Spectral Analysis of Forces During a Ball-burnishing Process Assisted by Vibrations

G. Gomez-Gras, J.A. Travieso-Rodriguez, J. Lluma & R. Jerez-Mesa
Escola Universitària d'Enginyeria Tècnica Industrial de Barcelon. Consorci Escola Industrial de Barcelona Universitat Politècnica de Catalunya. Barcelona TECH. Mechanical Engineering Department. (Spain)

ABSTRACT: One of the most recent innovations in manufacturing engineering has been the assistance of machining, finishing and superfinishing processes with vibrations as a means of improvingthe mechanical properties ofthe workpieces. Furthermore, vibrations have also shown their potential in improving and optimisingthe productivity parameters of a manufacturing process, by making the cutting and deforming operations faster and more efficient. This paper focuses on a vibrations-assisted ball-burnishing operation, offering an analytical model to explain how vibrations affect that process, and supporting them with experimental measures of the energy induced into the system by a self-design vibrating tool. Precisely the lack of commercial ball-burnishing tools assisted by vibrations, and the consequent ignorance about how the process would work, was the motivation for the development of this work. In effect, the tool used for the purpose of this paper has been self-designed and manufactured, thus offering an exclusive source of information to the matter. This paper deals with the ball burnishing of two different materials (aluminium alloy 2007 and steel alloy 1.1181) and evaluates the effectiveness of burnishing in the presence of vibrations, estimating the addition of energy they produce to the system.

1 INTRODUCTION

The plastic deformation process of a material by an acting force is described through its stress-strain curve. When the yield point is reached, the material deforms to a certain extent. The yield strength is not a purely intrinsic property of a material, for it has a different value depending on the exact composition and metallurgic state of the alloy. Some of the factors that influence its value are: chemical composition, preparation processes with which the material has been treated, and its microstructure, among others. The yield strength may change if the deforming process is being assisted by an external source of vibration (Kozlov et al. 1995).

This phenomena is called acoustoplasticity and occurs when a vibrating force adds its effect to that of a deforming force, and contributes to the deformation of the material's structure. That way, dislocations of its microstructure reallocate more easily, and that translates into a decrease of the yield point. In other words, the material can be deformed by the application of smaller forces.

The optimisation and improvement of manufacturing processes can be fulfilled also with other external agents, such as laser or electromagnetic pulses. Along with vibrations, the effective incorporation of these agents to a conventional manufacturing process is one of the challenges of today's industries.

Scientific literature and commercial houses, offer progressively in-situ improved tools (Tian & Shin 2007, Shiou & Ciou 2008). Brehl & Dow (2007) have made a vast assessment and state of the art of available tools assisted by vibrations, with which they have reached a significant relevance in scientific bibliography.

From all the conventional manufacturing and deforming manufacturing processes, ball-burnishing is the one to have incorporated more recently the vibrations assistance. The so called vibrations-assisted ball-burnishing process (VABB), has no current patented or commercial tool. Therefore, for the aim of this study, a newly designed tool has been used, based on the one published by Gomez-Gras et al. (2014a).

The VABB process has already been tested by the authors, obtaining very positive results. Comparing mechanical properties of specimens burnished with and without vibrations Introducing vibrations into the process. R_a is improved about 70% in the case of aluminum and about 50% in the steel, when the burnishing is performed with vibration. Microhardness also shows a 6% improvement in aluminum and 5% in the steel, and residual stresses are also better at around 10% for aluminum and 8% for steel. (Travieso-Rodríguez et al., 2014, 2015).

Starting from this point, in which empirical improvement of mechanical properties of the materials has been proved, this paper explores a mathematical model to assess the magnitude of increased energy in the system due to vibrations, and compare it with experimental measures. The materials used for the purpose of its characterisation are 2007 aluminium and 1.1181 steel, widely used in the industrial field. The obtained results will allow to show the advantages of VABB process, opposite to its conventional counterpart (non-vibrations-assisted ball-burnishing, NVABB).

2 BALL-BURNISHING TOOL AND SPECIMENS

2.1 Tool description

Figure 1a shows the tool used for the experiments of this paper. The cold plastic deformation is performed by a 10 mm diameter ball made of hardened chrome steel (100Cr6), covering a range of hardness of 55 – 66 HRC. That ball rolls freely during the whole process, independently of the applied deforming force.
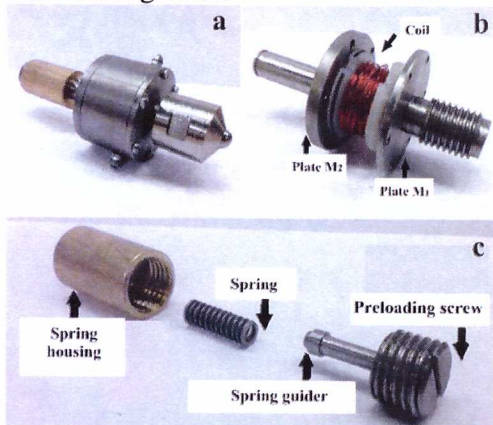

Figure 1. Ball-burnishing tool assisted with vibrations.
a. Compact tool.
b. Detail of coil that induces vibrations into the system.
c. Parts of preloading system.

Vibrations come from an external source, namely a coil rolled on the body of the tool (Fig. 1b). The generated magnetic field deflects the M_1 and M_2 plates. A cylindrical cover protects the coil, and is attached to the system between both plaques, responsible for transmitting the vibration to the burnishing ball. By loading the calibrated spring, the transmission of the vibrations are assured. The whole tool is assembled then with an ISO cone, unifying the system and making it move as a single object, and subjected only to the burnishing force defined for the operation.

The tool is therefore, a compact system able to transmit a homogeneous tool to the workpiece. It is a flexible system as well, for when the coil is not induced by electrical current, the tool can be used for a conventional burnishing process, like the one performed by commercial tools. Furthermore, the tool can be assisted by the coil and therefore been used for a VABB process.

2.2 Materials and specimen preparation

The tests have been performed on 2017 aluminium and 1.1181 steel alloys (coded by EN standards), previously machined in a CNC OPTIMAB 900 (SOMAB) machining centre. Properties were extracted from Travieso-Rodríguez (2010), and are shown in Table 1.

Table 2 shows the actual machining parameters in a previous preparatory phase consisting in a face milling, to establish the same starting conditions for the four tested specimens in terms of surface roughness and residual stress state. Lateral pass for each pass was 2 mm.

Table 1. Properties of materials, determined experimentally.

Properties	Aluminium 2007	Steel 1.1181
Density, ρ (g / cm^3)	2.79	7.84
Young's Modulus, E (GPa)	76.1	211.8
Limit stress to pure cut, K (MPa)	368	1117
Self-hardening rate, n (n/d*)	0.260	0.190
Pure tensile yield point, γ (MPa)	140	416
Compressibility Modulus, C (GPa)	160.091	76.652

*non-dimensional

As stated, four specimens were prepared, each pair made of one of the objective materials. At the same time, one of the specimens were subjected to a conventional NVABB process and VABB one, thus resulting in four different specimens in terms of materials and burnishing state.

Table 2. Milling parameters for the preparation of workpieces.

End mill radius	Ø 8 mm
Cutting speed	3000 min^{-1}
Feed	1380 mm / min
Depth of cut	0.5 mm

Burnishing parameters are presented in Table 3. Two of them, namely lateral pass width and ball diameter, were kept constant (Travieso-Rodriguez et al. 2011), and three of them were taken as variables, that is:

– Burnishing force (F), directly related to the pre-load of the tool through the compression of its inner spring.

– Feed (V_a), relative speed between the workpiece and the table to which the specimens are attached, thus moving together.

−Number of passes (*n*). In the operations undertaken with 3 and 5 passes, these were executed exactly following the same previous path.

Table 3. Variable and fix burnishing parameters.

Variable parameters	Levels		
Burnishing force, F (N)	75	90	100
Feed, V_a (mm / min)	400	500	600
Number of passes, n	1	3	5
Fixed parameters			
Lateral pass width, b	0.08 mm		
Ball diameter	10 mm		

The burnishing operations were performed in the same CNC machine as previous milling. When assisted by vibrations, a vibrations generator was attached to the tool, assisting it with a 2 kHz vibrations.

3 MAIN EFFECTS OF ASSISTED BURNISHING WITH RESPECT TO CONVENTIONAL BURNISHING

3.1 *Forces taking part in the system*

Assisting the ball-burnishing process with vibrations increases the forces acting in the system, making the process more practicable. This phenomena has been explained by Yin & Shinmura (2004).

At a microscopical level, the energy dissipated by the vibration waves release the dislocations, that is, the pollution located among the metal grains that compose the microstructure of the material, as explained by Holstein (1959). As shown experimentally below, the most relevant consequence of this newly introduced energy is that the results obtained with one pass of the VABB process, are the same as with five passes of the NVABB process.

The value of increase of energy introduced in the system through the vibrations can be estimated. For the VABB process, the total force applied to the material F_t, is the result of an addition of the preload of the tool F_m and a sinusoidal force produced by the vibrations and variable in time, F_v. Lastly, the vibrations due to the environment in which the workpiece is being burnished (η) must be considered as well. F_t can be the calculated as shown in Equation 1.

$$F_t = F_m + F_v(t) + \eta \tag{1}$$

The force of the burnishing tool can be assimilated to the one applied by the spring, and therefore calculated according to Hooke's Law (Eq. 2).

$$F_m = k(x_1 + x_2) + F_0 \tag{2}$$

where k = spring constant; x_1 = compression length of spring before the coil is excited; x_2 = average variation of compression length once the coil is excited; and F_0 the pre-load of the spring.

Two of the values of Equation 2 have been measured and are known: k = 15.22 N/mm and F_0 = 52.17 N.

Figure 2 shows the static tool calibration curve. The range of values to be used during the experiments is located between 0.25 and 3.75 mm, where the curve has essentially a linear behaviour. Equation 2 fits to this behaviour in the described context, with x_2 = 0, as the coil is not excited.

When the vibration is added to the system, the tool interacts with the workpiece, and the spring absorbs the displacements, x_3, and generate a new oscillatory force F_v, also dependent on the spring constant (Eq. 3).

$$F_v = k\, x_3(t) \tag{3}$$

Inserting (2) and (3) in (1), the equation to estimate the total force acting on the workpiece during the VABB process is obtained.

$$F_t = k(x_1 + x_2 + x_3(t)) + F_0 + \eta \tag{4}$$

The traditional NVABB process would be a particular case of Equation 4 where x_2 and x_3 equal zero.
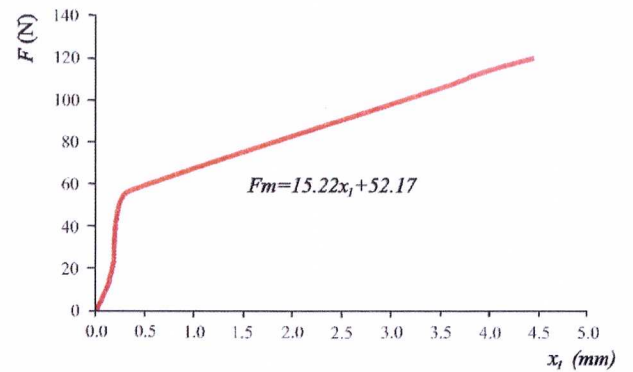

Figure 2. Calibration curve of ball-burnishing tool.

Parameters taking part in Equation 4 were assessed by performing the already explained burnishing processes, with the assistance of vibrations and without it, and measuring the forces during both cases with a Kistler force board, model 9257B. This device is able to monitor the process in real time and takes record of the value of applied forces. Results are shown in Table 4, and were taken using a sampling frequency of 10 kHz. The average values of force induced to the system when the tool is vibrating ($\Delta F_{v,ave}$) are around 5 N.

Table 4. Forces measured for different pre-load values of the tool (F_t), during the VABB and NVABB processes on aluminium and steel specimens.

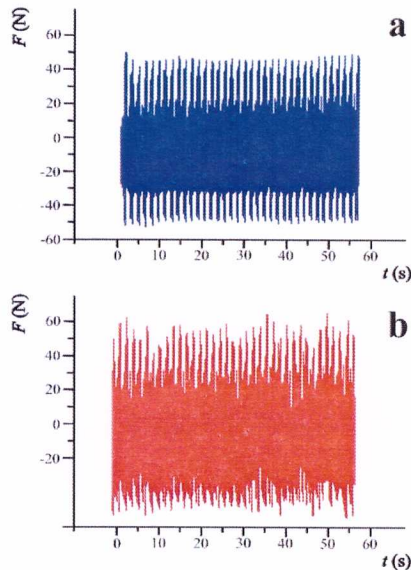| x_l (mm)	1.50	2.50	3.10	1.50	2.50	3.10
Static state						
$F_{preload}$ (N)	75	90	100	75	90	100
VABB process						
$F_{t,average}$ (N)	80.63	93.20	105.10	80.08	94.87	104.11
$A_{average}$ (mm)	6.23	6.76	6.78	8.43	7.56	5.62
$F_{deviation}$ (N)	4.00	4.43	4.33	6.48	5.92	3.25
NVABB process						
$F_{t,average}$ (N)	74.72	86.38	100.50	74.81	90.22	100.04
$A_{average}$ (mm)	4.17	2.88	2.78	3.90	3.49	3.88
$F_{deviation}$ (N)	2.81	2.36	1.80	2.70	1.19	2.88
$\Delta F_{v,ave}$ (N)	5.91	6.82	4.60	5.27	4.65	6.07

Figure 3. Force signals, measured during the burnishing of the steel specimens.
a. NVABB process
b. VABB process

A detailed study was performed on the steel specimens while they were being burnished, applying on them the maximum load. Figure 3 shows the measured vibration signals. They are oscillatory signals product of the previous milling operations and, in the case of the VABB process, the addition of the vibrating action of the coil.

3.2 Frequency domain

A Fourier transform applied on signals in Figure 3 takes them to the frequency domain. The purpose of the transformation is being able to distinguish more clearly the differences between both of them (Fig. 4).

Although the difference between the amplitudes of both signals is not especially remarkable, it is always bigger for the values of the assisted process, and certain frequencies show peaks with respect to the conventional burnishing operation. The most remarkable difference is found for 2.02 kHz, which is the coil's working frequency, and its fist harmonic, 4.05kHz. Nevertheless, similarities between both signals can be noted. Low frequencies show the same peaks corresponding to the vibration modes of the different elements of the system. Figure 5 shows an enlargement of the signal, so that main peaks can be distinguished more clearly.
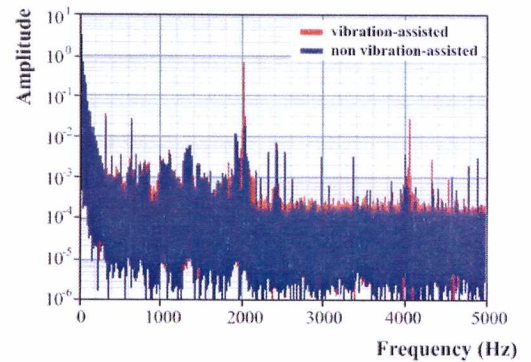

Figure 4. Fourier transform of forces measured during the burnishing of Steel specimens.
Red signal: VABB process
Blue signal: NVABB process

During the burnishing process, the tool experiences a linear movement which is equivalent to the desired dimension to be burnished. Then comes a short pause and the movement is resumed perpendicular to the burnishing direction, a length equal to the lateral pass width. All these movements produce a change in the signal, and are appreciable in the form of peaks every 15 Hz. These intervals are periodic.
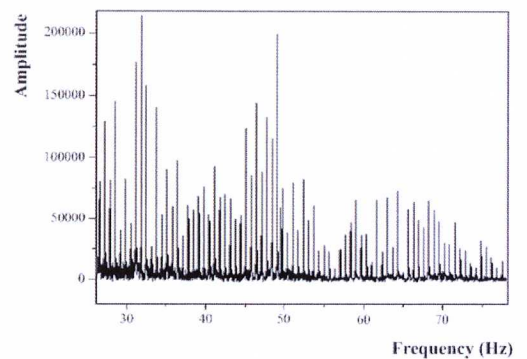

Figure 5. Detail of lowest frequencies for VABB of steel.

Additionally, because the tool is a resonator, it is sensitive to the movements of the system, fact that explains the presence of more sporadic peaks every time it starts working although the coil is not excited. That is the case of the NVABB process. As expected, those peaks grow when the coil is excited. The other relevant maximum is found in the 50Hz, and can be interpreted as the noise caused by the electric network to which the machinery is

connected. Mechanical inertias are not being considered for this analysis.

3.3 Energy dissipation of the tool

The value of the energy that the tool dissipates when vibrating at its working frequency is an important value for the characterisation of the assisted process. The registered signal computed after applying a band-pass filter to both resonant frequencies, enables to estimate the values of the $F_v(t)$ function added by the vibrations.

It is difficult to accurately determine the energy provided throughout the system when it is vibrating with respect to when the coil is not energized. However, it can reach estimated based on the conservative vibratory condition. Is, according to the principle of conservation of energy, the maximum kinetic energy must equal the maximum potential energy, or energy of maximum deformation.

The energy dissipated by the burnishing tool, as well as the applied force, have two fundamental components. That energy can be approximated to the maximal potential energy delivered by the system, as already explained. The first component is the dissipation by the tool when not vibrating, and the second one is caused by the electromagnetic field of the excited coil (Eq. 5).

$$E_p = \frac{1}{2} k (x_1^2 + x_2^2) + \frac{1}{2} k \, x_3^2 \qquad (5)$$

The vibration induced by the coil in the tool is produced by its displacement when excited, x_3. Its value can be obtained as the difference of the maximum amplitudes of the measured forces, during the conventional process, and the one assisted by vibrations. In our case, the average surface roughness (R_a) has been taken as an approximation of the actual displacement of the coil, considering that the only difference between them is the change produced by the deformation, and that the neutral line is identical. R_a would actually be a very good estimator if the only change in the workpieces dimensions would be the one created by the assistance of the vibrations.

The values of x_3 found for each testing conditions, and the potential energy derived from that variation in the amplitude of vibrations, E_{pv}, can be appreciated in Figure 6. The fact of assisting the tool with a vibration depends on the value of each applied force, and its behaviour is different in each material. Aluminium has a higher x_3 value (Figure 6a), and therefore, the energy added to the system is slightly higher than in the case of steel. For this material, the difference of amplitudes is lower, and as a consequence the energy delivered by vibration is lower (Figure 6b).
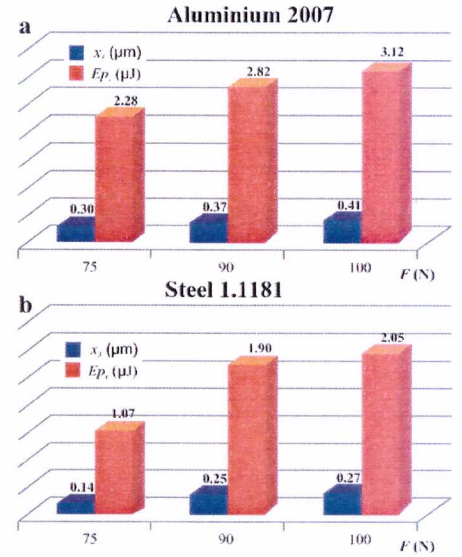

Figure 6. Differences of amplitudes, x_3, between the NVABB signal and VABB signal, and corresponding energy caused by the vibration, E_{pv}.
a. Aluminium.
b. Steel.

During the process, the energy is assumed to be transmitted from the tool to the burnished workpiece in a high percentage of efficiency.

$$E_{material} \approx E_{tool} \qquad (6)$$

If the material's behaviour is comparable to that of a spring, that is, of uniform deformation, the potential energy it receives is due to its deformation according to Equation 7.

$$E_{material} = \frac{1}{2} k_{material} e^2 \qquad (7)$$

Where e = dimensional difference between the initial milled surface and burnished surface, according to Travieso-Rodríguez (2010), and the deformation constant of the material, $k_{material}$, can be calculated through Equation 8.

$$k_{material} = C \, A_c \, p \qquad (8)$$

where C = compressibility ratio (Table 3); A_c = contact area ball-workpiece; and p = depth of penetration of the ball.

From this point on, the value of the burnishing dimensional effect, e, can be represented, as a function of the value of the energy transmitted from the tool to the material (Eq. 9), thus quantifying an approximation of the magnitude of the change in surface roughness of the burnished workpiece.

$$e = \sqrt{\frac{2 \cdot E_{tool}}{C \cdot A_c \cdot p}} \qquad (9)$$

291

Figure 7 shows the results obtained for the materials used for this paper, and the different burnishing forces. For a better comprehension, thenumerical values of burnishing dimensional effect are represented in Table 5.
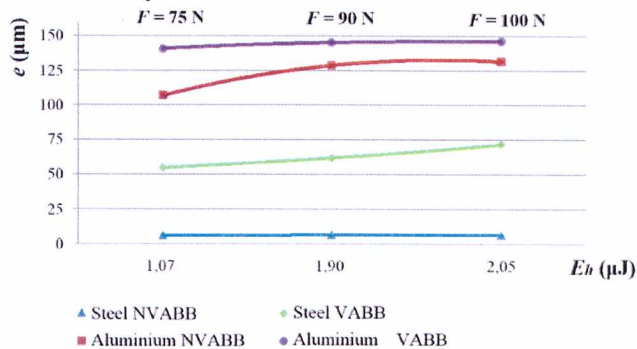

Figure 7. Resulting*e*, calculated with Equation 9, based on the energy added by the tool for each of the studied forces.

Table 5. Analytical values of burnishing dimensional effect, e(μm), also represented graphically in Figure 8.

	Steel		Aluminium	
	NVABB	VABB	NVABB	VABB
F = 75 N	6.29	106.68	54.50	140.88
F = 90 N	6.64	129.00	61.48	145.27
F = 100 N	6.99	131.83	71.24	146.07

Results obtained show that the assistance of the burnishing process with vibrations working at a frequency of 2.02kHz are of about 5 N (Table 5). That implies that the final properties of burnished workpieces should not be influenced by the presence of this additional load during the operation. Nevertheless, results obtained in Gomez-Gras et al. (2014a,b) contradict this statement, mainly due to the fact that the effect of the vibrating force is not due to the increase of load, but to the inducing elastic energy in the solid that helps depinning the dislocations an facilitates plastic deformation.

4 CONCLUSIONS

This study has analysed analytically and experimentally, the consequences of adding a low-amplitude vibration in a ball-burnishing tool as an assisting mechanism for the process, showing interesting results in terms of prospects.

The increase in the energy induced by the vibrations has been estimated as an approximation of the additional potential energy. Aluminium has proved to be more sensitive to vibrations than steel, for which the energy added by the vibrations is lower.

Although the results are not in a great magnitude better, the influence of the vibrations on burnishing has been proved. Increasing working frequency may lead to very successful results in the future.

REFERENCES

[1] Brehl, D.E. & Dow, T.A. 2007. Review of vibration-assisted machining. Precision engineering 32(3): 153–172.
[2] Gomez-Gras, G. et al. 2014. Study of a ball-burnishing vibration-assisted process. Proceedings of the Institution of Mechanical Engineers. Part B: Journal of Engineering Manufacture. doi:10.1177/0954405414526383
[3] Travieso-Rodriguez, J.A. et al. 2014. Experimental study on the mechanical effects of the vibration-assisted ball-burnishing process. (Submitted).
[4] Travieso-Rodriguez, J.A. et al. 2015. Effects of the ball-burnishing process assisted with vibrations in G10380 steel specimens. (Submitted).
[5] Holstein, T. 1959.Theory of ultrasonic absorption in metals: the collision-drag effect. Physical Review 113(2): 479–496.
[6] Kozlov, A.V. et al. 1995.On the additivity of acoustoplastic and electroplastic effects. Materials Science and Engineering190(1–2): 75–79.
[7] Shiou, F.J. & Ciou, H.S. 2008. Ultra-precision surface finish of the hardened stainless mold steel using vibration-assisted ball polishing process. International Journal of Machine Tools & Manufacture 48 (7–8): 721–732.
[8] Siua, K.W. et al. 2011. New insight on acoustoplasticity-ultrasonic irradiation enhances subgrain formation during deformation. International Journal of Plasticity 27(5): 788–800.
[9] Tian, Y. & Shin Y.C. 2007. Laser-assisted burnishing of metals. International Journal of Machine Tools & Manufacture 47(1): 14–2.
[10] Travieso-Rodriguez, J.A. 2010.Estudio para la mejora del acabado superficial de superficies complejas aplicando un proceso de deformación plástica (bruñido con bola). PhD Thesis. Universitat Politècnica de Catalunya, Barcelona, Spain.
[11] Travieso-Rodriguez, J.A. et al. 2011. Improving the Surface finish of concave and convex surfaces using a ball-burnishing process. Materials and manufacturing Processes 26(12): 1494–1502.
[12] Yin, S. & Shinmura, T. 2004. A comparative study: polishing characteristics and its mechanisms of three vibration modes in vibration-assisted magnetic abrasive polishing. International Journal of Machine Tools & Manufacture 44: 383–390.