Essola et al. International Journal of Mechanical and Materials Engineering (2019) 14:8
https://doi.org/10.1186/s40712-019-0103-8

International Journal of Mechanical and Materials Engineering

ORIGINAL PAPER Open Access

Enhancement of metallic machine parts mechanical properties by the use of vibratory processing for oxide coated films formation and MoS_2 solid lubricant coating deposit

Dieudonné Essola[1,2,3*], Jean Chills Amba[2], Claude Valery Ngayihi Abbe[2], Joseph Nkongho Anyi[2] and Vladimir Vitalevich Ivanov[1]

Abstract

Experimental studies have been carried out to establish the possibility of using vibratory machining technology through shock-wave transmission for oxide coating preparation on aluminum-alloyed machine components and also to discuss the technological possibilities of applying vibration mechanochemical solid lubricant coatings based on MoS_2 to improve the surface quality and performance properties of machine component parts. The coating characteristics are determined by measuring and comparing certain tribological properties of the samples before processing, after normal coating, and after vibratory coating process. A deeper study with a scanning microscope was made by comparing result of normal and vibratory coating. The vibratory coating shows a reduction of grain sizes, a regular orientation of the grain, and a dense grain structure leading to the formation of a thin layer covered by a film orientated parallel to the surface of friction giving an imparted surface finish. The reduction of microroughness is also accompanied with good performances in terms of increasing in wear resistance and decreasing in coefficient of friction. This reflects the presence of complex influence of mechanical and chemical components in the formation of coating on superficial layers during lower shock-wave vibration giving at the end structured ameliorated state of surface that leads to an increase in the part lifespan and equally shows technological opportunities that can be used to improve surface quality and performance properties of machine component parts.

Keywords: Vibratory machining, Oxidation of metal, Mechano-chemical coating, Solid lubricant, Machine parts

Introduction

In modern technological literature, special attention is paid on the improvement of the competitiveness of machines and units (Pereira, Fernandes, & Diz, 2010). One of the priority areas of applied science is to develop and to introduce into production highly efficient technological processes ensuring high quality and practical use, performance, and marketability of manufactured products (Babichev, Essola, Kovalenko, & Koval, 2011).

One of the main conditions in the resolution of such problems is by perfecting and developing a finishing method in processing (Babichev & Babichev, 2008) and depositing of coatings (Roy & Sahoo, 2014).

Coating is a method by which an artificial surface can be generated to the outer surface of the substrate material to protect it from corrosion and wear that can be considered like the two deteriorating phenomena which are the major sources of losses in industrial machineries and exposed structures. These not only reduce the lifespan of industrial components but also increase the

* Correspondence: essola_die@yahoo.com
[1]Laboratory of vibro-technology, Department of Mechanical Engineering, Don State Technical University, Rostov-on-Don, Russia
[2]Laboratory E3M, Faculty of Industrial Engineering, University of Douala, Douala, Cameroon
Full list of author information is available at the end of the article

maintenance cost and expenditure for replacement of their parts. Since corrosion and wear both occur at the surface of the substrate, they can be reduced or eliminated by surface treatment (Dehghan Ghadikolaei & Vahdati 2015; Shetty, Emigh & Krogstada 2019). In this respect, the metallic surface coating gives a practical solution (Wang, Tzeng, Chen, & Chang, 2012) since machine parts and structures are designed for specific applications (Babichev, Essola, et al., 2011; Fotovvati, Namdari, & Dehghanghadikolaei, 2019).

A wide variety of coating methods and materials are available for different coating applications with a common purpose of protecting parts or exposed structure from mechanical or chemical damages. Their choice mainly depends on the parts or structure mechanical properties, desired functionality, thermal properties, electrical conductibility, dynamic load bearing, and corrosion resistance and also on environmental parameters of the process including it cost (Fotovvati et al., 2019). Requirement of parts functional compatibility and safety should be met between the coated layer and the nearest environment to choose a concrete method for mechanical purpose (Babichev & Babichev, 2008).

On the other hands, machine parts manufactured by casting, forging, and other traditional manufacturing processes often require additional advanced machining operations before they can be considered ready for use or assembly. In many engineering applications, parts need to be interchangeable in order to suitably and reliably perform multi-functional tasks during their expected life expectancy. Therefore, control over dimensional accuracy and surface finish of those components is of critical importance during any machining operation (Prasad & Chakraborty, 2018).

There are many different processes in conventional machining such as turning, drilling, milling, planning, and shaping. These processes have been used for years for manufacturing of parts and machines and have developed over time with gradual increase on the requirements parts precision (Dehghanghadikolaei, Mohammadian, Namdari, & Fotovvati, 2018). These conventional machining processes have hardly maintained their suitability for the ever-growing demands for miniaturized products and features and high surface quality (Babichev & Babichev, 2008). This paves the way for finding out alternative machining processes that can produce surface finish (Smolentsev, Kondratyev, Ivanov, & Smolentsev 2017) in the range of small dimensions such as nanometers.

Nontraditional manufacturing processes is defined as a group of processes that remove excess material by various techniques involving mechanical, thermal, electrical, or chemical energy or their combination. They do not use a sharp cutting tool as for traditional manufacturing processes (Davim, 2013; Dehghanghadikolaei et al., 2018).

Actually, typical applications of nontraditional machining methods include high accuracies, good surface finish and complex geometries, parts machined without burrs or residual stresses, as well as work materials that cannot be machined by conventional methods (Davim, 2013). In general, the nontraditional processes are characterized by high specific energies and low removal rates when compared to conventional machining processes (Babichev & Babichev, 2008). Nowadays, nontraditional macro and micromachining processes present great importance for automotive, aircraft, and other advanced industries in industrialized or emerging countries (Davim, 2013).

Vibratory machining as a non-conventional machining (Babichev, Essola, et al., 2011) is characterized by dynamic influence of the processing medium in the form of set of impacts of its particles with the surface of the processing component part. The resulting effect favorizes mecanochemical interaction of processing medium with the material of the machine component part and also acoustic influence of shock waves according to Babichev theory (Babichev & Babichev, 2008).

During vibratory machining, the working medium and workpieces in the chamber in the appropriate quantitative ratio for process optimization are continuously subjected to variable accelerations (Essola, 2014). The mixture come into intensive relative movement, making two types of movements that are oscillations and slow circulation movement.

The resulting vibration waves due to shock possesses kinematic characteristics; they are characterized by physical phenomena (reflection, refraction, diffraction…) that can be controlled by forcing in simple (mixture of parts and free moving indentors working environment) or complex (mixture of solid indentors, components parts of machine, and complex metallic powder) working environment for manufacturing operations useful for technological purposes (Essola, 2014). In this condition, during processing, there is formation or removal of a superficial layer on the parts surface (Babichev & Babichev, 2008).

Some coatings are formed by mechanical attraction of the coating material with the metal surface through Van-Der-Waals forces; others are formed under chemical reaction conditions and if electrostatic forces are present in the boundary layer, the process becomes more complex with the formation of double electrical layer by the mean of hydration. However, as established in (Dontsov & Kirichek, 2017) for combination of vibrating mechanical and chemical process, regardless of the complexity of chemical processes, mechanical energy invariably remains the main activating force.

Although there is a large amount of literature that has focused on the coating performance of machine parts, there is limited literature dedicated to vibration wave processing coating (Popov, & Kirichek; 2017). Therefore, the present study is relevant as it focuses precisely on the use of low-frequency oscillations in the simple or complex environment for micro-film formation on the outer surface of the parts with the objective of investigating the parts performance for further engineering applications. This study is also vital, because of the rising interest in structures and parts as it can provide a simple, ecological, and low-cost method in term of realization of metal surfaces protection from external aggression. Another aspect consists to assurance of component parts life cycle, its extension, and to guarantee functional requirements of parts in a product. In fine, it gives ability to predict the quality of typical products under their operating conditions by taking into account the required life expectancy of the products and their resistance to external influences.

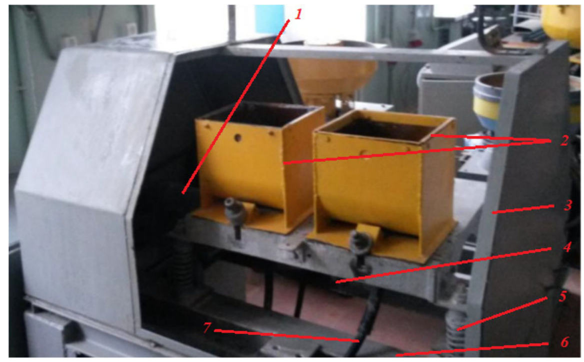

Fig. 1 Vibration machine УВГ 4 × 10. 1—electric motor; 2—working chamber; 3—case; 4—main shaft with unbalance vibrator (mass); 5—elastic elements; 6—base (frame); 7—pipeline; 8—vibrating plate

Methods/experimental

Experimentations describing the uses of vibratory machining with freely moving indentors for oxide-coated films formation on samples' surfaces have to be conduct to provide the strongest argument on the base of empirical observations for cause-effect relationships. In the same condition, formation of coating on the basis of MoS_2 has to be studied. This section explains the condition of the realization and the used materials for these purposes.

Oxide-coated films formation mechanism on machine parts during vibration processing

The study of the mechanism of oxide film formation is based on the method that consist of determining arrangement pattern, sizes, and depths of processing traces when working in polyethylene balls environment. Oxide film formation on machine component parts can be obtained during the process of oxidation without oxidizing solution. The quality of film and the general appearance of the surface will be investigated by the means of optical and electronic microscope.

In several studies, particularly according to AP Babichev's and VP Ustinov's point of view (Babichev & Babichev, 2008), there are data describing superficial layer formation during vibratory machining in the environment of metal bodies. These processes are accompanied by plastic deformation of the superficial layer of metallic parts in conditions of repeated collision of particles of the processing medium with the machine parts.

During vibratory machining, particles of the working medium strike the part's surface. In the contact zone, there is a pressure causing plastic deformation that leads to an increase in dislocation and formation of active vacant-dislocation centers (Babichev, Essola, et al., 2011; Ivanov, Marchenko, Samurgashev, & Sarabachev, 2016). Under the influence of circulation of both the processing medium and machine parts, a uniform layer of plastic deformed material is formed on the active metal. The frequency of the conducted vibratory process using the horizontal vibrating machine УВГ 4 × 10 (Fig. 1) is in the range of 60–100 Hz and the amplitude was standard and equal to 2.5 mm.

Due to the combination of vibratory machining method and oxidation, interaction of the working medium (polyethylene spheres) and superficial layer of processed material produces an interlaminar layer formed by oxide-coated film and solution which is found in their contact zone. According to the theory of chemical oxidation, the formation of oxide-coated film and its growth is the result of interaction of the metal with the processing medium which is carried out through pores of the film formed during oxidation (Ivanov, 2017a).

The increase in internal energy in the metals' superficial layers as a result of plastic deformation leads to an increase in the adsorption capacity of the metal surface.

The speed of chemical reactions depends on the number of active molecules. As a combined result of sliding metallic spheres on the surface of machine parts, mutual oscillation of molecular components' nuclear groups and increase in the kinetic energy of the processing environment, there is an activation of molecules of the oxidized solution due to the absorption of an additional energy by them. An increase in oxide-coated film thickness implies activation of molecules. The value obtained at vibratory machining is between 4.5 and 5 μm, comparing to the one without vibratory machining that is situated between 3 and 3.5 μm. The vibratory machining imparts to ions an additional energy necessary for overcoming the increasing distance between metal and growing oxide-coated films.

Thus, consecutively coating with great numbers of micro impacts of processing medium particles with their mutual collision and sliding leads to an increase in the chemical activity, not only for metallic surfaces but also for molecules of oxidized solution (Ivanov, 2017a).

A characteristic plot of sphere impact with oxidized film surface is shown on the sample in Fig. 2. The visual

Fig. 2 Characteristic plot of direct and slanting impact of sphere, on the surface of metal with oxide-coated film with thickness 1 μm

analysis of that picture gives the basis to consider that the impact of sphere deformation is directed toward the depth of the sample. This fact can also be confirmed with profile record print where insignificant bulks on edges of hole (Fig. 3) are visible beside projections of velocity vector of the sphere. The contours of the traces are uneven, which indicates the variable nature of the movement of the ball relative to the treated surface.

The vibrating environment, by coming in contact with oxide-coated films growing surface falls off, that permits and facilitates the access of oxidized solution to reach the surface of the metal. The reactivity of the solution is enhanced by the activation of its constituent components (Ivanov, Selemenev, & Marchenko, 2011).

The intensity of proceeding processes is observed not only in the reaction zone but also in the zone of direct contact. Under influence of normal and tangential forces, the superficial oxide-coated film layer is deformed due to the influence of spheres and also to the vibrating solution.

Oding IA refers to shift processes of plastic deformation as the sliding mechanism which shows the motion of one part of the grain with respect to another. External display of this motion is expressed by sliding strips formation on the surface of metal (Babichev & Babichev, 2008).

Fig. 3 Profile record print showing bulks on edges of hole. **a** Direct impact profile record print of sphere. **b** Profile record print of oblique (slanting) impact of a sphere

Implementation and realization condition of vibration coating process on the basis of MoS_2

The interest of many researchers on solid lubrication coverings on the basis of molybdenum disulfide is due to its unique properties which promotes an increase of wear-resistance of the machine parts entering into friction pairs with various products. Molybdenum disulfide has hexagonal closed packed lattice structure in the form of prismatic hexahedron, shown in Fig. 4. Such a structure of molybdenum disulfide proves its importance as a lubricant with high adhesive properties.

Molybdenum disulfide possesses layered structure in which there are “strong” and “dense” layers with enough space between each other. Thus, in the layer of coating, on the surface of friction, there are strong bonds, whereas bonds between layers are weak. Such properties of solid lubrication coverings provide “easy” sliding of contact surfaces on each other, essentially reducing friction coefficient and the wearing process of friction pair. High adhesion of molybdenum disulfide to metals is caused by strong molecular connections (bonds) forming sulfur atoms with metal (Dontsov & Kirichek, 2017; Ivanov, 2017b).

Experimental researches of operational characteristics were conducted on the Russian-made friction machine model СМЦ-2, by standard procedure after samples processing in vibration machine УВГ 4 × 10 with the condition mentioned in “Oxide-coated films formation mechanism on machine parts during vibration processing” section.

With the purpose of a deeper study of the surface, the electronic microscope SUPRA25 was used, allowing the investigation of metal’s surface, coating material, electron-beam lithography, continuous control of process, and supervision of materials with ultra-

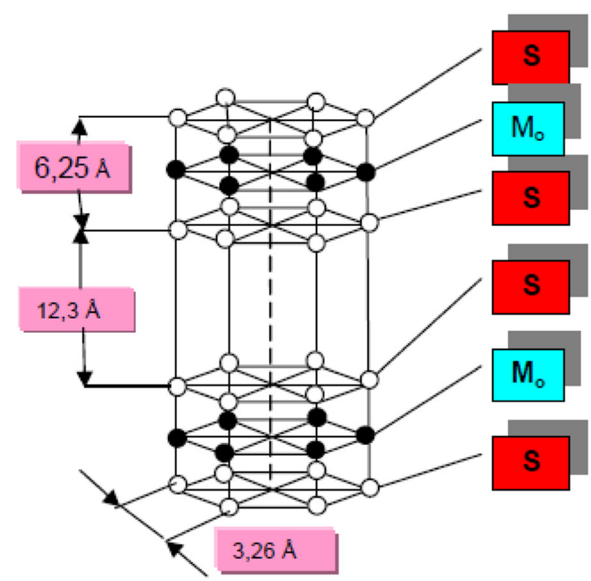

Fig. 4 Lattice structure of molybdenum disulfide (MoS_2)

smaller sizes (nanometer). Researches on the superficial layer were conducted on a scanning microscope tester Nanoeducator (NT-MDT) and the nano-profile of surfaces on a tunnel microscope PHYWE. Polished samples made with steel 45 having dimension 10 mm × 10 mm were used.

Result and discussion

Results of researches are presented on Figs. 5, 6, 7, 8, and 9.

Analysis and interpretation of oxide-coated films formation on machine parts made with aluminum alloys

The received structure of aluminum Russian-made АД1[1] (ГОСТ 4784-97) corresponding to American analogue 1230 (ISO 209-1 or ASTM B221 1060) before and after processing shows grains change, size reduction, and stretching them parallel to a plane of processing of aluminum grains.

The visual analysis in Fig. 5 shows that on the investigated surface, there are enormous number of randomly located traces of processing generated ledges and pores (cavities). They have different forms, depths, and sizes. Small-sized deepening and longitudinal multidirectional scratch marks with various forms and sizes are visible as a consequence of direct and inclined collisions. Contours of plots are irregular, that shows the variable nature of sphere's movement on the processable surface.

On various sides of surfaces, relief pattern crateriform plots showing direct influence of sphere about a surface are visible with deformation directed toward the center of the sample as in Fig. 2. A set of plots received from collision of spheres, directed at an angle to surface are also visible, which shows the sliding impact causing shift and fragile destruction of material. In fact, the direct impact of the medium is helping more in reducing the protrusions and feeding the hollows space until a certain level and slanting impact is obtained assuming the smooth and regular continuity of the surface shape. This testifies that the dynamic random character of the processing medium is necessary to establish relative uniformity to a considered surface being coated as shown in Fig. 2. Deformation processes during vibration exposure are accompanied by plastic deformation of a thin surface layer and the implementation of shock-wave processes. This implies the uniform hardening of a thin surface layer of all elements of the part, finishing and rounding of sharp edges, and finally smooth transitions. It is appropriate to note the high performance among mechanical processes due to the possibility of simultaneous processing of a large number of parts.

The intensity of the process lies on the governing parameters of resulting vibration such as amplitude and frequency. With an increase in the amplitude of oscillations, some mechanical characteristic and the coating formation increases as in usual vibratory machining (Babichev & Babichev, 2008; Essola, Babichev, & Mishnyakov, 2012). Such increase in the amplitude is explained by an increase in the forces of micro-shocks of the particles of the working medium and the path of their active influence on the surface being treated.

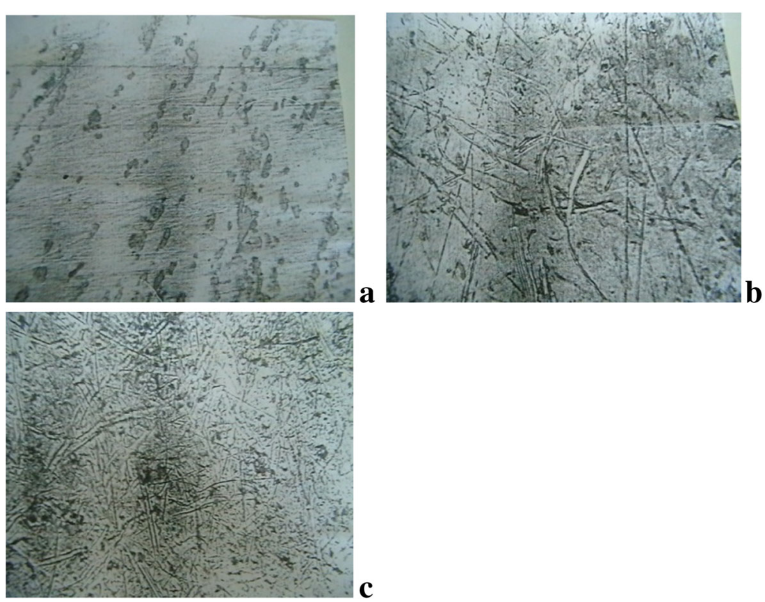

Fig. 5 Aspect of oxide-coated films formation showing traces on aluminum АД1* after vibration treatment in the medium of polyethylene balls (increase × 200). **a** Initial polished sample. **b** Sample after 15-min processing. **c** Sample after 30-min processing

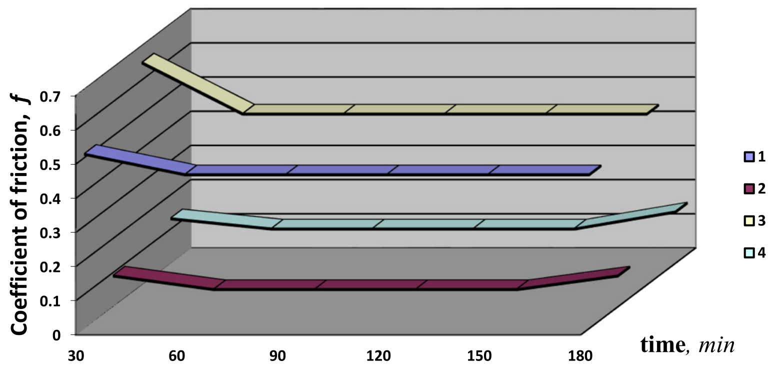

Fig. 6 Study of materials' friction pairs factor: 1 – steel 52100 -ANSI/ASTM (steel ШХ15*) with steel 5140 -ANSI/ASTM (steel 40X*) as initial pairs; 2 - pair of steel 52100 -ANSI/ASTM coated MoS2 (steel ШХ15*) with non-coated steel 5140 -ANSI/ASTM (steel 40X*); 3 - pair of steel 5140 -ANSI/ASTM (steel 40X*) with cast iron 30B -ANSI/ASTM (cast iron СЧ21-40*); 4 – pair of MoS2 coated steel 5140-ANSI/ASTM (steel 40X*) with non-coated cast iron 30B -ANSI/ASTM (cast iron СЧ21-40*)

The growth in formation of mechanical coating with an increase in the frequency of oscillations is explained by an increase in the forces and the number of micro-blows of abrasive particles on the treated surface per unit of time and consequently an increase in the speed of their relative slip. These forces are due to improvement of the accelerations of abrasive particles with their constant mass. Observation of the behavior of the working medium in the working chamber showed that with an increase in the oscillation frequency, the circulation (rotation) of the entire mass of the working medium accelerates (Babichev & Babichev, 2008). Consequently, the increase in the formation of coating in this case occurs due to more intensive mixing (circulation) of the working medium.

By considering surface samples pictures processed within 30 min (Fig. 5c), the heterogeneity of the processed surface is observed more than the one processed after 15 min (Fig. 5b). It represents the gradual intersection of the initial roughness with processing traces. In the surface of processed sample, the polished sides of the surface as shown in Fig. 5a and sides with traces of destruction differ from each other. The surface is covered with craters (pores) and various types of cavities but less in Fig. 5c, than in in Fig. 5b. This could be explained by the presence of certain discontinuing in the characteristic (mechanical and technological) of processed sample or the effect of shocks in certain places of the surface of parts more than other places. But the technological characteristic of the sample is responsible to the effect of relative leveling shown in Fig. 2; mechanical effect contributes to reduce the length of profile parameter by additive micro-cutting of higher dents, filling the crater with microchips, and fixing it in direct impact. The sliding impact compensate the slope created by dynamic random chocks during processing. Only the duration of the process is favorable through additional repeating impact constraining shifting of the surface with simultaneous better leveling.

In other words, vibration treatment provides additional energy needed to overcome the increasing distance between the metal and the growing oxide film. The vibrating medium in contact with the surface of the growing oxide film loosens it, thereby facilitating the access of the oxidizing solution to the metal surface. This creates the densification of material of surface due to the shocks, compensation of defect, and the destruction of

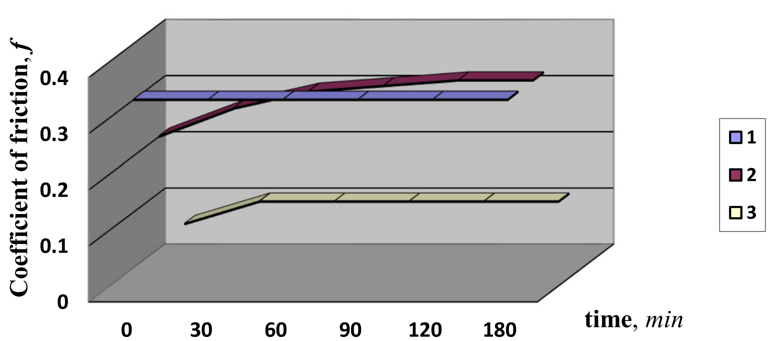

Fig. 7 Test results of samples from titanic alloys BT-20* at rolling friction with 20% slippage and loading 40 kg (q = 900 kgf/cm) at room temperature without greasing. 1—Initial. 2—After vibro-hardening processing. 3—After vibration processing and simultaneous MoS_2 coating

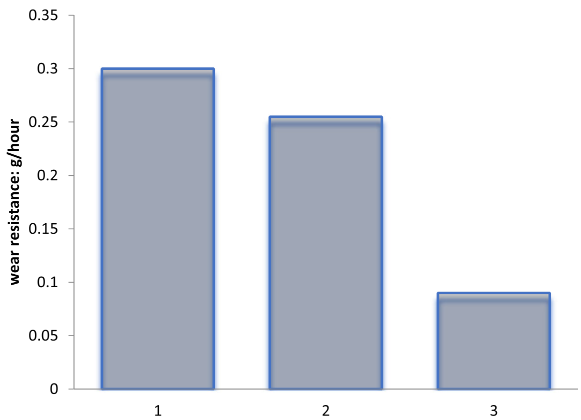

Fig. 8 Wear resistance of friction pairs of samples from alloy BT-20* and steel 1X12H2BMΦ*. 1—Initial sample. 2—Sample obtained after vibro-hardening processing. 3—Sample obtained after vibration processing and simultaneous MoS_2 coating

lower stable structure affecting the surface in the beginning of the process.

The main parameters of the mechanical action of the combined process are the speed and strength of the impact of the granules of the working medium with the surface of the parts and the contact pressure in the area of impact. An increase in such parameters shows the intensity of the process but till certain level due to the limitation of the vibration machine.

Increase in any of the considered parameter have positive impact to the operation, but as the machine is designed for range of amplitude, the bigger value of frequency can lead to easily cause negative consequences. In this condition, the wear of the working medium becomes so intense that the cost of processing increases dramatically, the load on the shaft bearings on which the imbalance is located increases as the disturbing force increases in proportion to the square of the angular frequency of the vibration, and the noise arising during the operation of the vibration unit increases sharply and acquires a high tone. For these reasons, the optimization of the processing can be reach with an uprising of amplitude.

As a result of the dynamic effect, activation of chemical and physicochemical processes occurring in the surface layer is provided that lead to the change of its geometrical and physicomechanical characteristics.

The process duration has a determinant aspect after choosing the needed equipment for operation. Metal removal rate in time proceeds non-linearly. In the beginning of processing, the incubatory period during which an appreciable loss of weight is not observes proceeds. As shown in complex researches (Babichev & Babichev, 2008; Babichev, Essola, et al., 2011, 2012), during that period dents as imprints are formed; moreover, there is accumulation of the latent energy of destruction and a brittle behavior of superficial layers of processable material.

At longer processing, contact and overlay of a set of individual traces are observed on the surface of the sample in places of accumulation and a large number of processing traces represents a repeatedly deformed layer.

By observing the plots, it is visible that separate spheres during collision with a processable surface leaves on it a discontinuous trace consisting of finer traces caused by the nature of movement of spheres.

At such cross-arrangement nature of the considered processing traces, an original micro relief is formed.

Analyzing the obtained results, it is proper to note that vibratory machining in the polyethylene balls environment on sample's surface are being formed traces having crater types as a consequence of direct impact. As a result of sliding of spheres on the processed surface, elongated form traces are also formed. Ultimately, on the surface of sample, mixed type traces are present as a consequence of both sliding and direct collision. That is why most parts of processed traces have mixed characteristics.

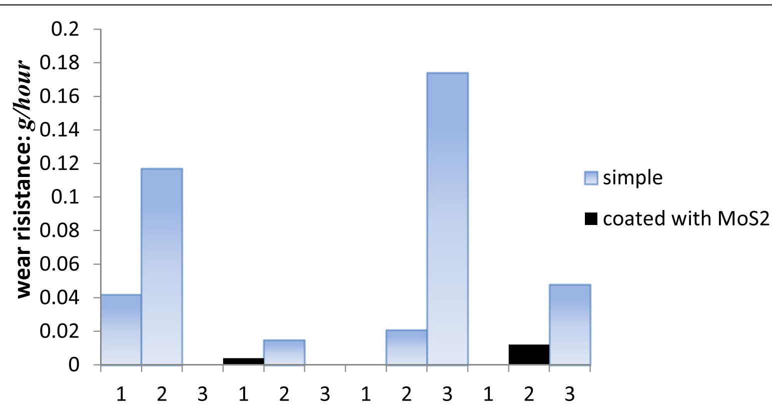

Fig. 9 The study of wear resistance of samples friction factor. 1—Steel 52,100 -ANSI/ASTM (steel ШХ15*). 2—steel 5140 -ANSI/ASTM (steel 40X*). 3—cast iron 30B -ANSI/ASTM (cast iron СЧ21–40*)

A large number of processed traces cover mostly all the surfaces of the sample, implying flow of plastic deformation processes at microlevel and lessening of superficial layer. These phenomena have great importance in the formation of oxide-coated film and microrelief of the surface because the direct contact of the sphere occurs on oxide-coated film.

Numerous studies have established the presence of plastic flow of material in a thin superficial layer of the sample in the course of movement of separate granules (Smolentsev, Kondratyev, Ivanov, & Smolentsev, 2017). At direct impact of a sphere, the deformation is directed deeply into the sample. The majority of traces are inherent to impacts of spheres directed with an angle to the surface which causes fragile oxide destruction and shift of separate particles. Such surface destruction allows oxide layer's lessening with formation of finely broken particles. Part of particles is seized by the juvenile oxide surfaces, falling sometimes into the pores and reducing their volume. The other part is partially carried away by the oxidizing solution, partially compacted by subsequent impacts of the balls and gets a polished appearance.

Initial contact of sphere occurs on top of microroughnesses. During processing, there is an increase in the area of covering's contact with surface as a result of rounding the radius of the protrusions. Profile record on polished surface after processing in polyethylene balls and overlapping with oxidation shows that as a result of combs' deformation of microroughnesses under influence of spheres' impacts, there is reduction of roughness and increase of crest blunt point radius (tops) of ledges.

Hence, as a result of vibration processing, oxide-coated film is lessened and smooth out during its growth (Smolentsev, Ivanov, & Kondratyev, 2017).

In the zone of contact, due to sliding impacts of spheres, oxide-coated film particles are orientated parallel to processing surface of the sample, that testify brilliant sides on the surface. These brilliant sides are well visible in micro photos (Fig. 5b, c) comparatively to initial polished sample picture (Fig. 5a). Additionally, by comparing coated films formation obtained at vibration processing and the one obtained by using traditional method, it is necessary to note that more than 50% of the surface of the covering obtained as a result of vibratory machining has orientation of particles parallel to planes of sliding (motion). That led to conclude that when coating is applied in stationary baths that is without a load being applied, the hydroxide grains have chaotic and random orientation while those obtained during the vibratory machining are oriented parallel to the slip plane.

Interpretation, analysis, and discussion of experimental result of vibration processing coating on the basis of MoS_2

Results of conducted researches have shown that vibratory processing solid lubrication coating with MoS_2 leads to a decrease in friction factor and an increase in wear resistance of friction pairs during operation. This happens not only in the air environment (dry friction) but also in an oily environment (wet friction). Deterioration within 3 h of processing is not practically observed. It is experimentally confirmed that the presence of layers of various atoms in molybdenum disulfide structure creates conditions of easy sliding.

Large influences on antifrictional properties of coating renders nano-dimensionality, orientation of its particles, and also nanorelief of the surface as seen in "Methods/experimental" section. The formation of molybdenum disulfide coating by means of vibration ensures orientation of particles with base planes parallel to the plane of sliding and the wearing of coatings in this case is not perceived (Babichev & Babichev, 2008; Ivanov, 2017b).

Depending on the conditions of operation and materials of friction pairs, reduction in factor of friction ranges from nine down to three times and the increase in their wear resistance from four up to 20 times.

Figures 10 and 11 present a series of photographs, illustrating the condition of the samples' surfaces made from steel 45 and MoS_2 powder in initial condition and after deposition of molybdenum disulfide coating. Pictures are made with various zooms, from various positions and by tilting. The adsorbed particles of firm greasing have no certain orientation (Fig. 10a), but in the zone of contact, due to the closeness and sliding impacts of indentors, particles are guided with base planes parallel to the processing surface that presents brilliant sides of coating. This can be seen on the photograph shown in Fig. 10b.

The obtained photos give evident representation of the relief's character of the covered surfaces and surface without solid lubrication coating. These photos open the mechanism of formation with vibration's impact influence in the steel indentors environment having diameter from 3 to 5 mm. Moreover, they also approve the influence of molybdenum disulfide powder on metal as oxide-coated films formation. In Fig. 11a, parallel lines are precisely visible on metal after machining. In Fig. 11b, the sizes and chaotic arrangement of powder are visible after normal deposition of coatings. By deposition of coating (Fig. 11c) using vibratory machining, the part of powder that was formed precisely on metal edges and which is contributed to chaotic morphological structure has been mechanically removed. The photograph in Fig. 11d gives a lateral metallographic microsections view, which confirms the orientation of molybdenum disulfide particles with respect to the rotation of the machine parts. Apart from the result of the lead researches, it is established that formed layers of firm greasing molybdenum disulfide during vibration processing becomes covered by a thin film having orientation of particles with the base planes parallel to the surface of friction. This result can also be observed with much detail in Figs. 12 and 13.

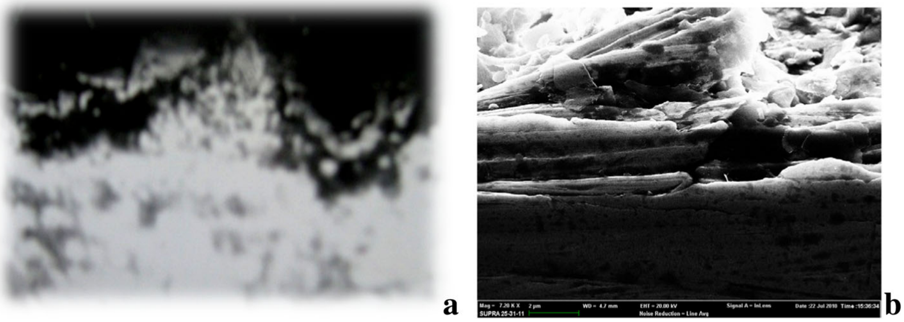

Fig. 10 The surface of micro section of steel 45* (HRC 28) with the introduced particles of molybdenum disulfide powder. **a** Obtained with ordinary microscope × 500. **b** Obtained with analytical auto issue electronic microscope Zeiss SUPRA25

In fact, as a complex result of (i) the sliding of the balls relative to the surface of the parts, (ii) the mutual oscillation of the atomic groups of the constituent molecules, and (iii) the increased energy of movement of the working medium, the polishing solution is activated by obtaining additional energy, which leads to the formation of a specular thin film on the metal surface.

As seen from the presented figures, the surface with molybdenum disulfide coating in comparison with unprocessed surface has become flatter and the microledges are rounded and more continue. Such structure of a film, as shown in the analysis, is caused by inclusion of nanodimensional structures (Fig. 13). The introduction of nanodimensional structures in vibrating mecano-chemical coatings increases the efficiency of firm greasing (solid lubricants). It is established that with the reduction of grain size from 1 μm down to 2 nm, the volume fraction of grain matter increases up to 88%. This gives possibility to obtain coatings with high and unique properties. For example, they have ameliorated durability as their hardness which range from two to seven times higher than the hardness of coarse-grained coatings; their toughness are 1.5 to 2 times higher and with the reduction of grain size from 10 μm down to 10 nm, the speed of deterioration of coating decreases up to ten times.

Conclusion

To sum up, it is clear to conclude that vibration processing in the environment of polyethylene spheres allows combining some technological stages:

(i) Preparation of a surface under covering can be conducted by cleaning of pollution and oxides, activation of superficial layer as a result of plastic

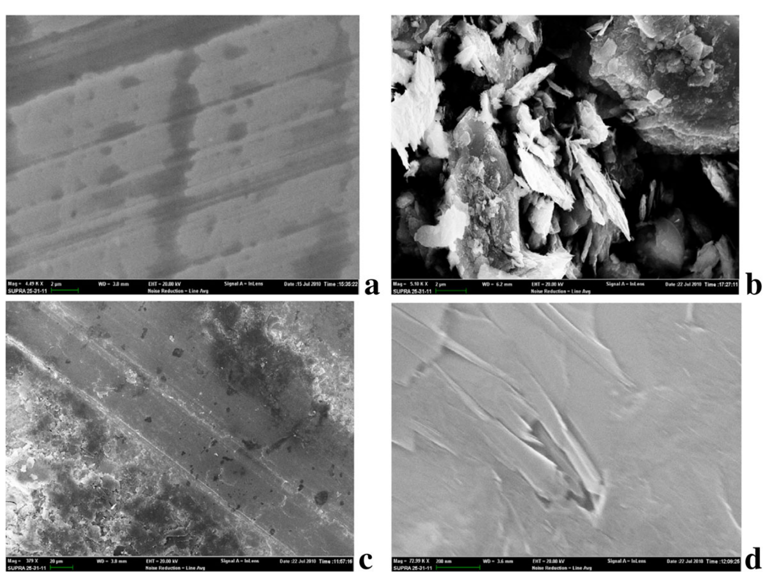

Fig. 11 The increased illustration of sample with steel 3 depending of condition. **a** Initial sample obtained by simple machining. **b** MoS_2 powder on normal coating. **c** MoS_2 powder on vibration coating. **d** MoS_2 powder on vibration coating showing particles orientation

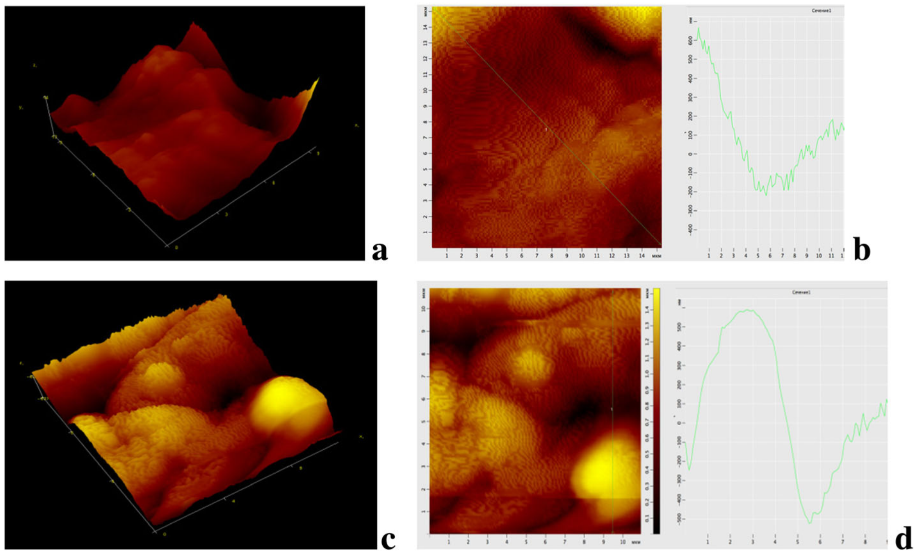

Fig. 12 Microrelief characteristic for formed layers of firm greasing molybdenum disulfide during vibration processing. **a** 3D model of initial surface. **b** Micro relief of initial surface. **c** 3D model of a surface with MoS_2 coating. **d** Micro relief of a surface with MoS_2 vibration-coating

deformation, and increase in depositions density of superficial layers.

(ii) Formation of juvenile surfaces by increasing the area of contact and absorption of oxide-coated film.

(iii) Refining of surface by the creation of a certain micro-relief which increases the reflective ability and quality of superficial layer.

Vibratory machining with mechano-chemical solid lubricant coatings on the basis of molybdenum disulfide works not only in a non-lubricated environment but also in a lubricated (oiled or greased) environment. The deposition of coating does not demand a complex equipment and high qualification of workers. The application of coating in friction pairs increases the service life of a product from ten to 20 times, and the introduction of nanodimensional structures opens unique opportunities for a new level of properties such as high hardness, durability, increase in wear resistance, and a high plasticity, keeping thus high operational properties of products.

The supplied external mechanical energy can compensate the costs of chemical reactions, accelerate the

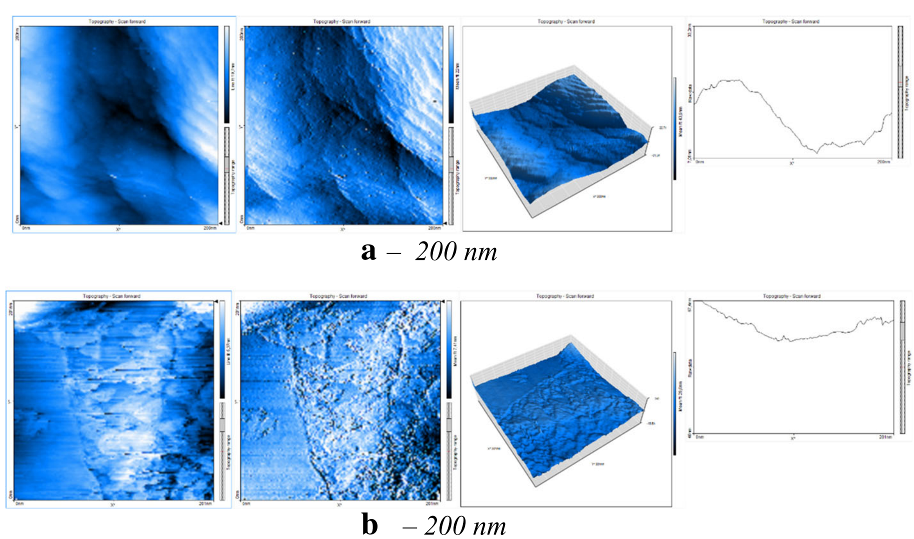

Fig. 13 Nano-dimensional (nanorelief) structure of surfaced. **a** Initial surface. **b** Surface with MoS_2 vibration-coating

combined processes, and facilitate obtention of a new state of coatings as a result of chemical transformations. It results to intensify transformations with the aim of achieving high technological indicators and parts lifespan.

In this condition, the solid lubricant coating on the basis of MoS_2 and oxide-coated film formation technology is developed during lower shock-wave of vibratory machining which reflects the presence of complex influence of mechanical and chemical components in the formation of coating on superficial layers. Moreover, the mechanism of oxide-coated film formation is made by combining complex interaction of vibration processing and oxidation.

Endnotes

[1]Russian designation according to standard GOST

Abbreviations

MoS_2: Molybdenum disulfide; УВГ 4 × 10: Universal horizontal vibrating machine with 4 working chamber of 10 dm^3 each

Acknowledgements

We wish to tank the successful cooperation with the mechanical engineering department of Don State Technical University for all facilitations of realization of this study and most of all to bend before the memory of Babitchev AP the fonder of laboratory «Вибротехнология» (vibrotechnology) who passed away 17 march 2018. Finally, the authors thank the editor and the anonymous reviewers that provided useful suggestions to improve the original manuscript.

Funding

None, inter-universities cooperation.

Availability of data and materials

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Authors' contributions

DE, CV and VV conceived of the presented idea. AJ and DE developed the theory. JC encouraged DE to investigate the vibration coating of aluminum and to compare its properties with initial sample VV supervised the findings of this work. All authors discussed the results and contributed to the final manuscript. DE and CV carried out the experiment. JC wrote the manuscript with support from AJ and VV. AJ and DE fabricated the samples. DE, JC, CV, AJ and VV contributed to the interpretation of the results. DE took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

Author details

[1]Laboratory of vibro-technology, Department of Mechanical Engineering, Don State Technical University, Rostov-on-Don, Russia. [2]Laboratory E3M, Faculty of Industrial Engineering, University of Douala, Douala, Cameroon. [3]Department of Construction Material Technology, Moscow Automobile and Road Construction State Technical University (MADI), Moscow, Russia.

Received: 3 April 2019 Accepted: 10 June 2019
Published online: 15 July 2019

References

Babichev, A. P., & Babichev, I. A. (2008). In The production centre of DSTU (Ed.), *Ocnovi vibrationnoi texnologyi (the basis of vibration technology)* (2nd ed.). Rostov-On-Don: ISBN 978-5-7890-0472-2.

Babichev, A. P., Essola, D., Kovalenko, E. N., & Koval, N. S. (2011). *Vibration and vibro-wave processing technology for repairing and recycling engineering product: Voproci vibrationnoi texnologyi (Questions of vibration technology): Collection of scientific art* (pp. 3–6). Rostov on Don: Center DSTU.

Davim, J.P., 2013, Nontraditional machining processes—Research advances. X, 232 p. 156 illus., Hardcover ISBN: 978–1–4471-5178-4.

Dehghan Ghadikolaei, A., & Vahdati, M. (2015). Experimental study on the effect of finishing parameters on surface roughness in magneto-rheological abrasive flow finishing process. *Proceedings of the Institution of Mechanical Engineers - Part B: Journal of Engineering Manufacture, 229*, 1517–1524. https://doi.org/10.1177/0954405414539488.

Dehghanghadikolaei Amir, Behrouz Mohammadian, Navid Namdari, Behzad Fotovvati (2018). Review article 5 1 DOI: https://doi.org/10.19080/JOJMS.2018.04.555654 JOJ.

Dontsov, N. S., & Kirichek, A. V. (2017). Mechanical zinc coating procedure under conditions of vibration mechanical-chemical impact. *Key Engineering Materials, 736*, 105–109.

Essola, D. (2014) Povysheniye effektivnosti remonta i utilizatsii izdeliy mashinostroyeniya na osnove razrabotki protsessov vibrovolnovoy razborki i ochistnykh operatsiy (improvement of the efficiency for repairing and recycling (utilization) of machine building engineering products through the development of vibrowave's disassembling process and clean-up operations). PhD dissertation, Rostov-on-Don.

Essola, D., Babichev, A. P., & Mishnyakov, N. T. (2012). A new approach to the development of a mathematical model of the formation of the part surface when performing vibration cleaning. *Vestnik Donskogo Gocudarstbennogo Texnicheckogo Univerciteta (Journal of Don State Technical University), 3*(64), 136–138 ISSN 1992-5980. Russia, Rostov-On-Don.

Fotovvati, B., Namdari, N., & Dehghanghadikolaei, A. (2019). On coating techniques for surface protection: A review. *Journal of Manufacturing and Materials Processing, 3*(1), 28.

Ivanov, V. V. (2017a). Processes of formation of a vibrating covering in conditions of the combined chemico-mechanical influence. *Jurnal "Bulletin Rybinskogo Gosudarstvo Aviationnoi Texnologiseskyi Akademy im. PA Soloveva" (Magazine « the Bulletin of Rybinsk State Aviation Technological Academy named P.A. Soloveva »), 2*(41), 137–140.

Ivanov, V. V. (2017b). Processes and methodology of creation of high-resource products superficials layers by vibrating formation of coverings by the combination of chemico-mechanical influence. In *"Avtoreferat doktora texnicheskyi nauk"(abstract of dissertation)* (p. 37). Voronezh.

Ivanov, V. V., Marchenko, E. V., Samurgashev, S. V., & Sarabachev, A. A. (2016). Complex research of hydroxide film $Al(OH)_3$ nanostructure generated in conditions with shock-wave technological systems. *Jurnal "Mir galvanikov"(Magazine « World galvanizers »), 1*(32).

Ivanov VV, Selemenev MF, Marchenko YV. (2011) Formation vibrating mechanochemical solid lubrificating coverings on the basis of molybdenum disulfide. Jurnal "Izvectie Orelskogo Gocudarstvennogo Universitet" (Magazine "News of Orel State Technical University") Fundamental and applied problems of technics and technology No 2 (286), Orel.

Pereira, E., Fernandes, A., & Diz, H. (2010). Competitiveness and industrial evolution: The case of the ceramics industry. *Evolutionary and Institutional Economics Review, 7*, 333–354. ISSN 1349–49. https://doi.org/10.14441/eier.7.333.

Popov, S. I., & Kirichek, A. V. (2017). Qualitative characteristics of MoS2 solid-lubricant coating formed by vibro-wave impact of free-moving indenters. *Key Engineering Materials, 736*, 18–22.

Prasad, K., & Chakraborty, S. (2018). A decision guidance framework for non-traditional machining processes selection. *Ain Shams Engineering Journal, 9*(2), 203–214. https://doi.org/10.1016/j.asej.2015.10.013 ISSN 2090-4479.

Roy, S., & Sahoo, P. (2014). Parametric optimization of corrosion and wear of electroless Ni-P-cu coating using grey relational coefficient coupled with

weighted principal component analysis. *International Journal of Mechanical and Materials Engineering, 9*(1), 10.
Shetty, P. P., Emigh, M. G., & Krogstada, J. A. (2019). Coupled oxidation resistance and thermal stability in sputter deposited nanograined alloys. *Journal of Materials Research, 34*(1), 48–57.
Smolentsev, V. P., Ivanov, V. V., & Kondratyev, M. V. (2017). Designing of technological processes of obtention (reception) highly ressource combined coverings. *Texnicheskyi Jurnal Mochnie Texnologyi i Pokritie (Technical Journal "Strengthening Technologies and Coverings"), 6*, 41–46 Moscow.
Smolentsev, V. P., Kondratyev, M. V., Ivanov, V. V., & Smolentsev, E. V. (2017). The combined methods of superficial layer's quality improvement in materials. *Fundamentalnyi i Prikladnie Problem v Texnike I Texnologyi (Magazine " Fundamental and Applied Problems of Technics and Technology "), 1*(321), 90–96 Orel.
Wang, C. F., Tzeng, F. S., Chen, H. G., & Chang, C. J. (2012). Ultraviolet-durable superhydrophobic zinc oxide-coated mesh films for surface and underwater-oil capture and transportation. *Langmuir, 28*(26), 10015–10019.