Damascus university journal
V… ( ): ??-??

مجلة جامعة دمشق للعلوم ....
المجلد ... العدد... : الصفحات.

سبائك Co-Cr-Mo للأطراف الاصطناعية الطبية: مراجعة

اسم وكنية الباحث الاول مسبوقة صفته العلمية المختصرة (م.، د، أ.د...))[١]، اسم وكنية الباحث الثاني ٢، اسم وكنية الباحث الثالث ٣

[1] الصفة العلمية، المركز البحثي أو الجامعة، التخصص الدقيق، البريد الالكتروني (للباحثين في جامعة دمشق البريد الإلكتروني الخاص بالجامعة للباحث)

[2] الصفة العلمية، المركز البحثي أو الجامعة، التخصص الدقيق، البريد الالكتروني (للباحثين في جامعة دمشق البريد الإلكتروني الخاص بالجامعة للباحث)

[٣] الصفة العلمية، المركز البحثي أو الجامعة، التخصص الدقيق، البريد الالكتروني (للباحثين في جامعة دمشق البريد الإلكتروني الخاص بالجامعة للباحث)

[*] توضع علامة النجمة فوق اسم الباحث الذي تتم المراسلات معه بغض النظر عن الترقيم او ترتيب الاسماء (كباحث رئيسي – طالب دراسات عليا)

الملخص:

يقدم المقال دراسة مرجعية لسبائك Co-Cr-Mo المستخدمة في الطب لتصنيع الأطراف الاصطناعية. يتم النظر في التركيبات الأساسية للسبائك من هذا النوع، وكذلك البنية المجهرية وخصائصها. يتم التطرق إلى مسائل التصنيع عن طريق الصب وكذلك طرق المعالجة الحرارية للمنتجات الطبية. وقد وجد أن استخدام المعالجة الحرارية يسمح بالحصول على البنية المجهرية اللازمة، وكذلك زيادة خصائص القوة. بالإضافة إلى ذلك، تم النظر في طرق تشطيب الأجهزة الطبية التي تساهم في تحسين الخصائص الاحتكاك.

تاريخ الايداع
تاريخ القبول

Co-Cr-Mo Alloys for Medical Endoprostheses: Review

Diana Kurach, MSc (Engineering)[*1], Pavel Lushchik, PhD (Engineering)[2], Heorgiy Viarshyna, PhD (Engineering)[3], Vladimir Minchenya, PhD (Engineering)[4], Leonid Dolgiy, PhD (Engineering)[5], Igor Rafalski, PhD (Engineering)[6].

[1]Junior Researcher, State enterprise "Science and technology park of BNTU Polytechnic", Engineering, dianakmtbnt@gmail.com

[2]Leading Researcher, State enterprise "Science and technology park of BNTU Polytechnic", Engineering, pavel-86lu@yandex.ru

[3]CEO, State enterprise "Science and technology park of BNTU Polytechnic", Engineering, gavershina@bntu.by

[4]Chief Researcher, State enterprise "Science and technology park of BNTU Polytechnic", Instrumentation, v.minchenya@bntu.by

[5]Leading Researcher, State enterprise "Science and technology park of BNTU Polytechnic", Engineering, metspl@tut.by

[6]Leading Researcher, State enterprise "Science and technology park of BNTU Polytechnic", Engineering, rafalski@park.bntu.by.

Received:
Accepted:

Abstract:

The article presents a literature review of Co-Cr-Mo alloys used in medicine for the manufacture of endoprostheses. The basic compositions of alloys of this type, as well as microstructure and their properties are considered. The questions of manufacturing by casting as well as methods of heat treatment of medical products are touched upon. It was found that the use of heat treatment allows to obtain the necessary microstructure, as well as to increase the strength properties. In addition, the methods of finishing of medical devices, which contribute to the improvement of tribological properties, were considered.

Keywords: Co-Cr-Mo alloys, Endoprostheses, Composition, Microstructure, Mechanical properties, Medical applications, Heat treatment, Finishing treatment, Surface treatment.

1. Introduction:

An actual direction of scientific search for new metal-based materials is the research devoted to the development of promising alloys for the production of medical devices. In Belarus, the medical industry is developing quite intensively, but in some of its segments there is a certain deficit of domestic products. Institutions are forced to purchase imported products, while all operating costs are tied to the foreign supplier (service, consumables). The lack of necessary products and equipment for traumatology, orthopedics and prosthetics significantly reduces the number of medical operations that can be performed annually by Belarusian specialists, which makes it impossible to fully provide those in need with appropriate treatment.

Endoprostheses are artificial bioimplants that provide restoration of the function of lost or damaged articular bone surfaces in patients with degenerative diseases and trauma consequences. Nowadays various classes of materials are used for their manufacturing: metal, polymeric, ceramic and composite materials, which function in biological media with different physical and chemical nature, and the solution of problems of their biochemical and mechanical interaction with organic tissues and bone material is a complex task of interdisciplinary fundamental research at the intersection of metal science and thermal processing of materials, biology and medicine. At the same time, in case of partial or complete loss of the implant performance, repeated surgical intervention is required to restore the functionality of the life support system of the organism.

One of the most widely used metal materials for medical applications are alloys based on the Co-Cr-Mo system due to their unique combination of the above mentioned properties for implant manufacturing. High corrosion resistance is achieved due to a thin surface oxide layer consisting mainly of chromium oxide with a small content of molybdenum oxides.

In addition, the establishment of the main factors determining the processes of structure formation and surface modification of metallic materials based on Co-Cr-Mo system is important for the development of Belarusian production of endoprostheses with high physical and mechanical, operational characteristics and biocompatibility for use in the field of traumatology and orthopedics.

2. Compositions, structures and properties of materials used for medical devices (endoprostheses)

It is recommended to use Co-Cr-Mo alloy for manufacturing many biomedical implants, which should have good tribological properties (Hashmi e at al., 2023).

The composition of Co-based biomedical alloys is usually divided into two types. One of them is Co-Cr-Mo alloy containing 5-7 % Mo and 27-30 % Cr. This material has been in use for more than 20 years and is increasingly used as the main material for bioimplants (Hashmi e at al., 2023; Silva e at al., 2023; Chen e at al., 2015; Patel e at al., 2012). Another type of cobalt alloy is Co-Ni-Cr-Mo consisting of Ni (33-37 %), Cr (19-21 %) and Mo (9-11 %). Compared to Co-Cr-Mo, it was used in the biomedical field later and found its application in the creation of highly loaded joints, including prosthetic legs (Patel e at al., 2012; Alvarado e at al., 2003). According to a number of studies, cobalt alloys have been found to be highly biocompatible and particularly resistant to corrosion even under conditions of high chloride content. It is believed that these properties are due to the presence of passive oxide layers spontaneously growing on the alloy surface. In a corrosive environment, these layers act as barriers and prevent corrosion (Chen e at al., 2015; Alvarado e at al., 2003; Evans, e at al., 1986; Öztürk e at al, 2006; Ramsden e at al., 2007).

Figure 1 shows the phase diagram of the state of alloys based on the Co-Cr system, which are used for the manufacture of endoprostheses depending on the peculiarities of the human body, its individual characteristics and other criteria. Molybdenum, nickel, titanium and other elements serve as the main alloying elements of such alloys (Wahi e at al, 2016).

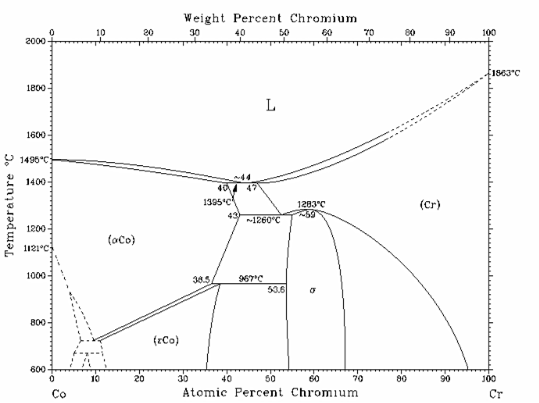

Figure 1 - Phase diagram of state of Co-Cr-based alloys (Ramsden e at al., 2007).

The studies (Hashmi e at al., 2023; Hiromoto e at al., 2005) considered alloys with different Ni content: low Co-29Cr-(6, 8)Mo (wt. %) and ordinary Co-29Cr-6Mo-1Ni (ASTM F75-92). The main purpose of these works was to study the alloys for corrosion resistance in the environment close to human and to study the effect of Ni on the human body, the high content of which can cause allergic reactions (Hiromoto e at al., 2005; Thyssen e at al., 2007). As a result, an alloy based on Co-Cr-Mo with low Ni content ~ 0.03 (wt. %) was obtained. At the same time, the decrease in Ni content contributed to a decrease in ductility. In order to neutralize this effect, it was decided to reduce the grain size by using die forging (Hiromoto e at al., 2005).

The authors' research (Liao e at al., 2012; Jenko e at al., 2018; Giacchi e at al., 2018) was aimed at studying the microstructure of cobalt-based alloy (Co-Cr-Mo) under cast and deformed conditions. The aim of this research was to obtain additional information about the microstructure of Co-Cr-Mo based alloys by identifying different phases and morphologies and evaluating their possible transformation during solidification and cooling under industrial conditions. Table 1 presents information on the compositions investigated in the works (Jenko e at al., 2018; Giacchi e at al., 2018).

Co-Cr-Mo based alloys combine face-centered cubic (FCC) and hexagonal close-packed (HCP) crystal structures. It is noted that at room temperature the predominant phase is (FCC). It is noted that the transition of one phase to another ((FCC → HCP) can be realized either isothermally or by deformation (Balagna e at al., 2012). In addition, the [C] present in the alloys contributes to the formation of carbides, the size and distribution of which is significantly influenced by the technological process. After casting and heat treatment provided by the technological process, various solid phases such as $M_{23}C_6$ (M=Cr, Mo, Co), M_7C_3 appear. In the works aimed at investigating the microstructure of Co-28Cr-6Mo (Fellah e at al., 2023; Efremenko e at al., 2023; Roudnicka e at al., 2021; Roudnická e at al., 2021; Murr e at al., 2011) and Co-29Cr-6Mo [21] foundry alloys, it is noted that through heat treatment the original cellular structure (72 %FCC-28 %GPU) disappears and it is replaced by σ-type intermetallic phases (Mo-, Co- and Si-type phases) (Fellah e at al., 2023; Efremenko e at al., 2023; Roudnicka e at al., 2021; Roudnická e at al., 2021; Murr e at al., 2011). It is noted that intermetallic and eutectic carbides have similar size. Their presence in the microstructure of Co-Cr-Mo-based alloys has a positive effect on the properties of endoprostheses: they contribute to the increase in strength. It is also noted that under the influence of heat treatment or in the presence of nitrogen, carbides of the $M_{23}C_6$ type form carbides of the M_6C type. They are located at grain boundaries and are smaller in size than $M_{23}C_6$ carbides (Liao e at al., 2012; Jenko e at al., 2018; Ghalme e at al., 2016).

In (Ghalme e at al., 2016) it is proposed to add 2-6 wt. % Ti in Co-Cr-Mo alloy. At the same time, carbides Cr_7C_3 and $Cr_{23}C_6$ were noticed along the grain boundaries, as well as phases α-Co, ε-Co, ß-Ti, $CoTi_2$.

Orthopedic implants made of Co-Cr-Mo alloys, which perform the function of bones to replace the failed hard tissues, usually operate under cyclic loads under living conditions (Atkinson e at al., 1980; Devine e at al., 1972; Niinomi e at al., 2002; Mani e at al., 2011). The reliability of such implants after insertion is largely determined by their strength and fracture toughness. Fatigue failure is one of the major problems leading to loosening and ultimate failure of implants (Niinomi e at al., 2007; Teoh e at al., 2000). Artificial joints made of Co-Cr-Mo alloys are now increasingly used in younger and more active patients, where the service life is significantly longer under more severe operating conditions. Therefore, the evaluation and improvement of mechanical properties of alloys used for the fabrication of metal elements of hip arthroplasties are becoming more and more of an issue (Wei e at al., 2018).

Table 1 - Composition of Co-Cr-based alloys studied in the works (Jenko e at al., 2018; Giacchi e at al., 2018)

Article, №	Alloy	Content of main components in the alloy							
		Cr	Co	Mo	Mn	Fe	Si	C	W
Jenko e at al., 2018	Co-Cr-Mo	0,28	63,9	6,4	0,36	0,30	0,73	-	-
Giacchi e at al., 2018	C1	30,60	60,75	6,14	-	-	1,29	0,13	0,36
	C2	28,93	62,99	5,83	-	-	1,05	≤0,021	0,38
	C3	27,01	64,13	6,30	-	-	1,08	≤0,021	0,40
	ASTM F75 (standard)	27,0-30,0	59,0-69,0	5,0-7,0	-	-	To 1	To 0,35	To 0,2

3. Processes of vacuum casting and heat treatment of metal bioimplants

It should be noted that when casting Co-Cr-based alloys as a result of crystallization, large dendritic grains are formed, the presence of which reduces the yield strength of the alloy and promotes the appearance of defects such as inclusions and micropores, which increase internal stresses (Fellah e at al., 2019). However, research in this area continues, and one option to solve this problem is the use of special types of casting followed by heat treatment. In the last few decades, Co-Cr-Mo (F75) casting alloy has been used for the fabrication of orthopedic implants by casting (Fellah e at al., 2019; Nalbant e at al., 2007).

In (Okazaki e at al., 2008; Lee e at al., 2005) the influence of annealing and hot forging on the microstructure and mechanical properties of Co-Cr-Mo alloy was investigated in order to obtain initial data for the development of a new forging process. The Co-Cr-Mo alloy was obtained by vacuum induction melting. The Co-Cr-Mo alloy ingot was first homogenized at 1250 °C for 5 h. A part of the homogenized ingot was aged at 1200 °C for 1 h, followed by hot forging in the form of 30 mm diameter rod samples. The rod specimens were reheated at 1200 °C for 1 h and hot forged as 20 mm diameter rods. The samples were then annealed at 1200 °C for 1 h and then cooled in air. The other part of the homogenized alloy was hot forged into 42 mm diameter rod samples after being annealed at 1200 °C for 1 h and hot forged into 42 mm diameter rod samples. Some of them were heat-treated by holding at 1100 °C for 1 h followed by hot forging to reduce the area of the investigated samples by 40%, 42%, 47%, 49% and 57%, respectively. To investigate the effect of heating temperature on microstructure, one of the rod samples was annealed at 1000 °C for 1 h and hot forged to reduce the area by 50% at an initial temperature of 1000 °C. In this way, annealed and hot forged Co-Cr-Mo alloys were obtained for microstructural studies and mechanical tests. As a result, it was found that a large number of precipitates were observed at the grain boundary of the annealed Co-Cr-Mo alloy, which was attributed to the relatively high carbon content. In addition, the hot-annealed Co-Cr-Mo alloy had a finer structure than the annealed Co-Cr-Mo alloy (Okazaki e at al., 2008).

It is mentioned in (Alvarado e at al., 2003) that casting as a method of manufacturing Co-Cr-Mo-based alloy endoprostheses on a commercial scale is widely used. It is also noted that the technology of endoprosthesis fabrication by casting requires faster processing time than, for example, the fabrication of bioimplants by forging. The research results obtained in this work have shown that both forged and cast Co-based alloy endoprostheses have high corrosion resistance and abrasion resistance. It is especially noted that cast medical devices made of this type of alloys have finer crystals than those obtained by forging, which has a positive effect on the properties of the obtained hip joints (Balagna e at al., 2012).

The authors of (Chen e at al., 2017) investigated the influence of carbon content in Co-Cr-Mo-based alloys on wear resistance. Samples (hip joint simulators) were made of Co-Cr-Mo alloy by vacuum induction melting. As a result, no significant difference in wear loss of Co-Cr-Mo alloys with low and high carbon content was found.

In (Cawley e at al., 2003), the Co-Cr-Mo alloy in different states was studied in detail: cast, heat-treated (HT), obtained by hot isostatic pressing (HIP), HIP followed by HT, obtained by sintering followed by HT and HIP) and concluded that the cast version has the highest wear resistance due to the high volume fraction of carbides.

The study (Roudnicka e at al., 2021; Takaichi e at al., 2019) compares Co-Cr-Mo alloy endoprostheses produced by investment casting and the material obtained by advanced 3D printing technology. The first set of results shows the different response of both materials to the hardness increase during annealing at increasing temperatures up to the transformation temperature. Based on these results, solution treatment and subsequent aging under conditions to achieve maximum hardness was applied

The work (Tonelli e at al., 2023) aimed to investigate the heat treatment of LPBF Co28Cr6Mo alloy (based on selective melting of subsequent layers of metal powders) by direct aging performed in the range of 600-900 °C for 180 minutes. The effects on the hardness and microstructural characteristics of the heat-treated alloys were also emphasized to investigate. In this case, it was found that soaking at 850 °C for 180 minutes followed by aging was the most optimal heat treatment method. Equally important was the dry sliding wear of the fabricated and heat-treated LPBF Co-28Cr-6Mo alloy, considering the conventional deformed alloy as a reference. Under test conditions close to the operational test conditions, the fabricated LPBF alloy showed wear resistance higher than that of the conventional deformed alloy. Optimized aging treatment significantly modified the finished LPBF microstructure, improved the hardness of the alloy and, in general, had a positive effect on its friction and wear resistance.

It is also noted that, as a rule, a conventional Co-Cr-Mo cast alloy is subjected to high temperature treatment at 1230 °C with a special solution followed by quenching (Tonelli e at al., 2023).

In (Mantrala e at al., 2015), a Co-Cr-Mo cast alloy was investigated by heat treating at 1200 °C for 30, 45 and 60 min, followed by quenching in water followed by isothermal aging at 850 °C for 2, 4 and 6 hours. The heat-treated samples were evaluated for microstructure, hardness, wear resistance and corrosion resistance. The results showed that the highest hardness of 512 ± 58 Hv and wear rate of 0,90±0,14×10-4 mm^3/N-m could be achieved by appropriate heat treatment after fabrication.

4. Finishing processes of metal elements of hip joint endoprostheses

One of the most important requirements for metal elements of hip joints are surface quality and dimensional accuracy, where one of the main indicators of surface quality is its roughness. Surface roughness is of great importance for functional properties such as, for example, wear resistance. As a result, it also determines the quality of the endoprosthesis itself.

It is noted in (Döbberthin e at al., 2020) that dimensional and shape accuracy are important aspects that can be controlled by selecting suitable machining processes. This paper presents an experimental analysis of shape accuracy in electrochemical (EC) polishing of femoral heads for hip arthroplasties. Femoral heads were pre-treated by barrel and drag grinding. The accuracy of the shape obtained after EC-polishing was evaluated by the authors taking into account the pretreatment processes. It is observed that EC polishing is a common process for surface smoothing of metallic materials. This method is based on anodic dissolution of metal. Like electrochemical machining, EC polishing is carried out with a power source and electrolyte between the cathode and anode. In contrast to mold removal, EC polishing uses a bath of electrolyte and current densities in the range of 0.4 to 3 A/cm². For this method, the workpiece is clamped on a movable holder and immersed in an electrolyte bath. According to the principle of the process, the entire surface of the anode is practically surface-removed. As a consequence, the roughness peaks are reduced and the edges and cracks are smoothed out. The advantages of using this method are also mentioned: compared to grinding, EC polishing produces less heat exchange with the workpiece surface and therefore ensures that the boundary layer is not influenced. A second advantage of using this method is that, limited only by the volume of the electrolyte bath, workpieces of different shapes and configurations can be machined. In addition, this method is highly efficient, which is due to the ability to treat the surface of the workpieces in a relatively short polishing time, as well as the possibility of simultaneous polishing of several workpieces, which allows the use of this method of surface treatment on an industrial scale.

The papers (Chu e at al., 2002; Sodhi e at al.,1996; Sioshansi e at al., 1987; Hegemann e at al., 2001; Quinet e at al., 1992) review plasma surface modification (PSM), which is an efficient and economical method for surface treatment of many materials and is of increasing interest in biomedical engineering. The articles review various common plasma technologies and experimental techniques used for the study of biomedical materials such as plasma spraying and etching, plasma implantation, plasma deposition, plasma polymerization, laser plasma deposition, plasma sputtering, etc. The unique advantage of plasma modification is that surface properties and biocompatibility can be improved locally without changing the basic properties of materials. Solid tissue substitutes, blood contact prostheses, ophthalmic devices and other medical devices have been considered as research samples. Using RPM as an economical and effective method of materials processing, it is possible to change the chemical composition and such properties as wettability, colorability, hardness, chemical inertness, biocompatibility of the materials surface, etc. in a continuous mode.

In (Wei e at al., 2016; Wang e at al., 2013; Mattei e at al., 2011; Gao e at al., 2012; Chyr e at al., 2014), the possibility of using laser interference lithography (LIL) to modify the surface of implantable Co-Cr-Mo alloy, which is universally used as a material for artificial joints in total endoprosthetics, is investigated. Experimental results show that the surface of samples modified by laser interference lithography has better tribological characteristics and hardness compared with untreated materials, including a 64 % reduction in the coefficient of friction and a 40 % increase in hardness, which is very promising for significantly reducing the average revision rate after primary total hip arthroplasty in the future. The results of Co-Cr-Mo alloy surface texture study (Wang e at al., 2013) showed that the petal-like surface texture can effectively reduce the friction and wear of Co-Cr-Mo artificial joints. In (Mattei e at al., 2011), they investigated surface texturing to modify the friction surface by electrical discharge etching to improve lubrication and found that the lubrication properties could be improved in pin-on-disk type experiments.

Researchers in (Gao e at al., 2012) studied the tribological effects of micro dimpled surface texturing for its application in ceramic-on-ceramic hip prostheses. Dimpled textures on ceramic surfaces were fabricated by microdrilling on CNC machines. Compared to surfaces without dimples, dimpled surfaces with high density and large dimple sizes showed a significant increase in tribological properties: friction was reduced by 22% and wear by 53%.

In (Chyr e at al., 2014), the possibility of using laser interference lithography to modify the surface of Co-Cr-Mo implantation alloy, which is universally used as a joint material for hip joint replacement and is one of the best materials for biomedical applications, possessing good wear resistance, mechanical properties, and biocompatibility, is investigated (Chyr e at al., 2014).

Laser interference lithography uses an interference pattern produced by two or more coherent laser beams to pattern a material. The LIL mode is a superposition of the electric field vectors of the interfering beams, and highly patterned depressions or lines can be produced on the material surface using interference patterns. Compared with other methods, LIL has advantages such as relatively short process time, easy setup, high resolution, no surface contamination, flexible configuration and large working distance, which allows inexpensive, efficient and large area creation of three-dimensional micro- and nanostructures on biomaterials, and the intrinsic biocompatibility of the materials used to create the structures is not altered by laser treatment (Mattei e at al., 2014).

Studies (Wei e at al., 2016; Wang e at al., 2013; Mattei e at al., 2011; Gao e at al., 2012; Chyr e at al., 2014) show that surface texturing can significantly reduce friction in artificial joints. However, in addition to the labor-intensive procedures and complex processes currently used, it is still quite challenging to ensure the long-term use of artificial joints in terms of low friction, biocompatibility, and high wear resistance.

5. Finishing processes of metal elements of hip joint endoprostheses

When developing medical devices, especially in the field of endoprosthetics, such products are subject to increased requirements, including high strength, wear resistance, high machinability of alloys, as such products should have a smooth mirror surface, which in turn reduces abrasion of implants and thus extends their service life. However, the most important requirement for bioimplants is biocompatibility. The reason for this is the direct purpose of such products: installation and operation of endoprostheses inside the human body, which is necessary to replace damaged, destroyed or missing body parts for any reason.

Co-Cr-Mo based alloys have been found to have good mechanical properties: high resistance to fatigue (400-450 Nlmm^2), corrosion resistance in aggressive media, wear resistance, ductility and strength (tensile strength of at least 1000 Nlmm^2) and, as one of the main requirements, excellent biocompatibility. In addition, alloys of this type have a high resistance to deformation over time (Jenko e at al., 2018; Giacchi e at al., 2011; Ghalme e at al., 2016). Therefore, it can be concluded that the metal elements of endoprostheses made of this type of alloys meet the requirements for them.

Table 2 shows the generalized composition of Co-Cr-Mo alloy with applied components that take into account the addition of various alloying elements such as Mo, Ni, Ti, W and others.

Table 2 - Table 2 - Content of components used in Co-Cr alloys [1-22]

Components	Co	Cr	Mo	C	Si	Mn	N	Fe	W	Ni	P	S	Ti	Al	B
The range	53-69	25-32	2-11	0.007-0.35	0.15-1.25	0.15-1	0.025-0.25	0.025-1	0.2-0.4	0.1-2.5	0.02-0.15	до 0.01	0.1-6	до 0.1	до 0.1

It is important to emphasize that no material in its pure form can meet all the requirements, so to improve the properties, structure and surface modification is often used to enhance the surface properties, thereby improving the tribological properties of metal elements of hip arthroplasties including hip joints.

Based on the literature review, the most commonly used technology for heat treatment of hip joint endoprostheses is aging at 900-1200 ℃ followed by quenching or aging.

As a result of the research, as well as their implementation in the technology of manufacturing and processing of medical devices, not only the basic properties of endoprostheses, including surface quality, are improved, but also contribute to the increase of tribological properties and service life of the manufactured endoprostheses. In addition, important advantages of Co-Cr-Mo alloys, compared, for example, with titanium alloys, are also their technological properties: high liquid-fluidity (possibility of obtaining castings of very complex geometry) and high quality of polishing after surface finishing.

To date, various studies have been conducted on the fabrication of metallic elements of endoprostheses. The most attention is paid to biocompatibility, durability, wear resistance, and corrosion resistance.

6. References:

1. Hashmi, A.W. A comprehensive review on surface post-treatments for freeform surfaces of bio-implants / A.W. Hashmi, H. S. Mali, [at al.] // Journal of Materials Research and Technology. 2023. Vol. 23. Pp. 4866-4908.

2. Silva, R. Scratch and Wear Behaviour of Co-Cr-Mo Alloy in Ringer’s Lactate Solution / R. Silva, M. D. dos Santos, R. Madureira, [at al.] // Materials. 2023. Vol. 16. 2923.

3. Chen, Q. Metallic implant biomaterials / Q. Chen, G.A. Thouas // Materials Science and Engineering: R: Reports. 2015. Vol. 87. P.1-57.

4. Patel, N.R. A review on biomaterials: scope, applications & human anatomy significance / N.R. Patel, P.P. Gohil // International Journal Emerging Technology Advanced Engineering. 2012. Vol. 2. Iss. 4. P. 91-101.

5. Alvarado, J. Biomechanics of hip and knee prostheses / J. Alvarado, R. Maldonado, J. Marxuach, R. Otero // Applications Engineering Mechanics Medicine. 2003. P. 6-22.

6. Evans, E.J. The in vitro toxicity of cobalt-chrome-molybdenum alloy and its constituent metals / E.J. Evans, I.T. Thomas // Biomaterials. 1986. Vol. 7. Iss. 1. P. 25-29.

7. Öztürk, O. Metal ion release from nitrogen ion implanted CoCrMo orthopedic implant material / O. Öztürk, U. Türkan, A.E. Eroglu // Surface Coatings Technology. 2006. Vol. 200. Iss. 20-21. P. 5687-5697.

8. Ramsden, J.J. The design and manufacture of biomedical surfaces / J.J. Ramsden, D.M. Allen [et al.] // CIRP Annals. 2007. Vol. 56. Iss. 2. P. 687-711.

9. Wahi, A. Effect of Sintering Temperature on Density, Hardness and Strength of MIM Co30Cr6Mo Biomedical Alloy / A. Wahi, N. Muhamad, A. B. Sulong, R. N. Ahmad // J. Jpn. Soc. Powder Powder Metallurgy. 2016. Vol. 63, № 7. Pp. 434-437.

10. Hiromoto, S. Microstructure and corrosion behaviour in biological environments of the new forged low-Ni Co–Cr–Mo alloys / S. Hiromoto, E. Onodera, A. Chiba, K. Asami, T. Hanawa // Biomaterials. 2005. Vol. 26. Iss. 24. Pp. 4912-4923.

11. Thyssen, J. P. The epidemiology of contact allergy in the general population – prevalence and main findings / J. P. Thyssen, A. Linneberg, T. Menne, J. D. Johansen // Contact Dermatitis. 2007. Vol. 57, Iss. 5. p. 287-299.

12. Liao, Y. New insights into hard phases of CoCrMo metal-on-metal hip replacements / Y. Liao, R. Pourzal, P. Stemmer, M.A. Wimmer, J.J. Jacobs, A. Fischer, L.D. Marks // Journal of the Mechanical Behavior of Biomedical Materials. 2012. Vol. 12. Pp. 39-49.

13. Jenko, M. Surface chemistry and microstructure of metallic biomaterials for hip and knee endoprostheses / M. Jenko [at al.] // Applied Surface Science. 2018. № 427. Pp. 584-593.

14. Giacchi, J.V. Microstructural characterization of as-cast biocompatible Co–Cr–Mo alloys / J.V. Giacchi, C.N. Morando, [at al.] // Materials Characterization. 2011. Vol. 62. Iss. 1. Pp. 53-61.

15. Balagna, C. Characterization of Co-Cr-Mo alloys after a thermal treatment for high wear resistance Materials / C. Balagna, S. Spriano, M.G. Faga // Science and Engineering, Mater Sci. Eng. C. 2012. Vol. 32. P. 1868–1877.

16. Fellah, M. Structural, mechanical and tribological performance of a nano structured biomaterial Co-Cr-Mo alloy synthesized via mechanical alloying / M. Fellah, N. Hezil, [at al.] // Journal of Materials Research and Technology. 2023. Vol. 25. Pp. 2152-2165.

17. Efremenko, V.G. Micromechanical, corrosion and wet sliding wear behaviours of Co-28Cr-6Mo alloy: Wrought vs. LPBF / V.G. Efremenko, A.G. Lekatou, Yu. G. Chabak // Materials Today Communications. 2023. Vol. 35. P. 17.

18. Roudnicka, M. Different Response of Cast and 3D-Printed Co-Cr-Mo Alloy to Heat Treatment: A Thorough Microstructure Characterization / M. Roudnicka, J. Bigas, O. Molnarova, D. Palousek, D. Vojtech // Metals. 2021. Vol. 11. Iss. 3. P. 21.

19. Roudnická, M. Heat treatment of laser powder-bed-fused Co–28Cr–6Mo alloy to remove its microstructural instability by massive fcc→hcp transformation // M. Roudnická, J. Kubásek, [at al.] // Additive Manufacturing. 2021. Vol. 47. 102265.

20.Murr L.E. Microstructure and mechanical properties of open-cellular biomaterials prototypes for total knee replacement implants fabricated by electron beam melting / L.E. Murr, K.N. Amato, S.J. Li, [at al.] // Journal of the Mechanical Behavior of Biomedical Materials. 2011. Vol. 4. Iss. 7. Pp. 1396-1411.

21.Kumar, P. Study of mechanical characteristics of additively manufactured Co-Cr-Mo-2/4/6Ti alloys for knee implant material / P. Kumar, M.S. Sawant, N. K. Jain, S. Gupta // CIRP Journal of Manufacturing Science and Technology. 2022. Vol. 39. Pp. 261-275.

22.Ghalme, S. G. Biomaterials in Hip Joint Replacement / S. G. Ghalme, A. Mankar, Y. Bhalerao // International Journal of Materials Science and Engineering. 2016. Vol. 4. № 2. Pp. 113-125.

23.Atkinson, J.R. Materials for internal prostheses: the present position and possible future developments / J.R. Atkinson, J.M. Dowling, R.Z. Cicek // Biomaterials. 1980. Vol. 1. Iss. 2. P. 89-99.

24.Devine, T.M. Wulff J. Wrought cobalt-chromium surgical implant alloys / Devine TM, F.J. Kummer, J. Wulff // Journal of Materials Science. 1972. Vol. 7. P. 126–128.

25.Niinomi, M. Recent metallic materials for biomedical applications. Metallurgical and Materials Transactions A. 2002. Vol. 33. P. 477-486.

26.Mani, A. Salinas-Rodrigez A, Lopez HF. Deformation induced FCC to HCP transformation in a Co–27Cr–5Mo– 0.05C alloy / A. Mani, A. Salinas-Rodrigez, H.F. Lopez // Materials Science and Engineering A. 2011. Vol. 528. Iss. 7. P. 3037-3043.

27.Niinomi, N. Fatigue characteristics of metallic biomaterials / N. Niinomi // International Journal of Fatigue. 2007. Vol. 29. P. 992-1000.

28.Teoh, S.H. Fatigue of biomaterials: a review / S.H. Teoh // International Journal of Fatigue. 2000. Vol. 22. P. 825-837.

29.Wei, D. Fatigue improvement of electron beam meltingfabricated biomedical Co-Cr-Mo alloy by accessible heat treatment / D. Wei, Y. Koizumi, T. Takashima, M. Nagasako, A. Chiba // Materials Research Letters. 2018. Vol. 6. № 1. Pp. 93-99.

30.Fellah, M. Effect of molybdenum content on structural, mechanical, and tribological properties of hot isostatically pressed b-type titanium alloys for orthopedic applications / M. Fellah, N. Hezil, M. Abdulsamad, R. Djellabi, A. Montagne, A. Mejias, [et al] // Journal of Materials Engineering and Performance. 2019. Vol. 28. Iss. 10. P.5988-5999.

31.Nalbant, M. The effect of cutting speed and cutting tool geometry on machinability properties of nickel-base Inconel 718 super alloys / M. Nalbant, A. Altin, H. Gokkaya // Materials & Design. 2007. Vol. 28. Iss. 4. P. 1334-1338.

32.Okazaki, Y. Effects of Heat Treatment and Hot Forging on Microstructure and Mechanical Properties of Co-Cr-Mo Alloy for Surgical Implants / Y. Okazaki // Materials Transactions. 2008. Vol. 49, № 4. P. 817-823.

33.Lee, S.-H. Effect of Heat Treatment on Microstructure and Mechanical Properties of Ni- and C-Free Co-Cr-Mo Alloys for Medical Applications / S.-H. Lee, E. Takahashi, N. Nomura, A. Chiba // Materials Transactions. 2005. Vol. 46, № 8. P. 1790-1793.

34.Alvarado, J. Biomechanics of hip and knee prostheses / J. Alvarado, R. Maldonado, J. Marxuach, R. Otero // Appl Eng Mech Med. 2003. P. 6-22.

35.Balagna, C. Tantalum-based multilayer coating on cobalt alloys in total hip and knee replacement / C. Balagna, M. Faga, S. Spriano // Materials Science and Engineering C. 2012. Vol. 32. Iss. 4. P. 887-895.

36.Chen, Y. Effects of carbon addition on wear mechanisms of CoCrMo metal-on-metal hip joint bearings / Y. Chen, Y. Li, Y. Koizumi, H. Haider, A. Chiba // Materials Science and Engineering C. 2017. Vol. 76. P. 997–1004.

37.Cawley, J. A tribological study of cobalt chromium molybdenum alloys used in metal-on-metal resurfacing hip arthroplasty / J. Cawley, J.E.P. Metcalf, A.H. Jones, T.J. Band, D.S. Skupien // Wear. 2003. Vol. 255. P. 999-1006.

38.Roudnicka, M. Different Response of Cast and 3D-Printed Co-Cr-Mo Alloy to Heat Treatment: A Thorough Microstructure Characterization / M. Roudnicka, J. Bigas, O. Molnarova, D. Palousek, D. Vojtech // Metals. 2021.Vol. 11. Iss. 5. P. 687.

39.Takaichi, A. Effect of heat treatment on the anisotropic microstructural and mechanical properties of Co-Cr-Mo alloys produced by selective laser melting / A. Takaichi, Y. Kajima, [at al.] // Journal of the Mechanical Behavior of Biomedical Materials. 2019. Vol. 102.

40.Tonelli, L. A novel heat treatment of the additively manufactured Co28Cr6Mo biomedical alloy and its efects on hardness, microstructure and sliding wear behavior / L. Tonelli, M.M.Z. Ahmed, L. Ceschini // Progress in Additive Manufacturing. 2023. Vol. 8. P. 313-329.

41.Mantrala, K. M. Additive manufacturing of Co-Cr-Mo alloy: influence of heat treatment on microstructure, tribological, and electrochemical properties / K. M. Mantrala, [at all] // Frontiers in Mechanical Engineering. 2015. Vol. 1. P. 7.

42.Döbberthin, Ch. Experimental Analysis of the Shape Accuracy in Electrochemical Polishing of Femoral Heads for Hip Endoprosthesis / Ch. Döbberthin, R. Müller, G. Meichsner, F. Welzel, M. Hackert-Oschätzchen // Procedia Manufacturing. 2020. Vol. 47. P. 719-724.

43.Chu, P.K. Plasma-surface modification of biomaterials / P.K. Chu, J.Y. Chen, L.P. Wang, N. Huang // Materials Science and Engineering R. 2002. Vol. 36. P. 143-206.

44.Sodhi, R.N.S. Application of surface analytical and modification techniques to biomaterials research / R.N.S. Sodhi // Journal of Electron Spectroscopy and Related Phenomena. 1996. Vol. 81 P. 269-284.

45.Sioshansi, P. Surface modification of industrial components by ion implantation / P. Sioshansi // Materials Science and Engineering. 1987. Vol. 90. P. 373-383.

46.Hegemann, D. Plasma Treatment of Polymers to Generate Stable, Hydrophobic Surfaces / D. Hegemann, H. Brunner, Ch. Oehr Plasma // Plasmas and Polymers. 2001. Vol. 6. P. 221–235.

47.Quinet, R.J. Total joint replacement of the hip and knee / R.J. Quinet, E.G. Winters // Medical Clinics of North America. 1992. Vol. 76. Iss. 5. P. 1235-1251.

48. Wei, X. Surface modification of Co–Cr–Mo implant alloy by laser interference lithography / X. Wei, W. Li, B. Liang, B. Li, [at al.] // Tribology International. 2016. Vol. 9. P. 212-217.

49. Wang, D. Direct modification of silicon surface by nanosecond laser interference lithography / D. Wang, Z. Wang, Z. Zhang, [at al.] // Applied Surface Science. 2013. Vol. 282. P. 67-72.

50. Mattei, L. Lubrication and wear modelling of artificial hip joints: A review / L. Mattei, F.D. Puccio, B. Piccigallo, [at al.] // Tribology International. 2011. Vol. 44. Iss. 5. P. 532-549.

51. Gao, L. Effect of surface texturing on the elastohydrodynamic lubrication analysis of metal-on-metal hip implants / L. Gao, P. Yang, I. Dymond, [at al.] // Tribology International. Vol. 43. Iss. 10. P. 1851-1860.

52. Chyr, A. A patterned microtexture to reduce friction and increase longevity of prosthetic hip joints / A. Chyr, M. Qiu, J.W. Speltz, [at al.] // Wear. 2014. Vol. 315. Iss. 1-2. P. 51-57.