THE EFFECT OF THE VELOCITY OF ROTATION IN THE VIBRO-GRINDING PROCESS ON THE SURFACE STATE

K. HAMOUDA [1], *H. BOURNINE* [1], *M. A. TAMARKIN* [2], *A. P. BABICHEV* [2], *D. SAIDI* [3], *H. E. AMROU* [1]

[1] *University of Sciences and Technology, Bab Ezzouar, Algeria;*
[2] *Don State Technical University, Rostov on Don, Russia;*
[3] *Algiers Polytechnic School, Algeria*

This paper considers one of the surface mechanical attrition treatment processes, namely the vibro-grinding technique. It is based on causing superficial plastic deformation to the surface of the treated part by bombarding it with granular flexible particles. This process is useful and reliable when high surface quality is required. The present work focuses on the effect of velocity on the outcomes of the centrifugal rotational process. Two aspects are considered, precisely, the surface roughness and its hardness after treatment. Both the mathematical model and obtained experimental results demonstrate the dependence of these two aspects on the speed of the chamber rotation. While this later has a beneficial effect on the hardness it affects negatively the surface roughness.

Keywords: *roughness, hardness, vibro-grinding.*

With the continuous advances in industry comes a need for highly complex parts as well as precision. Surface roughness and precise tolerances are hard to achieve in complex and small parts, therefore, new processing methods are developed and implemented continuously. One of these techniques is the surface mechanical attrition treatment process by vibro-grinding using granular flexible particles. In recent years the technique has been increasingly used in various industries because of its ability to treat different surfaces, which allows its use on parts of different shapes and sizes. In addition it provides a high quality surface finish.

The treatment is based on causing plastic deformation to a thin surface layer by bombarding it with granular flexible particles. Compared to other methods of surface treatment, this method has many advantages: it preserves the integrity of the fibbers and forms a fine-grained structure in the surface layer (a thin superficial layer). Further, it does not cause any thermally induced defects hence offering uniform (stable) surfaces.

The work conducted for this paper focuses on the effect of the treatment frequency on the outcome, namely on the roughness and hardness of the processed piece. The vibration frequency affects directly the velocity of all the particles in the treatment chamber, which in turn affects the impact energy hence changing the final state of the treated surface. The first aspect considered is the roughness which is quantified through its average. A mathematical formulation relating the average roughness to the speed of rotation is presented [1–3] followed by a set of experimental results to validate the analysis. The second aspect is the effect of the rotation speed on the hardness of the treated piece which is quantified through the depth of the hardened layer as presented in [4, 5].

Vibro-grinding mechanisms. The mechanism involves bombarding the surface of a processed piece by small particles. The aim of the process is to deform the asperities

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Corresponding author: HAMOUDA K, e-mail: hamoudakhaled_2000@yahoo.fr

of the treated surface hence reducing its roughness. Further, this process introduces plastic deformation to the surface increasing its hardness.

The process can be achieved using different methods. Each of these methods has its particular uses, advantages and disadvantages. Here we are considering two major mechanisms which are the vibrating hardening process (VHP) and the Centrifugal rotating process (CRP).

The particles that can be used could be of different shapes and sizes and made of different materials. The specific characteristics for each treatment are determined by the nature of the treated piece and the desired outcome.

The vibro-grinding process (VGP). The processed part is placed in a treatment chamber filled with particles (see Fig. 1) [1]. The chamber is made to vibrate which causes its content to move in all directions causing micro-impacts (collisions and sliding) of the particles and the surface of the processed pieces. The schematic of vibratory process is illustrated in Fig. 1.

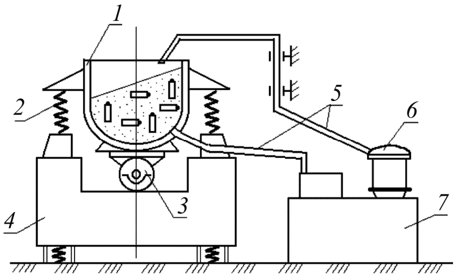

Fig. 1. A schematic of the VGP machine:
1 – treatment chamber; *2* – spring;
3 – actuator (vibrator); *4* – base;
5 – pipes for chemical additives and water;
6 – pump; *7* – tank.

The work-pieces can be either attached to the work chamber or free to move inside it. During the process the content of the chamber rotates inside it under the effect of its vibration. This rotation ensures a uniform treatment to the treated pieces. Otherwise the pieces placed at the bottom of the chamber would receive more impacts than the ones at the top.

The chamber is supplied with a liquid that serves as both lubricant and coolant either periodically or continuously.

VGP is a widely used process thanks to its ability to treat pieces of complex shapes and small sizes. Further, many pieces can be treated at once thus saving time and reducing cost.

Centrifugal-rotational process (CRP). The treatment chamber *1* is made of a fixed bottomless cylinder and a rotating plate *2*. During treatment the bottom plate is subject to a rotary motion around a vertical axis (Fig. 2). The centrifugal forces push the content of the chamber against its walls [3].

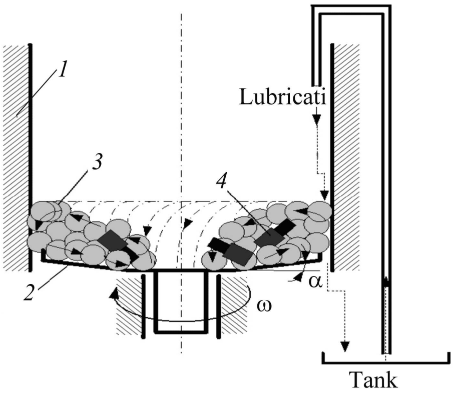

Fig. 2. Centrifugal rotary machine diagram:
1 – treatment chamber; *2* – rotating plate;
3 – granulated filler; *4* – treated details.

The CRP is a high intensity process in comparison to the VHP which makes the treatments faster. The equipment is fairly simple and easy to make. The process also offers the possibility of processing different parts simultaneously.

Theoretical modelling. The surface roughness change in a CRP depends on the mechanical properties of the grinding particles, the rotational velocity of the machine, the loading volume of the treatment chamber, the mechanical properties of the treated material including its initial roughness and other factors. In this section two models quantifying the change in roughness and hardness are presented.

Roughness evaluation. The surface roughness of a piece that underwent the treatment is a result of the traces left by the particles that hit the surface. These traces are elliptic with different depths and radii. The depth of the impact of a single particle $h_{\max}$ can be defined as:

$$h_{\max} = 2V_{eff} R \sin\alpha \sqrt{\frac{\rho_p}{3K_s C\sigma_s}}\,, \tag{1}$$

where V_{eff} is the effective speed of the particle (which depends on the type of the process); R is the particle radius; α is the impact angle on the work-piece surface; ρ_p is the density of the particle material; K_s is an empirical factor related to the work-piece roughness; C is the friction coefficient of the treated surface; σ_s is the elasticity limit of the work-piece material [1–3].

The effective speed can be calculated in the case of the CRP method as follows:

$$V_{eff} = V_{ch} \cdot K_v\,,$$

where V_{ch} is the chamber velocity $V_{ch} = \omega$, with ω – the chamber angular; K_v is the velocity reduction coefficient.

$$K_v = a^L \approx 0.9877^L\,,$$

where L is the distance between the axis of rotation and the particle.

The area of particle impact on the wok-piece surface takes an elliptic form due to the angle of impact. The radii of said ellipse b and a can be determined by:

$$b = \sqrt{R^2 + (R - h_{\max})^2} \quad \text{and} \quad a = \frac{\pi}{2}(\operatorname{ctg}\alpha - f)h_{\max} + b\,, \tag{2}$$

where f is the coefficient of friction between a particle and the surface of the work-piece and α is the impact angle [4].

The repeated impact of the particles on the work-piece surface leaves different traces. The microstructure of the treated surface is a result of the intersections of individual traces left by the particles. Therefore the established roughness of the treated surface is a function of the dimensions of these traces. Hence the finest achievable roughness i.e. the average established roughness can be defined by:

$$R_{ae} = K_R \sqrt{h_{\max} a b l_u / R^2}\,, \tag{3}$$

where l_u is the length of the measured area; K_R is an empirical factor related to the initial roughness, in this case $K_R = 0.006$ [5].

As noted in paper [6], the surface roughness decays exponentially with respect to the processing time and therefore can be expressed by:

$$R_a = (R_{ai} - R_{ae})e^{-k_u t} + R_{ae}\,, \tag{4}$$

where R_{ai} is the mean value of the initial roughness; k_u is the rate of roughness reduction; t is the processing time; R_{ae} is the established average roughness.

The time necessary to achieve a set roughness can be obtained from equation (4) as follows

$$t_f = -\frac{1}{k_u} \ln \frac{R_{as} - R_{ae}}{R_{ai} - R_{ae}}\,, \tag{5}$$

where R_{as} is the desired roughness.

Hardness evaluation. In addition to the surface roughness improvement, the vibro-abrasion treatment increases the hardness of the treated surfaces. Since increasing the hardness improves the mechanical properties of the treated piece (e.g. fatigue resistance) some vibro-abrasion treatments are carried out for this particular purpose.

The depth of the hardened layer from this treatment can be defined mathematically based on the theories of elasticity and plasticity [6, 7]. Following the work presented in [7, 8], it can be calculated as follows,

$$h_\sigma = 3k\sqrt{ab}\,, \tag{6}$$

where k is a factor that depends on the material hardening characteristics; a and b are the radii of the contact ellipse. The hardness due to impact is calculated by [10]:

$$\varepsilon = \sqrt{ab}\big/R\,. \tag{7}$$

Experimental procedure. A series of experiments was conducted to verify the theoretical predictions. The specimens used for this study where cylindrical of 16 mm diameter made of a steel alloy (E24). Each specimen was submitted to a vibro-grinding treatment in a commercial circular vibrator of type Reni CIRILLO for a period of 60 min. The angular speed was varied for each treatment.

The grinding particles are of spherical shapes with a mean diameter of 12 mm and made of ceramics (their mechanical properties). The chemical additive used as a lubricant and a polishing agent is a Lauryl-ether-sulphate solution.

Once the series of treatments is completed, the roughness of the specimens was measured prior and posterior to each treatment using a surface roughness.

In addition to the surface roughness measurements, Rockwell hardness tests were carried out on the specimens before and after treatments.

Comparison of theoretical and experimental studies. *The numerical model.* A numerical stochastic model was created to estimate the roughness and the hardness of the specimen after treatment.

The particles are assumed to be spherical with a normally distributed N (5 mm, 10%) diameter. Their initial positions are uniformly distributed in cylindrical coordinates (R, α, H). The positions are then transformed into Cartesian coordinates.

The treated piece is assumed to be fixed in a single position in the chamber. The impact angle of each particle on its surface is also simulated through a random function. The final result is the accumulation of the effect of individual impacts of each particle.

The experimental results. Comparison between the theoretical and experimental values of the relation between the surface roughness and the angular speed of the rotor, the theoretical model shows that the roughness increases proportionally with the angular speed of the rotor is given in Fig. 3*a*. The experimental results demonstrate a good agreement with the theoretical expectations.

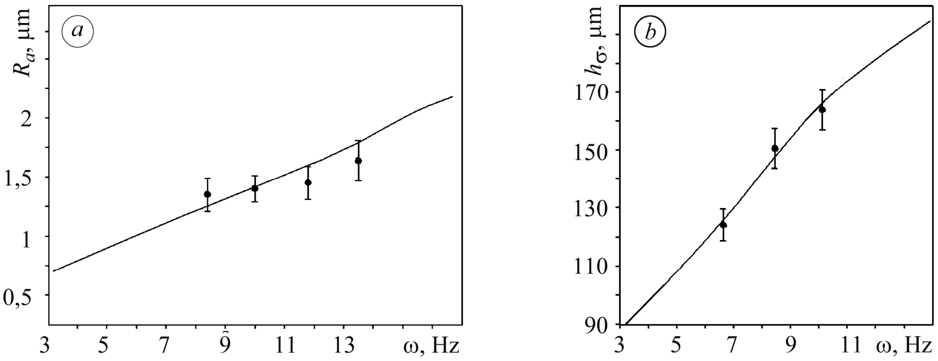

Fig. 3. Roughness of the surface (*a*) and depth of the hardened layer (*b*) vs. the rotor angular speed: ● – experimental values; — – theoretical values.

Fig. 3*b* presents comparison between the theoretical and experimental values of the relation between the hardened layer depth and the angular speed of the rotor. It seems the hardening increases proportionally with the speed of the rotor. The graph shows a good agreement between the experimental results and theoretical expectations.

CONCLUSION

With the aim of analysing the effect of the speed of the process on vibro-grinded surfaces, a numerical model was introduced. The model shows that the surface roughness after the treatment is directly related to the speed of the particles that bombard it. The velocity of these particles is controlled by their position in the chamber and the angular speed of the chamber. Since the position of the particles is random and the user has no control over it, the only control parameter is, in fact, the angular speed of the chamber.

Increasing the speed of the particles increases the size of the impact wells thus increasing the roughness and the depth of the hardened layer. While the increased roughness is an undesired outcome, increasing the hardness is a desirable feature. Therefore, the optimum speed is a compromise between these two aspects. It should be low enough to reduce the roughness and high enough to increase to hardness.

РЕЗЮМЕ. Розглянуто метод механічної обробки поверхні віброшліфуванням. Він базується на неглибокій пластичній деформації поверхні оброблюваної деталі, спричиненої її бомбардуванням гранульованими пружними частинками. Цей процес є ефективним щодо отримання поверхні високої якості. Акцент зроблено на вплив швидкості обертання центрифуги на результати обробки. Розглядали шорсткість поверхні та її твердість після оброблення. Математична модель та отримані експериментальні результати демонструють залежність цих двох аспектів від швидкості обертання камери. Зростання швидкості позитивно впливає на твердість, однак негативно на шорсткість поверхні.

РЕЗЮМЕ. Рассмотрен метод механической обработки поверхности виброшлифованием. Он базируется на неглубокой пластической деформации поверхности обрабатываемой детали, вызванной ее бомбардировкой гранулированными упругими частицами. Этот процесс является эффективным для получения поверхности высокого качества. Акцент сделан на влияние скорости вращения центрифуги на результаты обработки. Рассматривали шероховатость поверхности и ее твердость после обработки. Математическая модель и полученные экспериментальные результаты демонстрируют зависимость этих двух аспектов от скорости вращения камеры. Увеличение скорости положительно влияет на твердость, однако негативно на шероховатость поверхности.

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Received 26.02.2016