ISSN 2409-9066. Sci. innov. 2015, 11(3): 5—10

doi: http://dx.doi.org/10.15407/scine11.03.005

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THE USE OF TITANIUM IN THE FRICTION UNITS OF ARTIFICIAL JOINTS

The possibility of using titanium in the friction units of artificial joints has been studied. Tribological characteristics of the titanium–Chirulen friction pair have been discussed. A technique for diamond-abrasive machining, polishing, and gas-phase thermal nitridation of spherical heads of pure titanium implants for hip joint endoprostheses has been developed. It is proved the increases of titanium head hardness achieved by pre-grinding the surface layer structure after cold plastic deformation.

Keywords: pure titanium, tearing, plastic deformation, Chirulen, and nitridation.

Titanium has the highest strength-to-density ratio among all construction materials. It is nontoxic, corrosion and erosion resistant [1]. Thanks to these properties, titanium is increasingly used in the aerospace industry, medicine, cryogenic engineering, chemical industry, and shipbuilding.

However, titanium and its alloys have a high propensity for seizure that prevents its use for the manufacture of friction components [1]. The solution of this problem is very relevant primarily for medicine and aviation for which biocompatibility and weight reduction, respectively, are of paramount importance. In the first case, it would enable the application of titanium to making hip joint endoprostheses, while in the second one, it would make it possible to manufacture aircraft friction pairs.

Today, in medicine, the most frequent bone surgery is hip joint replacement. The global statistics show that every year, in average, 500–1000 patients per 1 million of population require hip joint replacement [2].

General view of hip joint endoprosthesis is showed in Fig. 1. Worldwide, including Ukraine, the vast majority of patients has an implanted endoprosthesis consisting of a metallic ball-shaped head and acetabular cup with Chirulen inlay. Thus, according to the data on 35 U.S. hospitals, in 2007, the share of such joints in the hip joint replacement surgeries accounted for 55% [3], with the heads of CoCrMo alloy being used in most cases. However, this alloy is not an optimal one in terms of biocompatibility. Fig. 2 shows that titanium alloys have much better indices [4], with pure titanium being the most biocompatible material. However, its use is prevented by increased susceptibility to tearing.

Most researchers believe that titanium alloys as a material component of friction joints cannot be used unless the working surface is modified in a way that ensures an optimal combination of strength and adhesion inertness.

To obtain the mentioned effect it is necessary to modify the surface layer using thermodiffusion saturation with nitrogen [5]. This technique allows the researchers to widely vary technological regimes, resulting properties of the nitrided layer, and its triboengineering characteristics. The existence of a wide range of homogeneity in the Ti-N system enables controlling the physicochemical properties of the compound and its crystallographic and electronic structures. In addition, this tech-

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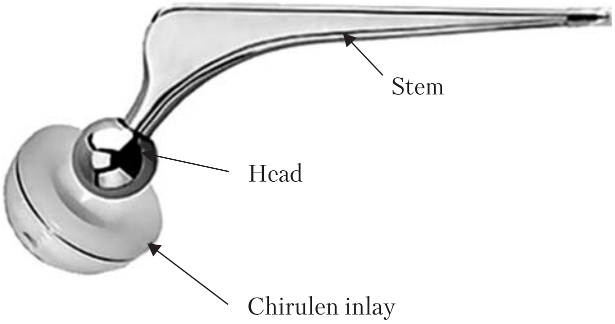

Fig. 1. General view of hip joint endoprosthesis

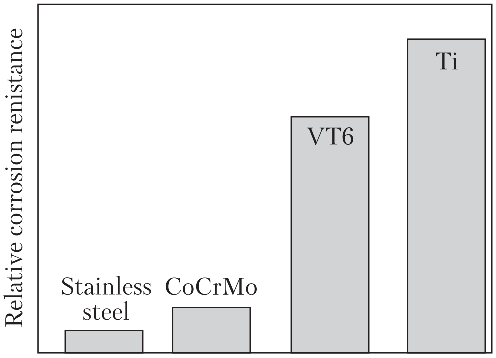

Fig. 2. Biocompatibility of materials

nique has an advantage of complete reproducibility of results and the formation transitional diffusion layer that eliminates any delamination of coating.

The process parameters of nitridation were chosen on the basis of tribotechnical tests of pure titanium-Chirulen friction joints.

The tests were performed using a friction machine, according to the *ring-plane* scheme. The regimes were selected in accordance with ASTM F732-82: speed of relative movement of samples $V = 0.057$ m/s; contact pressure $q = 3.54$ MPa; with human blood serum as working fluid. For comparison, zirconium ceramic–Chirulen, steel X18H10T–Chirulen, and CoCrMo alloy–Chirulen were also tested. The efficiency of material was assessed on the basis of friction coefficient and specific wear of Chirulen component (ratio of the wear of an area of 1 mm^2 to the rubbing path). Over 20 titanium components saturated with nitrogen at different regimes have been tested. Fig. 3 shows titanium samples having the best performance.

One can see that the titanium component modified by saturation with nitrogen has the best tribotechnical properties. It has friction coefficient and wear resistance comparable to zirconium ceramic. Its brittle fracture under dynamic loads is prevented with certainty. Having passed a rubbing path of 200 km that corresponds to ~23 million load cycles, the titanium component does not have any signs of wear. Fig. 4 shows structure and distribution of

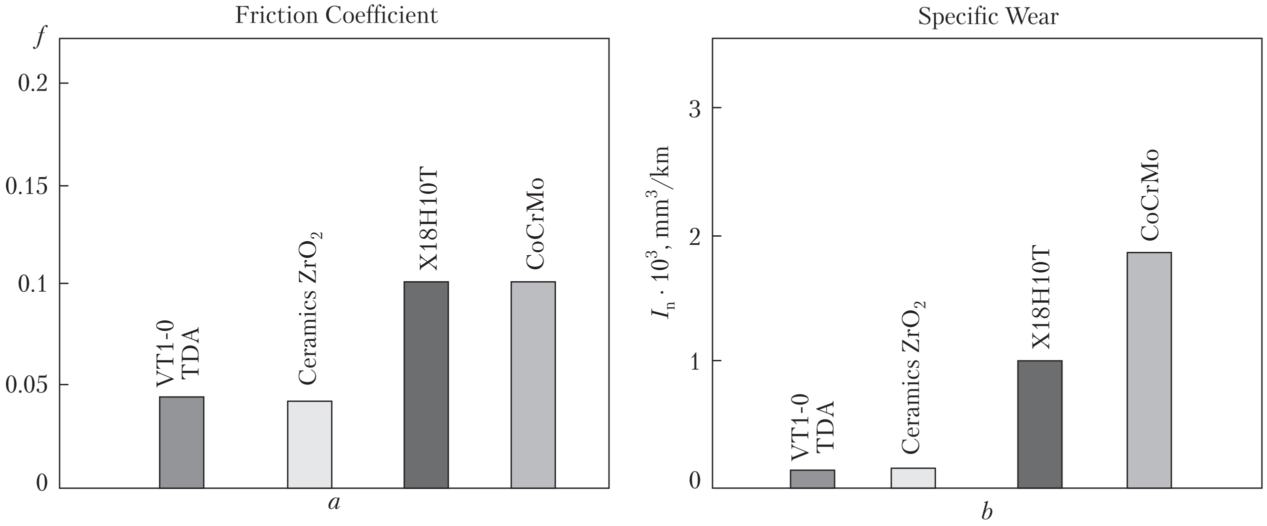

Fig. 3. Friction coefficient of VT1-0 titanium saturated with nitrogen – *Chirulen* (*a*) and specific wear of Chirulen component (*b*) in tests with the use of friction machine

micro-hardness in the surface layer of VT1-0 titanium saturated with nitrogen under optimal process parameters. They are ensured by the following parameters to strengthen the surface: nitride films ~ 5.7 mm, solid-solution diffusion layer ~70 microns, surface micro-hardness 16.7 GPa (load of 0.49 N).

Thus, the surface hardening by thermodiffusion saturation of VT1-0 titanium with nitrogen enables the use of implants with titanium components in friction joints with Chirulen.

The technological process for manufacturing the spherical head of hip joint endoprostheses of VT1-0 titanium should consist of preliminary and finishing operations. The preliminary operations include shaping and reaching the required accuracy of product shape, while the finishing ones ensure a surface roughness R_a of 0.05 micron, which meets the requirements of GOST R ISO 7206-2-2005.

The experience has showed that to obtain the required accuracy of the product shape the loose lapping method can be used quite effectively (see Fig. 5) [6]. It does not require any expensive sophisticated equipment and can be implemented using standard machinery. The lap *3* mounted in bracket *4* based on hinge joint 5 is pressed at an angle α to the item *1* put on mandrel *2* and inserted in the lathe chuck. The distinguishing characteristic of this method is low speed of relative movement of the tool along the work piece. The researchers of Institute of Superhard Materials (ISM) of the NAS of Ukraine have developed a special abrasive composite [7] that contains synthetic diamonds as an active component and prevents any impregnation of treated surface and tearing. This composite is designed to be used for manufacturing laps for preliminary precision diamond machining of spherical heads of pure titanium endoprostheses.

For traditional abrasive composites the tops of cutting grains are at different heights on the surface. Therefore, as a rule, only a small fraction of grains on which considerable load is concentrated contacts the treated surface. This leads to the destruction of grains with separation of large fragments. This increases the likelihood of direct contact between the processed material (titanium) and the binding agent, which leads to seizure and tearing.

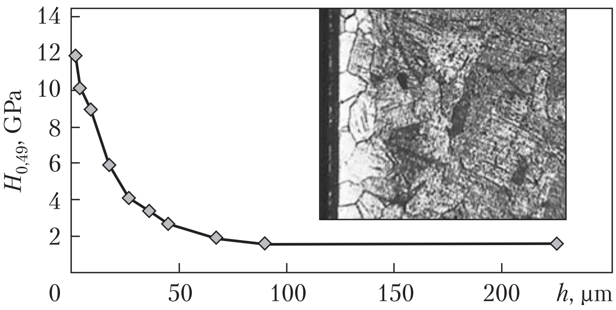

Fig. 4. Microstructure and distribution of micro-hardness in the surface layer of VT1-0 titanium after thermodiffusion saturation with nitrogen

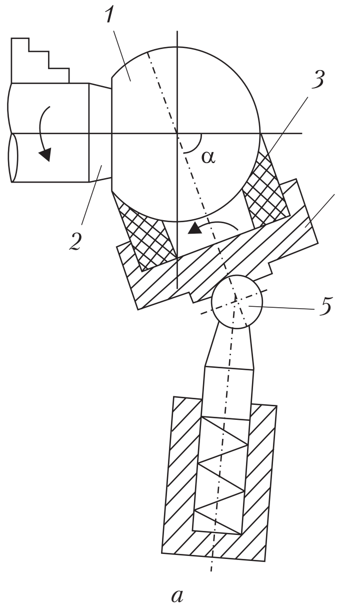

Fig. 5. Process parameters of machining the spherical heads by loose lapping method: *a* – machining pattern; *b* – laps for machining of titanium prefabrications

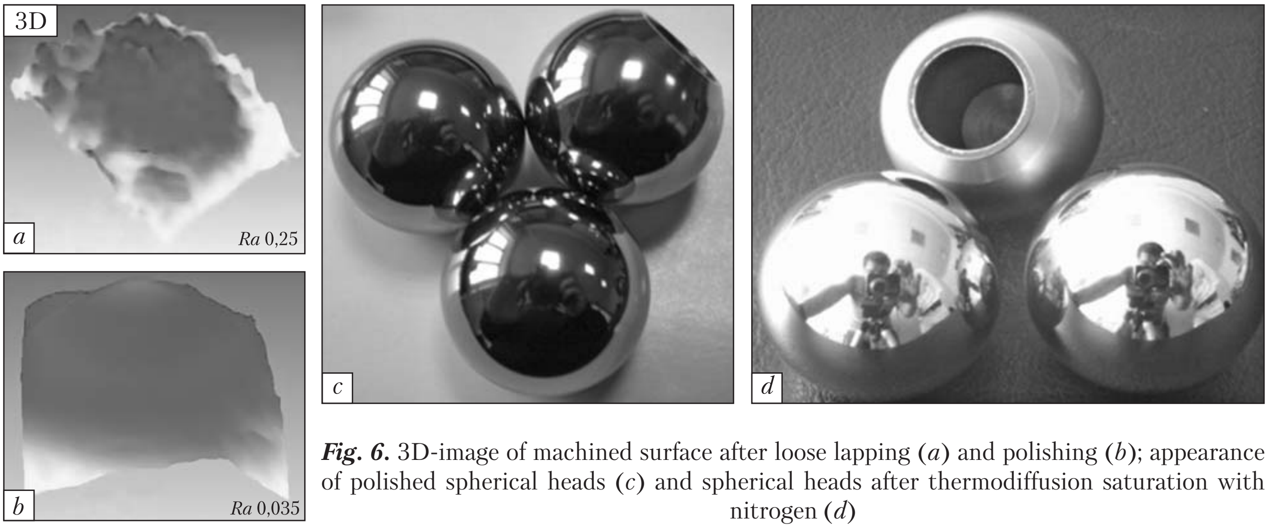

Fig. 6. 3D-image of machined surface after loose lapping (*a*) and polishing (*b*); appearance of polished spherical heads (*c*) and spherical heads after thermodiffusion saturation with nitrogen (*d*)

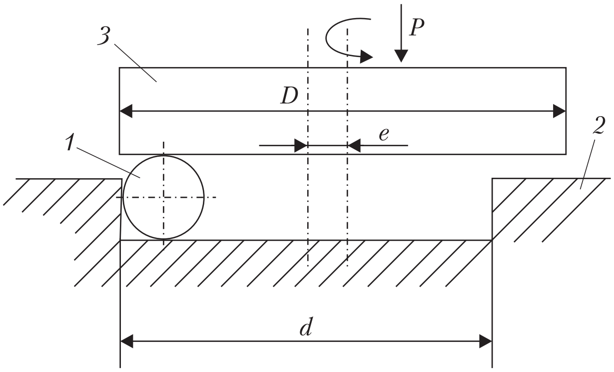

Fig. 7. Rolling of spherical prefabrications with flat surfaces

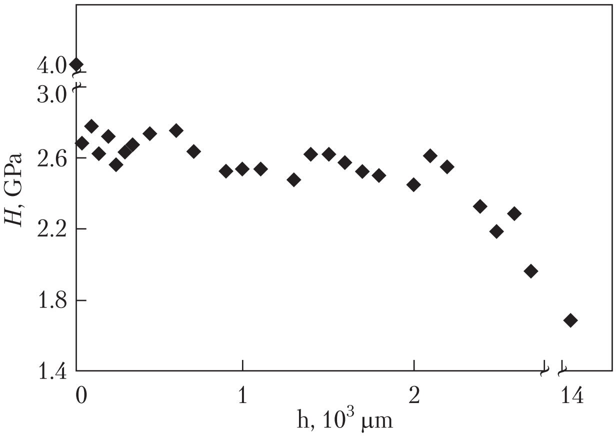

Fig. 8. Distribution of micro-hardness in the surface layer of spherical head after rolling

To avoid these negative effects it is necessary to use abrasive composites whose binding agent has elastic modulus that decreases as mechanical load on the abrasive grain increases. Epoxy-acrylate resin filled with powdered calcium carbonate has the required property. During its use, the group of most protruding grains can deepen without damage and the number of grains that make up the base of contact may increase thereby creating a reliable gap between the binding agent and the treated material. Application of this technique makes it possible to reach a deviation from sphericity of less than 5 microns and a roughness of R_a=0.25 enabling subsequent polishing to a specified roughness of the machined surface. For polishing pure titanium heads, a water-soluble compound containing modified non-drying vegetable oil has been used. Aluminum oxide embrittled after heat treatment was used as active component of polishing paste.

It has been empirically established that the best results can be obtained using seamless cotton discs having a diameter of 150 mm at n=1000/min. Fig. 6 shows a 3D image of the machined surface after loose lapping and polishing and a general view of ball-shaped heads polished and saturated with nitrogen.

Thus, the developed technique of machining the spherical heads of hip joint endoprosthesis ensures their full compliance with the requirements of GOST R ISO 7206-2-2005.

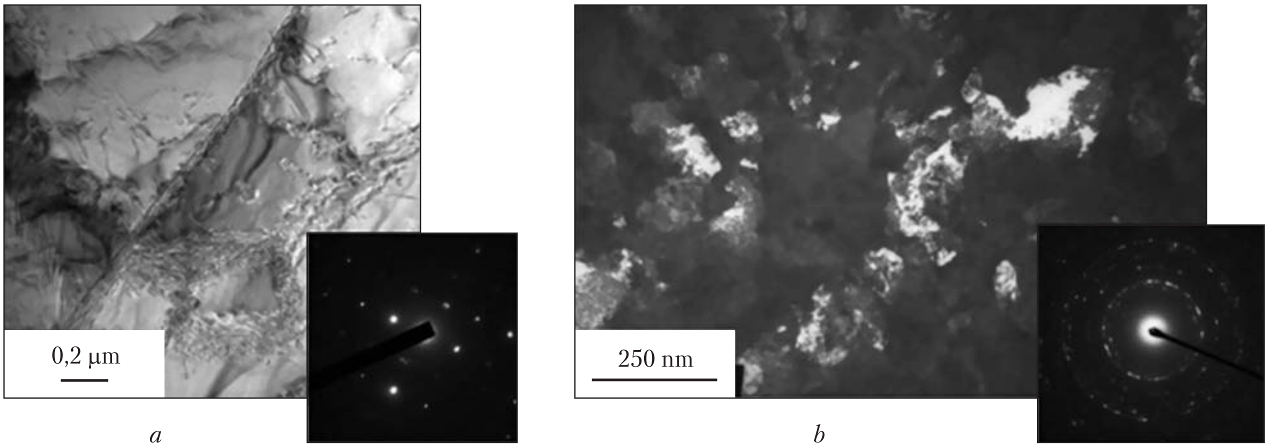

Fig. 9. Structure of VT1-0 in the original state (*a*) and formed cellular structure of the surface layer after deformation (*b*)

However, given the fact that the friction components are extremely important part of any endoprosthesis, which largely determines its service life, it is feasible to develop methods ensuring their highest reliability and durability. Among effective methods of improving the performance of surface layer saturated with nitrogen there is strengthening of its hardness and deepening through the intensification of nitrogen diffusion. This can be reached by increasing the area of distance between the grains of the surface layer of material as a result of size reduction.

The research [8] has showed that the fragmentation of VT20 titanium alloy structure before ion-plasma nitridation can significantly increase the hardness and depth of layer saturated with nitrogen. An effective method of fragmentation of structure of ductile metals and alloys is cold surface plastic deformation (CSPD) [9].

For CSPD of surface layer of the head of hip joint endoprosthesis, the ISM of the NAS of Ukraine has designed a technique of rolling with flat surfaces (Fig. 7) [10, 11]. The spherical product *1* is placed in cylindrical chamber *2*. The treatment is made using rotating tool *3* forced against the product with some force *P*. In order to ensure efficiency and quality of the machined surface and the surface layer it is necessary to ensure that the impress of tool on the product consistently covers the whole surface. A necessary condition is the displacement of rotation axis of the tool about the axis of the chamber by some eccentricity *e*.

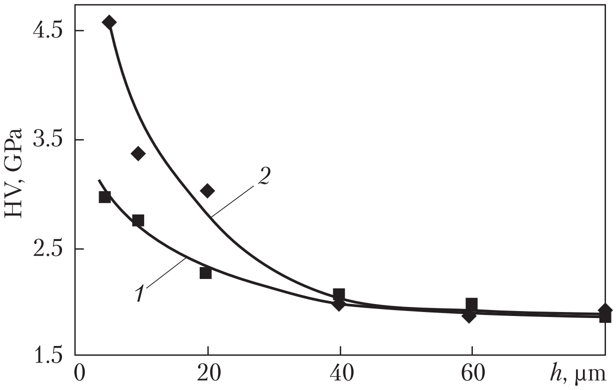

Fig. 10. Distribution of micro-hardness by depth of surface layer after thermodiffusion saturation with nitrogen with and without preliminary rolling

Micro-hardness of surface layer was measured by *Micron-gamma* device using Berkovich pyramid [12] with a load of 0.49 *N*. The study has showed that the technique ensures the formation of strengthened layer of up to 2 mm and increases its hardness 1.7 times, with the thin surface layer getting 2.5 times harder (Fig. 8).

The fine structure of the surface layer of spherical metallic head was studied using transmission electron microscopy, on JEM-2100F microscope. Fig. 9a shows the original unstrained structure of VT1-0; Fig. 9 features the cellular structure formed in the surface layer after deformation. The size of individual cells is less than 100 nm.

Fig. 10 shows the distribution of micro-hardness by depth of the surface layer after thermodiffusion saturation with nitrogen with and without prior rolling. One can see that the micro-hardness of the layer saturated with nitrogen after rolling is significantly greater than that of the layer that does not undergo the rolling treatment.

CONCLUSIONS

1. Modification of titanium by thermodiffusion saturation with nitrogen opens the possibility of using titanium components in friction joints of hip joint endoprostheses: the anti-friction properties of VT1-0–Chirulen saturated with nitrogen are significantly better as compared with traditional CoCrMo–Chirulen.
2. The technique for machining the titanium heads of hip joint endoprosthesis ensures the product compliance with GOST R ISO 7206-2-2005.
3. The cold plastic deformation of the surface layer of spherical heads preceding the saturation with nitrogen leads to the formation of nitrogen-saturated layer having much higher hardness.
4. The technique is ready for industrial application.

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ДО ПИТАННЯ ВИКОРИСТАННЯ ТИТАНУ У ВУЗЛАХ ТЕРТЯ ШТУЧНИХ СУГЛОБІВ

Вивчена можливість застосування титану у вузлах тертя штучних суглобів. Досліджено триботехнічні характеристики пари тертя *титан–хірулен*, розроблена технологія алмазно-абразивної обробки, поліровки і газотермічного азотування сферичних головок з чистого титану для ендопротезів кульшового суглобу людини. Показано, що попереднє подрібнення структури поверхневого шару титанової головки холодним пластичним деформуванням сприяє збільшенню його твердості.

Ключові слова: чистий титан, задироутворення, пластичне деформування, хірулен, азотування.

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К ВОПРОСУ ИСПОЛЬЗОВАНИЯ ТИТАНА В УЗЛАХ ТРЕНИЯ ИСКУССТВЕННЫХ СУСТАВОВ

Изучена возможность применения титана в узлах трения искусственных суставов. Исследованы триботехнические характеристики пары трения титан–хирулен, разработана технология алмазно-абразивной обработки, полировки и газотермического азотирования сферических головок из чистого титана для эндопротезов тазобедренного сустава человека. Показано, что предварительное измельчение структуры поверхностного слоя титановой головки холодным пластическим деформированием способствует увеличению его твердости.

Ключевые слова: чистый титан, задирообразование, пластическое деформирование, хирулен, азотирование.

Received 18.11.14