests, the influence of the burnishing force is demonstrated because the vibrations measured in the tool axis have higher amplitudes than those that correspond to the other directions.

The amplitudes of the signals measured at the rear point (P3 of Figure 1(b)) are slightly higher than those measured at the frontal part (P1 and P2). This may be due to the point P3 is the free end of the tool when the burnishing process start.

All measurements performed with and without a feed movement of the tool show similar results.

The results obtained in the lathe bed accelerometers show an acceptable vibration level. Therefore, the VABB results are independent of the state of the machine.

Natural frequencies appear in a wide band (between 800 Hz and 1400 Hz) during the burnishing process appear at the rear point and in the lathe bed, with a very low amplitude. This behaviour is similar in both materials (C45 and GJL250), it is not affected by the presence or absence of vibration assistance nor by the burnishing force.

The ODS shows a pitching motion of the tool in the vertical direction that overlaps with a translation in the horizontal direction. However, the amplitudes of these movements are under the limits that could affect the burnishing process.

Referring to the AE measurements, the only measured signal is the ultrasonic vibration assistance. Consequently, no damage is produced in the material in any case and the AE permits the frequency characterization of the assisting ultrasonic vibration.

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Include the digital object identifier (DOI) for all references where available.

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