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INCREASING THE DURABILITY OF LARGE-CALIBRE CANNON BARRELS THROUGH STRENGTHENING THEM BY SURFACE PLASTIC DEFORMATION

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ABSTRACT

The paper presents a technology for strengthening the internal surface of the bore of cannon and tank barrels through surface plastic deformation. It is recommended to carry out the strengthening treatment in two stages: firstly, ball peening of the inner working surface of the barrel with hardened steel balls; secondly, application of a heat-resistant hard alloy coating using deforming bodies made of the VK6 alloy. It was established that as a result of this strengthening treatment, residual compressive stresses are formed in the near-surface layer of the bore material, its surface microhardness increases and the resistance of the metal in the working surface of the barrel against burnout and cracking improves. Overall, the resistance of the barrel material to wear during cannon shots increases. A design of the strengthening device for this treatment has been developed. It consists of a cylindrical hardener with deforming bodies, an electric drive motor and a torque transmission mechanism from the motor shaft to the hardener. During the strengthening treatment, the device is moved along the channel of the cannon barrel, allowing the hardener to roll over the processed inner surface of the barrel and peen its material. The provided strengthening thickness is 0.15–0.20 mm, while the thickness of the applied hard alloy coating is up to a 100 μm.

Keywords: cannon barrel, hard alloy, coating, wear, surface strengthening, ball peening

INTRODUCTION

During each shot of the cannon, the internal surface layers of its barrel channel are exposed to the active destructive influence of high temperatures (up to 1,000°C), the chemical action of powder gases, extremely high pressures and mechanical wear from the movement of a projectile along the barrel. This leads to the destruction of the structure, a decrease in the strength and density of the metal surface layers, its burning and wear, which ultimately results in a violation of the geometry of the working surface of the bore. The violation of the geometry of the working surface of the cannon barrel channel negatively affects the range and, most importantly, the accuracy of aiming and other accuracy-related tactical and technical characteristics

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of the cannon. The excessively worn inner working surface of the bore is almost impossible to repair and restore. As a result, each cannon is characterised by a permissible number of aimed shots, which – to some extent – limits the duration of the effective use of cannons.

The analysis of the technological processes of forming monoblock cannon barrels and liners (replaceable pipes) of multilayer barrels, as well as the technological operations of their further mechanical processing, proves that all of them ultimately form tensile stresses along the radial direction of the surface layers of the barrel material. High-temperature heating during shots, accompanied by pressures up to several thousand atmospheres, also tend to break the barrel and attempts to increase its diameter. Then, operational loads additionally form operational tensile stresses in the near-surface layers of the material. In total, technological and operational tensile stresses reach a fairly high gradient. The induced stresses tend to break intermolecular bonds of the material on the surface of the borehole, forming microcracks in the near-surface layer of the metal. As a result, microscopic pieces of metal peel off from the working surface of the barrel and burn in the flame and high-temperature powder gases. Due to this, the geometry of the barrel bore is disturbed, and the accuracy of aimed shooting deteriorates.

Taking this into account, designers and developers are striving to improve the operational properties of parts and assemblies through technological methods (Shyrokov, Kusyi, Aftanaziv, Borovets & Kuk, 2010; Kusyi & Kuk, 2015). This is achieved by the technologically enhancing the characteristics of the most heavily loaded surface layers of the material of the parts, particularly their roughness and surface microhardness, in order to establish a material stress state which would be capable of withstanding operational loads (Kusyi & Topilnytskyi, 2009; 2013). Shyrokov et al. (2010) investigated the potential for increasing the wear resistance of the inner surface of drill pump sleeves through strengthening by surface plastic deformation. This resulted in an over 25% increase in the wear resistance of the pump material. However, abrasive wear is not typical for cannon bores. Therefore, the results of these studies cannot be applied without proper refinement to enhance the durability of cannon barrels.

The resistance of the barrel material to operational wear could be significantly increased by incorporating strengthening operations into the manufacturing process of cannon barrels, which would ensure the formation of compressive stresses in the outer layers of the barrel material (Aftanaziv & Shevchuk, 2018a; 2018b; 2018c).

The purpose of the research is the development of technology for strengthening internal channels of large-calibre cannon barrels by surface plastic deformation to increase their strength characteristics, reliability and durability. In order to achieve this goal, it is necessary to solve the following problems:

- analysis of operational loads acting on the material of the cannon barrel during firing,
- development of structural schemes of new strengthening technological equipment, suitable for effective strengthening treatment of the barrel channel of large-calibre cannons.

MATERIAL AND METHODS

Strengthening by surface plastic deformation of the inner surface of artillery cannon barrels through the proposed technology of vibration-centrifugal strengthening treatment is carried out as follows. A strengthening device (Fig. 1) includes an electric drive (*1*) and a cylindrical hardener (*2*). The hardener has deforming bodies (*3*) that are rotatably placed on its outer surface and take the form of hardened steel balls or carbide deforming bodies of a special configuration. The device is located inside the cannon barrel (*4*) being processed. The electric drive (*1*) and the cylindrical hardener (*2*) are connected to each other by a mechanism (*5*) that transmits torque and rotational motion. A feature of the rotational motion transmission mechanism (*5*) in this device is that, in addition to transmitting torque to the hardener (*2*) with deforming bodies (*3*), it also facilitates the rotational movement of the hardener around the symmetry axis of the cannon barrel (*4*). For this purpose, the mechanism (*5*) employs either a cardan or flexible shaft.

When a voltage is applied to the drive electric motor (*1*), the torque from its shaft is transmitted through the rotating motion transmission mechanism (*5*) – either a cardan or flexible shaft – to the hardener, which thus acquires a rotating motion with a frequency corresponding to the rotational speed of the electric drive shaft (*1*).

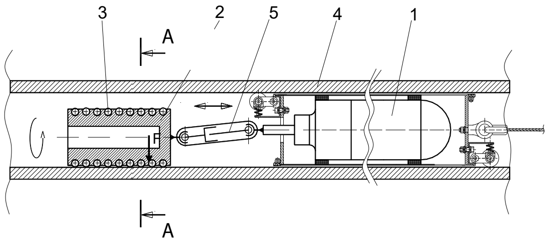

Fig. 1. Device for strengthening the cannon barrel (description in the text)

Source: own work.

In Figure 1, the directions of movement and rotation of the hardener (*2*) are indicated by arrows. Since the hardener (*2*) with deforming bodies (*3*) is designed with an eccentric displacement of its mass centre and axis of rotation relative to the geometric axis of the treated surface, the hardener, under the influence of the torque applied to it, self-engages in the mode of planetary rolling motion along the internal treated surface via its outer cylindrical surface.

To ensure this working rolling movement functions correctly and that the quality of the strengthening treatment is adequate, the geometric dimensions and parameters of the strengthening movement are selected to fulfil a relationship (Fig. 2):

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

where:

ε – eccentricity of the mass centre of the hardener (*2*) relative to the geometric axis of the machined surface of the barrel (*4*) of the cannon,
σ_m – yield point of the material of the strengthened cannon barrel (*4*),
d – the diameter of the processed surface resulting from the impact contact of the deforming body with the cannon barrel (*4*),
l – length of the external cylindrical surface of the hardener, on which the deforming bodies are installed.
m – mass of the hardener (*2*) with deforming bodies (*3*),
D – diameter of spherical deforming bodies,
n – rolling frequency of the hardener (*2*) on the inner surface of the cannon barrel (*4*),
l – length of the external cylindrical surface of the hardener, on which the deforming bodies are installed.

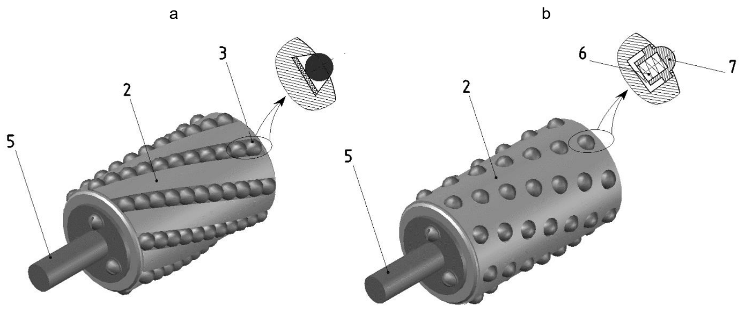

Fig. 2. Reinforcement of the inner surface of the cannon barrel with deforming bodies in the form of hardened steel balls (a) and hard alloy deforming bodies (b), (description in the text)

Source: developed by the authors.

During the rolling movement of the hardener along the internal processing surface of the cannon barrel (*4*), the hardener is subjected to the action of a centrifugal force *F*, the rotating vector of which is set in the centre of the hardener's mass and runs perpendicularly to the geometric axes of the hardener and the treated surface (Fig. 1). In Figure 1, the direction of action of the centrifugal force is shown by an arrow with the letter F.

The magnitude of this centrifugal force *F* is proportional to the mass *m* and eccentricity of the hardener *ε* and the square of the circular frequency *n* of its rolling motion. It is determined as follows:

$$F = m \cdot \varepsilon \cdot \omega^2, \tag{2}$$

where:
$\omega = 2\pi n$ – circular frequency of the rolling motion of the hardener.

At any time, the hardener contacts the treated surface of the barrel (*4*) through deforming bodies (*3*); for example, hardened steel balls placed along the cylindrical outer surface of the hardener. The contact with the duty group of deforming bodies located along the forming hardener occurs with impact interaction.

The rolling movement of the hardener (*2*) along the internal machined surface of the cannon barrel (*4*) is carried out simultaneously with the uniform movement of the strengthening device along the generatrix of the surface being hardened and the axis of the barrel. This ensures a uniform strengthening of the treated surface both along the circumference of its cross-section and along the length of the generatrix. If it is necessary to increase the thickness of the strengthened layer of material on the treated surface, movements of the hardening device along the axis of the barrel (*4*) are repeated or the mass of the hardener (*2*) can be increased.

After the completion of the first stage of the strengthening treatment of the inner surface of the cannon barrel (*4*), the cylindrical hardener (*2*) with spherical deforming bodies (*3*) of hardened steel is disconnected from the electric drive motor (*2*) and a similar hardener with spring-loaded hard alloy elastic elements (*6*) is attached. The second stage of strengthening treatment using carbide deforming bodies (*7*) is carried out similarly to the first one.

In this stage, at the points of impact contact of the carbide deforming bodies (*7*) with the already hardened inner surface of the cannon barrel (*4*), due to the transfer of microparticles of the powdered carbide alloy from which these deforming bodies are made of, the transfer of blocks of carbide molecules into the roughness cavities occurs at the molecular level. Then, since the cylindrical hardener (*2*) is rolled along the inner surface of the barrel (*4*) with a frequency equal to the rotational speed of the shaft of the electric motor of the drive (*1*), preferably equal to 16 Hz or 24 Hz, each of several hundred carbide deforming bodies (*2*) arranged on the hardener (*2*) causes 16 blows on the processed trunk surface per second. Since each blow of the deforming body (*7*) is accompanied by the transfer of hard alloy microparticles to the treated surface, the processed inner surface of the cannon barrel (*4*) is covered with a uniform layer of hard alloy pressed into the unevenness of the surface layer of the barrel metal. Moreover, each subsequent blow to a hard alloy microparticle already applied to the metal barrel not only adds the next portion of material but also "presses" the previous hard alloy microparticles into surface irregularities. Thanks to the gluing of carbide microparticles into the roughness of the barrel surface, such a carbide coating does not peel off from the thickness of the base material, connecting to it at the level of micro-welding. Since, during processing the hardener (*2*) with hard alloy deforming bodies (*7*) moves along the geometric axis of the hardened barrel (*4*), the entire inner surface of the barrel is covered with a uniform thin layer of hard alloy coating, having a thickness of several tens of microns. Despite the insignificant thickness of such a hard alloy coating on the inner surface of the cannon barrel, due to the high melting point, this coating will reliably resist the burnout of microparticles of the barrel metal when the cannon is fired.

In the technological process of manufacturing a cannon barrel, this two-stage strengthening treatment is the final finishing operation.

RESULTS AND DISCUSSION

The second stage of strengthening treatment, in accordance with this utility model, was carried out using hard alloy deforming bodies made of VK6 alloy, formed by sintering. The configuration of hard alloy deforming bodies and their location on reinforcement (*2*) is shown in Figure 2b. The diameter (*D*) of their spherical impact part was 10 mm. Strengthening treatment with carbide deforming bodies, in order to apply a carbide coating to the inner surface of a cylindrical sample reinforced with hardened steel balls, was carried out in three alternating passes along the generatrix of this cylindrical sample equal to 100 cm.

Measurements of the thickness of the hardened layer on the inner surface of the cylindrical sample after strengthening with hardened steel balls were carried out on ring samples cut from the hardened part using a metal microhardness measuring device PMT-3. Depending on the main technological parameters of the strengthening treatment with hardened steel balls, namely the mass of the hardener, the frequency of its rolling movement along the inner surface of the barrel, the speed of movement of the hardener along the generatrix of the fastening surface and the number of repeated transitions, the strengthening depth varied in the range of 0.1–0.2 mm.

The thickness of the VK6 hard alloy coating applied with hard alloy deforming bodies was measured on thin sections of samples treated by hardening using a Nikon E200 microscope with 100× magnification. Depending on the aforementioned technological parameters, it varied in a range from several tens to hundreds of microns.

A comparative test of the effectiveness of the proposed method of step-by-step hardening of the inner surface of cylindrical parts was carried out based on data from wearing tests on hardened samples, conducted on an experimental installation designed to determine the wear resistance of materials. This installation followed the scheme of a standardised Pin-on-Disk Test type (ASTM G99) installation for testing material wear. Its standardised technique involves measuring wear between two surfaces, one being the surface of the test piece and the other being the surface of a rotating disk. The wear of three groups of samples was compared, namely the original non-strengthened samples made of alloyed structural steel grade 12XH3A, whose characteristics are close to those of the material used in cannon barrels, and similar samples subjected to hardening treatment by deforming bodies. Testing of samples from all the aforementioned groups was preceded by exposing them to a flame of alcohol vapours for 5 min to simulate the effect of flame and powder gases accompanying cannon shots on the metal of cannon barrels.

Experimental studies revealed that the wear resistance of the samples with the surfaces strengthened by hardened steel deforming bodies and subjected to high-temperature treatment is 35–40% higher than that of non-strengthened similar samples. It was established that the wear resistance of the samples strengthened in stages with steel and hard alloy deforming bodies is 25–30% higher than that of samples strengthened only with steel deforming bodies. In general, a comparison of the wear resistance of non-strengthened samples and those strengthened in stages with hardened steel and hard alloy deforming bodies indicates that two-stage strengthening treatment can increase the wear resistance of steel parts by 60–70%. Of course, taking into account the entire complex of negative factors affecting the metal of cannon barrels, such as the combination of high temperatures with enormous pressures accompanying a cannon shot, the effect of strengthening treatment will be significantly reduced. However, thanks to the two-stage strengthening with the final formation of a hard alloy coating on the inner working surface of the cannon barrel, it is reasonable to hope for an increase in the durability of cannon barrels by 20–25%. The true magnitude of changes in the durability of large-calibre cannon barrels reinforced alternately with hardened steel and carbide deforming bodies can only be established on the basis of data from so-called full-scale bench or field firing tests.

The advantage of the method for increasing the durability of artillery barrels, in accordance with the proposed utility model, is that the carbide coating applied to the inner surface of the cannon barrel can significantly enhance the heat resistance of the material under high-temperature operating conditions. The presence of the carbide coating provided by the proposed method manifests itself positively in the following aspects:

- it forms a so-called thermal barrier – an obstacle that reduces heat transfer to the main body of the barrel metal, which helps reduce overheating of the barrel metal and results in decrease in strength,
- it increases the resistance of the metal against oxidation and corrosion – the formed carbide protective layer of the metal is resistant to chemical attack and reduces the rate of oxidation of the material and, accordingly, its corrosion,
- it protects the structure of the surface layer of the metal, improving its resistance to deformation and cracking under the influence of high temperatures.

CONCLUSIONS

1. A fundamentally new method of vibration-centrifugal strengthening treatment has been created, belonging to the group of methods of surface plastic deformation. It is characterised by providing a significant level of deformation energy for the material of the parts being strengthened. The method falls within the category of dynamic surface hardening techniques, delivering a hardening layer thickness of 0.15–0.20 mm on the internal surfaces of cylindrical long parts. Due to the substantial energy of the impact interaction between the tool and the material of the workpiece, residual compressive stresses with a significant gradient are formed in its surface layers. As a result, this enhances the strength and reliability of the hardened parts.
2. It has been proposed that new designs of hardeners be used for a two-stage strengthening treatment employing the method of vibration-centrifugal strengthening for the barrel channels of large-calibre artillery cannons. The proposed hardeners are simple in design, energy-saving, and do not require highly qualified maintenance personnel for upkeep.
3. During the final, second stage, strengthening the inner surface of cannon barrels with carbide deforming bodies made of VK6 alloy ensures an increases the heat resistance of the barrel material and its resistance to high-temperature heating during firing.

Authors' contributions

Conceptualisation: I.A., I.S., O.S.; methodology: I.A. I.S., O.S.; validation: Y.R., O.B.; formal analysis: Y.R., O.B.; investigation: D.B., N.K.; resources: D.B., N.K.; writing – original draft preparation: I.A., I.S., O.S.; writing – review and editing: D.B., N.K., M.C.; visualisation: I.A., I.S., O.S.; supervision: I.A.; project administration: N.K.; funding acquisition: N.K.

All authors have read and agreed to the published version of the manuscript.

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ZWIĘKSZANIE WYTRZYMAŁOŚCI LUF DUŻEGO KALIBRU POPRZEZ POWIERZCHNIOWE WZMOCNIENIE ODKSZTAŁCENIA PLASTYCZNEGO

STRESZCZENIE

W artykule przedstawiono technologię wzmacniania powierzchni wewnętrznej luf armat i czołgów poprzez powierzchniowe odkształcenia plastyczne. Zaleca się przeprowadzenie obróbki wzmacniającej w dwóch etapach – kulkowanie naporowe wewnętrznej powierzchni roboczej lufy kulkami ze stali hartowanej, a następnie nałożenie żaroodpornej powłoki z twardego stopu z odkształcalnymi korpusami ze stopu VK6. Ustalono, że w wyniku tej obróbki wzmacniającej w przypowierzchniowej warstwie materiału otworu wiertniczego powstają szczątkowe naprężenia ściskające, zwiększają się jego mikrotwardość powierzchniowa oraz odporność metalu powierzchni roboczej lufy na wypalenie i pękanie. Łącznie zwiększa to odporność materiału lufy na zużycie podczas strzałów. Powstał projekt urządzenia wzmacniającego do tego zabiegu. Składa się ono z cylindrycznego utwardzacza z odkształcalnymi korpusami, elektrycznego silnika napędowego oraz mechanizmu przenoszenia momentu obrotowego z wału silnika na utwardzacz. W procesie obróbki wzmacniającej urządzenie przesuwa się wzdłuż kanału lufy, utwardzacz toczy się po obrobionej powierzchni wewnętrznej lufy i kulkuje jej materiał. Przewidywana grubość wzmocnienia wynosi 0,15–0,20 mm, grubość nałożonej powłoki z twardego stopu dochodzi do 100 μm.

Słowa kluczowe: działa, twardy stop, powłoka, zużycie, wzmocnienie powierzchniowe, kulkowanie naporowe