Супутні гарматним пострілам високі температури та хімічна дія порохових газів активно руйнують поверхневий шар матеріалу каналу ствола. Це порушує геометрію каналу ствола, понижує точність прицільної стрільби гармати. Запропонована технологія зміцнення поверхневим пластичним деформуванням внутрішньої поверхні каналу стволів крупнокаліберних артилерійських і танкових гармат. Зміцнювальна технологія грунтується на проклепуванні металу каналу ствола сферичними деформівними тілами, що встановлені на масивному циліндричному зміцнювачі. Зміцнювачу в процесі обробки надають обкочувального руху по оброблюваній внутрішній поверхні каналу ствола та переміщень вздовж геометричної осі оброблюваного ствола гармати. У результаті цієї зміцнювальної обробки у товщі матеріалу каналу ствола формуються залишкові напруження стиску, підвищується його поверхнева мікротвердість. Це підвищує опір матеріалу каналу ствола його вигоранню та зношуванню під час гарматних пострілів.

Зміцнювальний пристрій для здійснення цієї обробки складається із циліндричного зміцнювача із деформівними тілами, електродвигуна приводу та механізму передачі крутного моменту від валу двигуна до зміцнювача. У процесі зміцнювальної обробки пристрій переміщається вздовж каналу ствола гармати, зміцнювач обкочується по оброблюваній внутрішній поверхні ствола та проклепує його матеріал. Забезпечувана товщина зміцнення 0,15–0,20 мм.

Зміцнений поверхневий шар матеріалу каналу ствола гармати завдяки підвищеній мікротвердості надійно протистоїть формуванню в ньому експлуатаційних мікротріщин. Наведені в товщі металу каналу ствола напруження стиску протистоять температурному розростанню мікротріщин. Завдяки цьому підвищується опір зміцненого металу ствола експлуатаційному руйнуванню, підвищуються надійність та довговічність вартісного артилерійського озброєння

Ключові слова: артилерійська гармата, канал ствола гармати, високотемпературне вигорання, зношування, поверхневе зміцнення, підвищення мікротвердості

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DEVELOPMENT OF A TECHNOLOGY FOR THE SURFACE STRENGTHENING OF BARREL CHANNELS IN THE LARGE-CALIBER ARTILLERY GUNS

I. Aftanaziv
Doctor of Technical Sciences, Professor*
E-mail: ivan.aftanaziv@gmail.com
L. Shevchuk
Doctor of Technical Sciences, Professor
Department of Technology of Organic Products**
E-mail: shev.lili2206@gmail.com
I. Samsin
Doctor of Law, Professor
Department of Administrative and Financial Law
Khmelnytsky University of Management and Law
Heroiv Maidanu str., 8, Khmelnytsky, Ukraine, 29000
E-mail: Sam.kiev.ua@gmail.com
L. Strutynska
PhD, Associate Professor
Department of Human Resourse Management and Administration**
E-mail: lesyastrutyn@gmail.com
O. Strogan
PhD, Assistant*
E-mail: Orestastrogan@gmail.com
*Department of Descriptive Geometry and Engineering Graphics**
**Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013

1. Introduction

The barrels of artillery guns, along with a pointing shooting sighting system, are one of the most important components of the gun, which not only ensures the range and accuracy of a sighting shot, but also defines the durability of the gun in general. After all, at each shot, barrels undergo a certain destructive wear. The reasons that predetermine the wear of barrels can conditionally be divided into three main groups of chemical, mechanical, and thermal nature.

At each shot from a gun, the surface layers of its barrel channel metal are exposed to the destructive active effect of high-temperatures (up to 1,000 °C), the chemical action from powder gases, superhigh pressure, and mechanical wear caused by a shell moving along the barrel. This predetermines the destruction of the structure, strength, and density of a metal at surface layers, its burnout and wear, which eventually leads to the distorted geometry of the working surface of a barrel channel. Distorting the geometry of the working surface of a gun barrel channel negatively affects the range, and, above all, the accuracy of sighting a fire, as well as other tactical-technical characteristics of cannon weaponry related to precision. The excessively worn-out inner working surface of a barrel channel is almost not subject to repair and restoration. That predetermines such a characteristic of cannon weaponry as the permissible number of aimed fire shots, which to some extent limits the duration of the effective use of guns.

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The active destruction of a barrel's working inner surface, the so-called barrel channel, at the increasing number of shots is inherent both to mono- and multi-layer structures in the guns barrels. The difference is in the fact that the barrel pipe in a multilayer structure can be replaced, while the mono-unit barrel is almost unrecoverable at excessive wear. However, in both cases, guns are subject to overhaul due to the excessive wear of a barrel.

An analysis of technological processes aimed at forming the shape of mono-unit gun barrels and liners (interchangeable pipes) of multilayered barrels, as well as technological operations during their subsequent machining, reveals that they all ultimately build stretching stresses in the thickness of the surface layers of a barrel channel material. The high temperature heating at shooting, the accompanying pressures of up to several thousand bars, are also related to fracturing and enlarging the diameter of a barrel channel. Thus, operational loads also form the operating stretching stresses in the surface layers of a material. Taken together, the technological and operational stretching stresses add up to a rather high gradient. These stresses are aimed to break the intermolecular bonds of a material at the surface of a barrel channel, to form microcracks in the metal's near-surface thickness. The microcracks, which grow at repeated shots, merge and turn into fatigue cracks. The high temperature smoke gases that form when another charge is burned penetrate the cracks, burn out a metal within, thereby further widening them. Consequently, the microscopic pieces of a metal exfoliate from the working surface of a barrel channel and burn in the flame and high-temperature powder gases. The result is the distorted barrel channel geometry, the worsened precision of aimed fire.

Thus, it is a relevant task to undertake studies into the development of innovative technological processes aimed at improving the reliability and durability of artillery weapons. Those include, for instance, new technological processes intended to increase the resistance of a gun barrel material to operational loads that manifest themselves during shooting. One of these fields of research is the development of a technology to enhance the strength characteristics of the surface layer of a barrel channel material.

2. Literature review and problem statement

The experience of using cannon weapons reaches millenniums. Over all this time, designers and technologists have focused on maximizing the utilization of strength characteristics of materials used for the manufacture of guns. However, the high-quality alloyed heat-resistant steels, used at present for the manufacture of barrels guns, have almost exhausted the material's reserves in terms of its resistance to high-temperature wear. Also ineffective are the attempts to apply specialized wear-resistant coatings on the working inner surfaces of a barrel – the high-temperature flame from a shot and the chemical effect of powder gases actively corrode, destroy, and burn the thin film of coatings. It is followed by an even faster rate of destruction of the working surface of a barrel.

It should be clearly recognized that the strength characteristics of those materials that are used for the manufacture of barrels guns have been exhausted as far as their resistance to working loads is concerned. That is why designers and engineers started paying attention to the technological possibilities for improving the usability of these important elements. It is possible to achieve this through the technological improvement of characteristics of the most loaded surface layers of the components' material. For example, their roughness, surface microhardness, formation of a material capable to withstand the operational loads of the stressed state, etc. This is convincingly confirmed by the experience of using responsible parts made from the grades of steel related to the material of gun barrels. An example of such a successful technological solution is the approach, described in paper [1], to improving the durability of heavily-loaded steel parts in drilling equipment. The authors investigated a possibility to increase wear resistance of the inner surface of drill pumps sleeves by strengthening them with surface plastic deformation [2]. This helped achieve a substantial, 25 %, improvement in the wear resistance of a pumps' material. However, the channels of gun barrels are not characterized by abrasive wear. Therefore, the results from that study cannot be applied without a proper revision in order to improve the durability of gun barrels.

Vivid examples of the technological improvement of the properties of parts' materials are the use of high-temperature hardening operations in the manufacture of steel components. Specifically, normalizing, hardening, etc., as well as the accompanying grinding, polishing the parts' working surfaces, and a series of other technological finishing operations [3]. Not the last in their list are the strengthening operations for surface layers of a parts' material by various methods of surface plastic deformation, commonly referred to as the «SPD methods» [4]. Different strengthening SPD methods are not only thoroughly explored, but described in scientific works, for example, [5, 6]. The most efficient ones from the cohort of strengthening SPD methods, such as a roller-based application [7], stamping, burnishing [8], shot-blasting and vibro-strengthening treatments [9], and so on, are widely used in industrial sectors. The advantage of these strengthening technologies is that they, while not exposing parts to energy-intensive high-temperature heating, improve the strength characteristics and operational properties of the most-loaded surface layers of their material. Universally recognized by manufacturers of mission-critical components is the fact that the use of SPD methods in the technological processes of parts fabrication contributes to increasing their reliability and durability [10].

Thus, papers [5, 7] report results from theoretical and experimental research into the influence of strengthening technologies on the performance of responsible heavily-loaded parts. It is shown that along with the improvement in the strength characteristics of the material of the parts strengthened by PPD, their reliability, durability, and the capability to resist operational loads are considerably affected by the residual stresses formed in the thickness of the strengthened material [5]. In this case, it was proven that for those parts that work under conditions of surface wear the crucial factors to their durability is the roughness of the surface and its microhardness. For parts that are exposed to cyclic loads, particularly sign-changing, the primary factor that determines durability is the character (compression or stretching) and the level of residual stresses in the thickness of a material's surface layers [3]. It was established that for friction pairs the more favorable, in terms of durability, are the stretching stresses in the surface layers, while for parts that are exposed to impact or sign-changing cyclic loads – the compression stresses.

However, despite a rather thorough research into the influence of strengthening technologies on the operational properties of various parts, still unsolved are the issues on strengthening the inner surfaces of long parts. The reason for this is the objective difficulties that are predetermined by the length of these surfaces. It is too difficult, given known strengthening devices, to transmit the forces sufficient for the qualitative strengthening of material deformation lengthwise a confined space at a distance of several meters. An option for overcoming these difficulties could be those strengthening devices that are used for treating the internal surfaces of casing pipes for drill strings. That was the very approach suggested in papers [10, 11]. However, the designs of these reinforcers are not suitable for the treatment of long inner surfaces, which are confined to small diameters that are inherent to the barrels of artillery guns.

The practice of using surface strengthening of responsible parts reveals that it might be possible to improve the resistance of a barrel channel material to operational wear by introducing strengthening operations to the technological process of manufacturing barrels for guns. The requirement for these strengthening operations is to ensure that compression stresses should form in the outer layers of a barrel channel material. Along with it, the strengthening must ensure the formation of a surface layer with enhanced hardness in them, to improve the structure of a metal in its surface layers [12, 13].

The set of the above-described operational loads, to which the surface and material of gun barrels channels are exposed to, is not typical, quite universal. No any other parts, except for weapons, are exposed to a simultaneous destructive action of high temperatures on the material of steel elements, significant stretching stresses, active effect of chemical products from the combustion of powder gases. However, the positive effect of surface strengthening on the resistance to certain above factors is quite common. Thus, paper [14] proved that the vibration-centrifugal strengthening of drums and aircraft landing gear wheel flanges ensures the reliable resistance of these parts not only against impact loads, but against their heating to high temperatures during braking at aircraft landing. This is inherent to steel elements as well [15]. The studies reported by authors of papers [16, 17] established that operational stretching stresses in the thickness of a material are reliably opposed by the compression stresses, formed in advance in the metal's surface layers. And one of the possible technological means to ensure compression stresses in a parts' material is their strengthening by surface plastic deformation [18]. That was verified by the results of a research reported in [19]. The fact that is generally recognized by scientists is that the surface strengthening, owing to the enhanced microhardness of a material, significantly improves the wear resistance of steel parts. Specifically, this is reflected in papers [20, 21].

Thus, the above-noted research results allow us to expect that the high-quality strengthening of the surface layer of a guns' barrels channel material could ensure the resistance against operational loads. That, in turn, would improve the durability of guns barrels and, consequently, artillery weapons in general.

Among the dynamic methods of surface strengthening, the most common and widely used one is the strengthening of parts using shot blasting [22, 23]. Especially advanced is the strengthening of parts by shot blasting at present in Germany. It is a home to the firm Rosler, well-known to the general community of machine builders, which is the global market leader in the mass finishing and shot blasting industry. Different methods of surface hardening have been also widely applied at the machine-building enterprises in Russia. There, the strengthening treatment is mostly dominated by pressing with a roller [16, 24]. It is especially successfully applied to strengthen the radius transitions between shafts [16] and to improve the reliability of threaded connections between drill strings [24].

However, as already noted, given the specificity of the structure of long parts in general, and the channels of barrels guns in particular, neither the shot blasting strengthening, no the roller-based hardening are used to improve the mechanical properties of a metal of inner surfaces. It is too difficult to apply these strengthening techniques to transfer a deforming effort, required for high-quality treatment, inside the inner surface, limited in diameter, located at a distance of 2–3 meters from the ends of a tubular part.

Thus, the peculiarities of design structure of such specific parts as guns barrels predetermine certain difficulties when using the known SPD methods for their strengthening. The specificity of applying the known SPD methods to strengthen the barrels' channel is associated closely with the structure of guns barrels, namely a rather long working surface of a barrel's channel, that should be strengthened, as well as its small diameter. In other words, this is a very large, massive, long tubular piece, with a length from two to six meters, and a diameter of the inner surface to be strengthened in the range of 125–250 mm. In addition, the strengthening of such a long inner surface of a barrel channel is required not in order to improve the surface finish, but to achieve the high-quality cold hardening to induce compression stresses with a significant gradient in the thickness of a material. Such a circumstance makes it impossible to employ all static SPD methods (knurling, burnishing, etc.). Likewise, of little use are such common methods of dynamic strengthening as vibration-impact treatment [2] or shot blasting due to the insufficient energy for deforming a part's material, limited by a negligible mass of the deforming balls or fraction. In terms of energy capacities, a competing technique might be stamping, it is, however, inapplicable for strengthening such long and inner surfaces.

Therefore, at present there is no any SPD hardening method for strengthening the channels of barrels guns. This allows us to argue that it is expedient to undertake a research aimed at engineering the technologies and equipment in order to strengthen, by plastic deformation, the internal surfaces of long parts, specifically the channels of barrels of artillery guns.

3. The aim and objectives of the study

The aim of this study is to develop innovative technologies and equipment to strengthen, by using SPD, the inner surface of a barrels' channel in large-caliber artillery guns in order to improve their mechanical characteristics, reliability, and durability.

To accomplish the aim, the following tasks have been set:

– to analyze operating loads acting on a gun barrel's channel material while firing;

– to analyze the technological capabilities and efficiency of known variants of methods for surface plastic deformation in terms of their applicability to strengthen the channel of guns barrels;

– to devise a structural scheme for the new strengthening technological equipment, suitable for the efficient strengthening treatment of a guns' barrels channel, to define the basic technological and structural parameters for the strengthening equipment;

– to design the technological process for strengthening a gun barrel channel by the vibratory-centrifugal treatment.

4. Principal circuit of a strengthening device for treating a gun barrel channel

A group of researchers at the National University «Lviv Polytechnic» (Ukraine) built a fundamentally new method for strengthening, by surface plastic deformation, the parts of a round cross-section, which the authors called the vibratory-centrifugal strengthening treatment (VCST) [9, 10].

The peculiarity of such a strengthening is the relatively large (up to 100–150 N) forces that deformation a part's material, which is ensured through an impact contact between the massive machined part and the tool. The impact contact is enabled via a limited number of deforming bodies. Owing to this, significant contact stresses form in a material of the strengthened part. In this case, a high degree of hardening and the formation of residual compression stresses of high gradient are ensured [11].

This newly-created method of strengthening treatment was successfully tested under industrial setting for strengthening the drums and flanges of aircraft wheels, testifying to a two-fold increase in the operational performance of these critical parts when compared with the non-strengthened ones [10]. The essence of this method of strengthening treatment is given in more detail when describing the equipment that implements it.

Fig. 1 schematically shows the location inside a gun barrel channel of a device for strengthening its material by using the vibratory-centrifugal strengthening treatment.

The inner surface of an artillery guns' barrels channel is strengthened by the surface plastic deformation under the technology of vibratory-centrifugal strengthening treatment in the following way. The strengthening device is placed inside a treated gun's barrel. The basic components of the strengthening device are electric drive 1, cylindrical reinforcer 2, mechanism 4 to transmit the torque and rotary motion, connecting the electric drive's shaft and the reinforcer (Fig. 1, *a*). The outer surface of reinforcer 2 holds deforming bodies 3 in the form of steel hardened balls of high hardness.

Mechanism 4 that transfers the rotary motion to reinforcer 2 implies the rotation and radial displacement of the reinforcer relative to the geometric axis of gun barrel 5. Therefore, it is expedient to use, as a mechanism for transmitting torque and rotary motion, either a cardan or a flexible shaft. Reinforcer 2 holds fixed unbalanced mass 6 (Fig. 1, *c*). Electric drive 1 is inside case 7, which, by means of rollers 8, is centered uniaxially along the surface of machined gun barrel 5. The displacement of the strengthening device along the generatrix of the strengthened surface is enabled by wire rope 9, attached to casing 7, which is wound onto the winch drum (not shown in Fig. 1).

The maximum diameter D_1 of the circle that covers deforming balls 3 placed on reinforcer 2 is taken to be equal to:

$$D_1=(0.75–0.85)D_i,$$

where D_i is the diameter of the inner strengthened surface of a gun barrel, that is its channel in the cylindrical part.

In this case, eccentricity ε of reinforcer 2 with deforming balls 3 is equal to:

$$\varepsilon=\frac{D_i-(D_c+D)}{2},$$

where D is the diameter of the deforming steel hardened balls 3; D_i is the diameter of the inner strengthened surface of a gun barrel; D_c is the diameter of the circle where the geometric centers of deforming spherical balls 3 are located.

The principal working movement of reinforcer 2, which enables its impact interaction with the treated surface of barrel channel 5, is the mode of the planetary rolling motion over the reinforcer by the deforming bodies, which are placed at its outer cylindrical surface along the inner treated surface of barrel channel 5. Under a rolling motion, reinforcer 2 is exposed to centrifugal force F, directed radially from the center of mass of the reinforcer along the normal to the machined inner surface of the barrel channel. It is the centrifugal force F that enables the impact interaction between the reinforcer and the treated surface. It is proportional to the mass and frequency of the rolling movement of the reinforcer, as well as to the magnitude of eccentricity ε, at which the reinforcer is installed inside a barrel channel.

The quality of the strengthening treatment VCST is defined by the ensured thickness of a strengthened metal layer at the inner machined surface of a barrel channel. The thickness of strengthening is inextricably linked with the diameter of the stamps at the treated

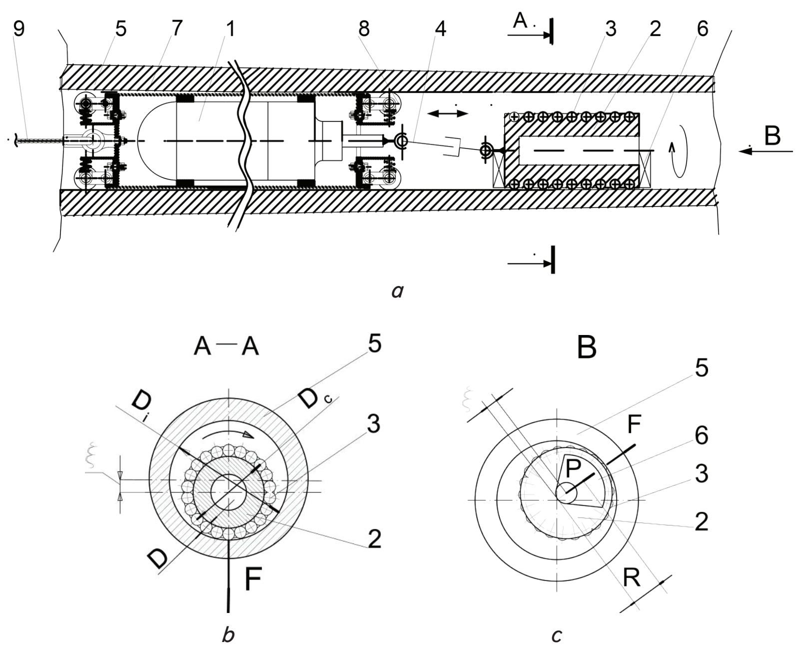

Fig. 1. Device for strengthening a gun barrel channel: *a* — location of the strengthening device inside a gun barrel channel; *b* — cross-section A—A perpendicular to the geometrical axis of the barrel; *c* — view along the direction denoted by arrow B (Fig. 1, *a*), reflecting the forces acting on the reinforcer in the course of strengthening treatment

surface after its impact interaction with deforming balls 3, as well as the mechanical properties of a strengthened material.

To ensure the predefined parameters of strengthening treatment, the magnitude for eccentricity ε is adjusted using dependence:

$$\varepsilon = \frac{\sigma_m \cdot d^2 \cdot l}{50 \cdot m \cdot D \cdot n^2}, \qquad (1)$$

where ε is the eccentricity of the reinforcer, that is the displacement of the center of mass of reinforcer 2 relative to the geometric axis of the machined surface of gun barrel 5; n is the rolling frequency of reinforcer 2 along the inner surface of barrel channel 5; σ_y is the yield strength of a material of the strengthened gun barrel 5; m is the total mass of reinforcer 2 with deforming balls 3 and unbalanced mass 6; d is the stamp diameter at the machined surface caused by the impact contact between deforming ball 3 and the surface of barrel 5; D is the diameter of the deforming spherical balls 3; l is the length of the generatrix of the outer cylindrical surface of reinforcer 2, which holds deforming balls 3.

To ensure the working rolling motion, reinforcer 2 holds unbalanced mass 6, whose mass, as well as the distance between the center of mass from the axis of rotation of reinforcer 2, are derived from dependence:

$$m_d = \frac{\varepsilon \cdot m}{2R - \varepsilon}, \qquad (2)$$

where m_d is the mass of unbalanced mass 6; m is the mass of reinforcer 2 with deforming balls 3; ε is the eccentricity of reinforcer 2; R is the distance from the center of mass of unbalanced mass 6 to the axis of its rotation.

Cylindrical reinforcer 2 revolves around its natural axis together with unbalanced mass 6 fixed on it. Shifting the center of weight of unbalanced mass 6 at distance R from the axis of rotation of the reinforcer contributes to the development of centrifugal force P, shown in Fig. 1, *c*. Under the influence of this centrifugal force *P*, given the condition assigned from dependence (2) for the mass of unbalanced mass 6, the reinforcer is self-engaged in the rolling movement. The rolling of reinforcer 6 occurs along the inner machined surface of a gun barrel channel. That is, it eliminates the danger of irregular strengthening across the entire length of the cross-section circle of the treated barrel channel 5.

Directions of displacement and rotation of reinforcer 2 are shown by arrows.

5. Technological process for strengthening a gun barrel channel by the vibratory-centrifugal treatment

Strengthening a gun barrel channel by surface plastic deformation using a given strengthening device is performed in the following way. The strengthening device is installed inside gun barrel channel 5; its electric motor drive 1 is fed power voltage (Fig. 1). When feeding power voltage to the electric motor of drive 1, the torque from its shaft, through mechanism 4 that transfers rotary motion (a cardan or flexible shaft), is transmitted to reinforcer 2, which is set into rotary motion at a frequency equal to the rotation frequency of the shaft of electric drive 1 (Fig. 1, *b*). In the process of rotation of reinforcer 2, at the rotation of unbalanced mass 6, attached to the reinforcer, the reinforcer is exposed to disturbing force *P* (Fig. 1, *c*), which is equal to the product of the mass of the unbalanced masses by the distance from the center of their mass to the axis of rotation. In wind engineering, this force is called a «static moment». The rotational vector of action from force *P* passes through the rotation axis of the reinforcer and the center of mass of unbalanced mass 6. While respecting the magnitudes for the mass of unbalanced mass 6 and the distance from the axis of rotation to the center of mass, predetermined by dependence (2), reinforcer 2, under the action of the torque, transmitted to it, as well as force P, is self-engaged in the mode of working planetary rolling motion. This movement is executed by deforming balls 3, located at its outer cylindrical surface, along the inner machined surface of barrel channel 5.

At the rolling motion of reinforcer 2 along the inner machined surface of part 5, the reinforcer is exposed to centrifugal force *F* whose effect's rotational vector is directed from the center of mass of the reinforcer and runs perpendicular to the geometric axes of the reinforcer and the machined surface. In Fig. 1, *b*, the direction of action of the centrifugal force is shown by arrow denoted by *F*. The magnitude of this centrifugal force *F* is proportional to mass *m* and eccentricity ε of reinforcer 2 and the square of circular frequency *n* of its rolling motion; it is derived from dependence:

$$F = m \cdot \varepsilon \cdot \omega^2,$$

where ω=2Πn is the circular frequency of the rolling motion of reinforcer 2.

In any time interval, reinforcer 2 is in contact with the machined surface of barrel channel 5 via deforming balls 3, placed along the generatrix of the cylindrical outer surface of the reinforcer. A contact with the next group of deforming balls 3, placed along the generatrix of the reinforcer, occurs through the impact interaction. In this case, the force of the impact on each deforming body 3 is proportional to the centrifugal force *F* acting on a rotary reinforcer, and is inversely proportional to the number $N=l/D$ of deforming balls 3, located along the generatrix of the reinforcer, that is:

$$F_y = \frac{F}{N} = \frac{m \cdot \varepsilon \cdot D \cdot \omega^2}{l},$$

where l is the length of the generatrix of the cylindrical surface of reinforcer 2; N is the number of deforming balls 3, placed along the generatrix of reinforcer 2.

The magnitude of contact stresses, ensured in places of contact with deforming balls 3 in the near-surface layers of the machined surface material as a result of the impact interaction, is determined from dependence [12]:

$$\sigma_{con} = \frac{F_y}{S} = \frac{10 \cdot m \cdot \varepsilon \cdot D \cdot n^2}{l \cdot d^2},$$

where $S = \Pi d^2/4$ is the area of the resulting stamp, proper to ensure the high-quality strengthening of the machined surface of barrel channel 5, after the impact contact with a deforming spherical body (a ball).

The rolling motion of reinforcer 2 along the inner machined surface of barrel channel 5 is executed simultaneously with a uniform axial movement of the strengthening device along the generatrix of the machined surface. This axial movement is performed by using rope 9, which is wound onto the winch drum (not shown in Fig. 1) and which pulls the entire device along the inner strengthened surface of gun 5. That provides for the uniformity of machined surface both lengthwise the circle of its cross-section and lengthwise the generatrix. If it is needed to increase the thickness of location of the strengthened layer of a material, the machined surface is exposed to repeated movements of the strengthening device along the axis of barrel channel 5, or the mass of reinforcer 2 is built up.

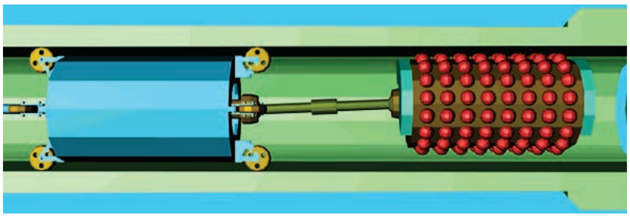

Fig. 2. Solid-body 3D model of the vibratory-centrifugal reinforcer of a gun barrel channel

Depending on the need, machining may include one or more repeated movements of the strengthening device along the generatrix of the machined surface of a barrel channel. Upon completion of the strengthening treatment of gun barrel 5, the strengthening device is driven, by rope 9, out of the strengthened barrel, and is installed inside the next barrel to be strengthened. Its strengthening treatment is conducted similarly to the treatment applied to a previous barrel.

We tested technological possibilities for strengthening a gun barrel channel using the method of vibratory-centrifugal treatment on a model of a gun barrel with the inner-surface diameter D_i=125 mm. The model of a barrel was in the shape of a pipe with a length of 1 m and was manufactured from the alloyed structural steel of grade 12XH3A with a yield strength of the material σ_y=750 MPa. The material of the barrel model in terms of its physical and mechanical properties is close to a certain extent to the materials used for the manufacture of cannon barrels.

The conditions of the experiment implied that the vibratory-centrifugal strengthening treatment should ensure that the thickness of the strengthened layer in the thickness of the metal of the machined inner cylindrical surface is within h=0.15÷0.20 mm.

Under the surface plastic deformation of steel parts by spherical deforming bodies the thickness of location of the strengthened layer of metal is related to a diameter of stamps at the machined surface via dependence $d=2h$ [13]. Thus, the diameter of the stamp, appropriate to ensure the predefined thickness of strengthening, is:

$$d=2\cdot 0.2=0.4 \text{ mm}.$$

The following geometric parameters for the reinforcer and the treatment parameters are assigned: D=10 mm is the diameter of deforming bodies (hardened steel balls); l=0.5 m is the length of the reinforcer; m=30 kg is the mass of the reinforcer with deforming bodies; N=50 is the number of deforming bodies along the generatrix of the reinforcer; n=940 rpm=16 1/sec is the rotation frequency of the electric drive motor shaft.

Substitute numeric values in dependence (1) to determine the eccentricity of the reinforcer:

$$\varepsilon=\frac{\sigma_m\cdot d^2\cdot l}{50\cdot m\cdot D\cdot n^2}=\frac{750\cdot 10^6\cdot(0.4\cdot 10^{-3})^2\cdot 0.5}{50\cdot 30\cdot 10\cdot 10^{-3}\cdot 16^2}=15.6 \text{ mm}.$$

Thus, we have defined the basic geometric parameter for the reinforcer, maintaining which would ensure the high-quality strengthening of the inner surface of a gun barrel by the proposed method of vibratory-centrifugal treatment.

6. Discussion of results of studying the vibratory-centrifugal strengthening of a gun barrel channel

The most significant result of the current study is, in our opinion, a possibility, suggested to the developers and producers of new equipment, to perform the strengthening treatment of inner surfaces of long parts. The variety of these parts is quite common. In addition to gun armament, these include the casing and drill pipes for wells, as well as their couplings and nipples, sleeves for pumps in drilling equipment. There are also the high-pressure pipes and the elements of round cross-section of uprights at aircraft chassis, etc. Implementing the strengthening of the inner surfaces of these parts using the described vibratory-centrifugal treatment will not only improve the durability and reliability of these important components. The strengthening opens up a prospect of reducing their mass, which promises significant savings in the cost of a metal.

A specific feature of the described strengthening technology is the application, in the device that implements it, of the reinforcer's considerable energy as the energy of deformation, which rolls along the inner machined surface. Its source is the centrifugal force, which is proportional to the mass and speed of the reinforcer. The mass of a reinforcer can reach $m\approx 50$ kg, its speed during rolling planetary motion is, accordingly, $V\approx 0.75$–1.1 m/s. This provides for a force of the impact on each deforming ball within 50–75 N. Given that the area of the contact between a deforming ball and a strengthened surface does not exceed several square millimeters in the thickness of a strengthened material, the places of contact undergo significant contact stresses. These contact stresses are close to the yield strength of a strengthened material, which ensures the strengthening thickness within 0.15–0.2 mm.

Compared with other types of SPD strengthening treatment, only stamping ensures similar values for both the forces of impact interaction and the thickness of the strengthened layer of a material. However, stamping is inapplicable for the strengthening treatments of parts' inner surfaces. The novelty and originality of the method of vibratory-centrifugal strengthening treatment of internal surfaces of long parts, including cannon barrels, as well as the design of the reinforcer, are protected by Ukrainian patents for inventions [10]. To some extent, this confirms the priority of Ukraine in the field of strengthening technologies and designs for reinforcers aimed at machining the surfaces of long parts.

In addition to strengthening the inner surfaces of tank and artillery guns of large caliber, these designs of devices are suitable for the high-quality strengthening treatment of outer and inner surfaces of high-pressure pipes, outer surfaces of tank torsion shafts and torsion shafts for multi-tonnage self-propelled artillery units, drilling and casing pipes for well-boring machines, etc. However, there are certain limitations on the use of the current research results. The most essential of them is the lack of data on «field tests» of the strengthened gun barrels. We were not able to perform such tests. And this is absolutely crucial in terms of the expediency for industrial implementation of the proposed strengthening technology and its effectiveness.

Of course, this is a flaw of this study. Its elimination could involve laboratory tests of the strengthened models of gun barrels by exposing them to high-temperature heating and burning the strengthened surface with a flame. A possible criterion for evaluating the effectiveness of strengthening could be to test the strengthened and burnt-out surface for wear.

However, such tests require specialized equipment whose certain elements such as a furnace for blowing the surface with a flame will have to be designed. And all this would entail temporal and tangible financial costs. However, we hope we shall be able to implement it in the future.

7. Conclusions

1. We have analyzed operational loads acting on a material of the artillery gun barrel channel. It was established that the high temperatures and pressures that accompany gun shots form the operational stretching stresses in the thickness of a barrel channel material. These stretching stresses contribute to the development and propagation of microcracks, which distort the geometry of a barrel channel.

2. Our research into the strengthening methods by surface plastic deformation has established that none of known variants is suitable for the high-quality strengthening of the inner surfaces of long parts. This has necessitated conducting our research aimed to design equipment for the high-quality strengthening of channels in the barrels of artillery weapons.

3. We have proposed the design of reinforcers for strengthening treatment by surface plastic deformation using the method of vibratory-centrifugal strengthening of channels in the large-caliber barrels of artillery guns. The suggested reinforcers are simple in structure, energy-intensive, they do not need any highly qualified staff.

4. A new method of the vibratory-centrifugal strengthening treatment has been constructed, which belongs to the group of dynamic methods of surface plastic deformation. It is distinguished by ensuring a significant level of deformation energy for the material of strengthened parts and is suitable for the strengthening treatment of the inner surfaces of long parts. The ensured thickness of the strengthened layer of a steel parts' material is 0.15–0.20 mm.

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Запропоновані методи вираховування індексних оцінок при відборі верстатників забезпечують більшу точність, чим відбір на основі експертних оцінок та їх інтегрованих показників груп експертних оцінок.

Індексні оцінки вираховуються на основі алгоритму об'єднання самооцінок і експертних оцінок у Індекс якості сформованості професійної компетентності верстатника (ІПК), а об'єднання експертних оцінок і нормованих оцінок – у Індекс якості підготовки верстатника (ІЯП). Запропоновані методи вираховування індексних оцінок комплексно характеризують елемент функціонування соціальної підсистеми системи «Верстатник – Верстат з числовим програмним керуванням – Керуюча програма виготовлення деталі», ВВКП.

Індексні оцінки характеризують міру узгодженості/розбалансованості самооцінок і експертних оцінок та експертних оцінок і нормованих оцінок, а також системних взаємозв'язків верстатника з елементами соціальної, технічної та інформаційної підсистем відкритої системи.

Переваги відбору верстатників на основі індексних оцінок, у порівнянні з експертними оцінками, спостерігалися при співставленні двох рядів рангових місць у списку прізвищ. Ряди рангових місць отримані з використанням методів – лінійної згортки, мультиплікативної згортки. Доведено, що відбір верстатників з використанням методу лінійної згортки значно точніший, якщо проводиться на основі індексних оцінок, при порівнянні з експертними оцінками. Для відбору верстатників згідно вимог Замовника доцільно використовувати метод бінарного пошуку

Ключові слова: самооцінки, експертні оцінки, нормовані оцінки, об'єктивні оцінки, індексні оцінки

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APPLICATION OF INDEX ESTIMATES FOR IMPROVING ACCURACY DURING SELECTION OF MACHINE OPERATORS

A. Laktionov
Lecturer
Poltava Polytechnic College of the National Technical University «Kharkiv Polytechnic Institute»
Pushkina str., 83a, Poltava, Ukraine, 36000
E-mail: laktionov.alexander@ukr.net

1. Introduction

Self-assessments estimate personality characteristics while expert estimates describe products from machine operators' activities. Therefore, the selection of machine operators that act as elements of complex systems is successfully carried out using expert estimates.

A method of fuzzy logic proposed in paper [1] for the selection of professionals based on expert estimates makes it possible to obtain stable ranked lists of surnames that are consistently repeated. The selection of machine operators based on expert estimates only has its limitations. Specifically, it does not make it possible to use for its analysis the indicators defining the degree of consistency between expert