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The Impact of Cryogenic Temperatures on the Hardness and Tribological Properties of Cobalt Alloys

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This article explores the effect of cryogenic temperatures on the properties of cobalt alloys, specifically Stellite 6 and Stellite 12. These alloys are commonly used in applications that require resistance to mechanical, thermal, and chemical wear. In this study, the focus is on the valve seats for internal combustion engines, which are made from cobalt alloys and undergo a freezing process before assembly into the cylinder head. The purpose of freezing is to reduce the diameter of valve seats, making them easier to fit into the cylinder head. However, the length of time spent in freezing can significantly affect the hardness and tribological characteristics of the material.

Keywords: Cobalt alloys, Cryogenic treatment, Tribological properties, Valve, Valve seats

1 Introduction

Cobalt-based superalloys, particularly Stellites, are renowned for their outstanding mechanical and tribological properties. These alloys possess high hardness, strength, excellent wear resistance, and impressive ability to withstand cavitation and erosion. They are specifically engineered for use in applications that require exceptional wear resistance in non-lubricated systems that operate at high temperatures. As a result of their superior properties, Stellite alloys are commonly used across various industries. [1, 2]

Stellite alloys are a type of cobalt and chromium alloys that can also contain tungsten, molybdenum, and small amounts of carbon. The alloys are strengthened by the precipitation of carbides within a solid solution matrix of cobalt. The unique properties of Stellite alloys come from the crystallographic nature of cobalt, the strengthening effect of chromium, and the additional benefits of tungsten and molybdenum. [2, 3]

The wear-resistant Stellites are distinguished by their carbon content, which influences the volume fraction of carbides. These alloys are classified as medium and high-carbon, with chromium playing a dual role in carbide formation and acting as a crucial alloying element that provides resistance against corrosion and oxidation. Additionally, tungsten and molybdenum contribute to the strength of the matrix, hindering dislocation flow due to their sizable atomic size. [4, 5]

Stellite 6 has a face-centered cubic (FCC) crystal lattice structure. It has good ductility, a high melting point, and provides excellent resistance to wear and corrosion. On the other hand, Stellite 12 features a hexagonal close-packed (HCP) crystal lattice structure, which makes it highly resistant to oxidation and deformation at elevated temperatures. Additionally, it is known for its high hardness and thermal stability. [6, 7]

Elwood Haynes invented these alloys in the early 20th century. Later, Deloro Stellite Company started using them. In the beginning, these alloys only contained cobalt and chromium. However, with the introduction of ternary alloys, like Co-Cr-Mo and Co-Cr-W, the strengthening effects of molybdenum and tungsten in the cobalt-chromium system were discovered. [3, 8]

Stellite alloys are widely used in applications that require high wear resistance in harsh and corrosive environments. These alloys are capable of operating effectively at temperatures that are beyond the capabilities of conventional materials like steel. This remarkable quality is due to a century-old discovery that has made Stellite alloys a vital component in modern engineering and industry.

This study aims to investigate the relationship between cryogenic treatment duration and resulting material properties, shedding light on optimal conditions for achieving desired tribological performance in practical applications.

2 Mechanical properties of stellites

Stellite alloys are known for their high Young's modulus and tensile strength. However, their ductility is limited due to excessive carbide content in their microstructure. Low-carbon variants of Stellite alloys, particularly solution-strengthened ones, have better ductility. When evaluating their mechanical strength, short-term tensile strength and deformation during high temperature are typically considered. Hardening mechanisms involve solid solution matrix hardening and carbide precipitation. [9]

The morphology and placement of carbide in a material's structure greatly affect its strengthening effects. These effects are vital for optimal precipitation enhancement within grains and at grain boundaries. Precipitates that form at grain boundaries prevent crystal plane sliding and boundary migration, creating a supportive network. Intragranular precipitation, on the other hand, strengthens the matrix by hindering dislocation movement and impeding crystallographic slip. [6, 10, 11, 12]

The way a metal solidifies, such as the temperature at which it is cast and the speed at which it cools, determines the distribution of carbides. For manufacturing purposes, short-term tensile properties are very important. The ductility of the metal determines if it can be easily shaped when it's hot or cold. When the metal is in its as-cast state, it can stretch up to 8 % at room temperature, and this number increases as the temperature increases. If the metal is aged at 732 °C for 50 hours, it can only stretch up to 1-2 %, but the ductility can be restored above the aging temperature. Stellite alloys become harder very quickly due to cold work, especially when their compositions are not fully stabilized (see Tab. 1).

The article [3] discusses the potential of Stellite 6 as a self-lubricating coating. This coating exhibits a uniform microstructure with finely-grained particles, which enhances wear resistance and reduces friction. The addition of NbC and h-BN particles further enhances its tribological properties, indicating its excellent potential for a wide range of applications.

The study [10] examines the behavior of wear at different temperatures. The results suggest that the wear rate increases with temperature due to thermal softening and hardness reduction. At higher temperatures, the wear mechanism shifts from abrasive to adhesive wear, which has significant implications for the industries that use Stellite 6 in high-temperature applications. To improve the high-temperature performance of Stellite 6 alloy, the study recommends alloying it with chromium and tungsten, along with coatings or surface modifications. These findings provide valuable insights for researchers and underline the necessity for further exploration of alloying and surface modification techniques to optimize the tribological properties of Stellite 6 alloy in high-temperature environments.

The chemical composition of the stellites used for testing is presented in Tab. 2, while the chemical composition of the covering material (P37S) is listed in Tab. 3.

***Tab. 1** Hardness of Stellites*

Material	HRC
Stellite 6	42 - 48
Stellite 12	48 - 52

***Tab. 2** Chemical compound of Stellites used for testing*

Element [%]	C	Cr	W	Fe	Ni	Si	Mn	Mo	B	Co
Stellite 6	1.0 – 1.4	26 – 32	4 – 7	max. 3	max. 3	max. 2	max. 1	max. 1	max. 0.5	Balance
Stellite 12	10.4 – 10.9	28 – 33	7 – 11	max. 3	max. 3	max. 2	max. 1	max. 1	max. 0.5	Balance

***Tab. 3** Chemical compound of P37S overlay material*

C [%]	Si [%]	Mn [%]	Cr [%]	Ni [%]	W [%]	Fe [%]	Material base	Hardness HRC	Density [g/cm^3]
1.75	1.1	≤ 0.3	28.0	22.5	12.3	≤ 1.4	Cobalt base	≥ 40	8.5

3 Heat treatment of cobalt alloys

Cobalt alloys are considered supermaterials and are ideal for applications that require exceptional abrasion resistance. These alloys contain alloying elements such as chromium, tungsten, molybdenum, and a small amount of carbon that contribute to their unique properties. The microstructure of these alloys includes chromium carbides (which have a melting temperature of 1250–1895 °C) and tungsten carbides (which can withstand temperatures of up to around 2870 °C), making them incredibly durable. [12]

Stellite is a cobalt alloy known for its high-temperature resistance. It can be annealed for stress relief in castings, welded parts, and cold-drawn components, with annealing temperatures ranging from 250 °C to 650 °C. [2]

After the casting process, Stellite materials undergo a critical step known as solution annealing. During this process, Stellite castings are subjected to temperatures between 1050 °C to 1200 °C and held at these temperatures for a specific duration of time. This helps to dissolve carbides, resulting in a shift in microstructure. The outcome is a reduction in residual stresses and the formation of a more uniform and refined grain structure. After solution annealing, rapid cooling is necessary through water quenching or air cooling to prevent carbide reprecipitation, maintain an optimized microstructure and avoid negative effects on mechanical properties.

Stellite materials subjected to heat treatment exhibit significant improvements such as enhanced dimensional stability, reduced internal stresses, and superior mechanical properties, including increased hardness, strength, and wear resistance. These attributes are particularly valuable in situations where Stellite components are exposed to high temperatures, abrasive environments, or extreme mechanical loads, highlighting the crucial function of heat treatment in optimizing their performance. [2]

4 Cryogenic heat treatment of cobalt alloys

Cryogenic heat treatment is a field that has recently been gaining attention, particularly for ferrous metals and cast iron. However, it remains underexplored for cobalt alloys. This innovative approach has shown significant benefits, especially in refining Wolfram Carbide (WC) and spheroidizing cobalt alloys, which results in a longer tool service life. [3]

The cryogenic process involves three primary stages: cooling to extremely low temperatures, maintaining this temperature for a set period, and then warming up to room temperature, followed by annealing to remove residual stress. Typically, liquid nitrogen is used as a cryogenic medium to achieve temperatures ranging from approximately -30 °C to -196 °C. However, to reach even lower temperatures near absolute zero, liquid helium is required.

It is important to take into account the cooling time at cryogenic temperatures, as it can vary depending on the type of cryogenic medium being used. Previous studies have shown that the cooling time can range from 2 to 180 hours when using liquid nitrogen. It is crucial to control the cooling and heating rates, as internal stresses that can damage the material may arise if the rates exceed 20 °C to 30 °C/h. [12]

The FCC crystal structure gives Stellite 6 its resilience, high melting point, and ability to resist wear and corrosion. The microstructure of Stellite 6 can be seen in Fig. 1a. On the other hand, Stellite 12 has a HCP (Hexagonal Close-Packed) crystal structure which makes it extremely hard, thermally stable, and resistant to oxidation and deformation at high temperatures. The microstructure of Stellite 12 can be observed in Fig. 1b.

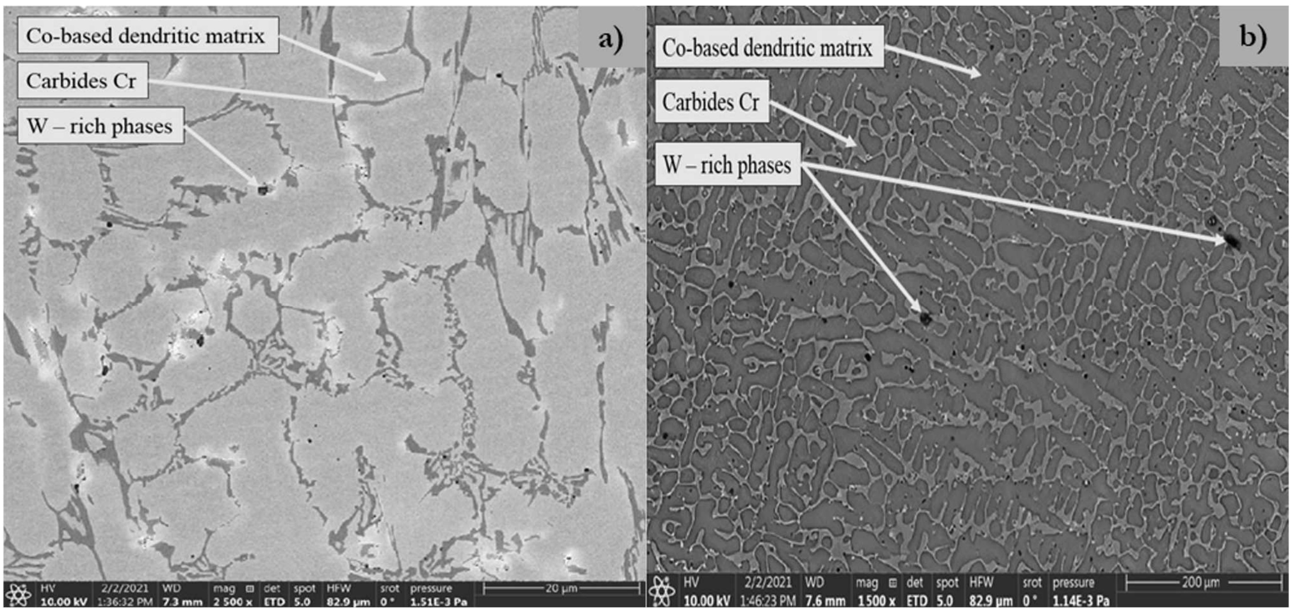

Fig. 1 *Microstructure of a) Stellite 6 [6] and of b) Stellite 12 [11]*

The article referenced as [6] discusses the usage of Stellite 6 for self-lubricating coating in tribological applications. The laser-clad coating displays a uniform microstructure with small, refined grains, which enhances its wear resistance and reduces friction. Furthermore, the addition of NbC and h-BN particles enhances its tribological properties, which shows significant potential for better wear resistance and self-lubricating characteristics.

According to a study conducted by Skalante et al. [10], cryogenic conditions have a significant impact on the surface quality of materials used in tribological applications. The research aimed to investigate the changes in the surface characteristics of materials under cryogenic friction conditions, which could provide valuable insights into roughness, wear, and friction alterations. The study revealed that cryogenic conditions can improve surface quality by reducing surface defects such as micro-cracks and roughness. These findings suggest that cryogenic treatment is an effective method to enhance the surface quality of materials used in tribological systems. This could have significant implications for various industries, including cutting tools, mining, drilling equipment, and automotive components.

5 Influence of Cryogenic Temperature on the Hardness of Stellite 6 and Stellite 12

The objective of this study is to investigate the impact of cryogenic temperatures on the hardness of Stellite 6 and Stellite 12. The research aims to identify any potential correlations between variations in freezing time and material properties. By understanding these effects, we can gain valuable insights into optimizing manufacturing and operational processes, particularly in applications where Stellite alloys play a crucial role in ensuring component longevity.

The intake valve seats are made of Stellite 6 material, while the exhaust valve seats are made of Stellite 12 material. These valve seats are manufactured by PBS Velká Bíteš a.s. using the precision casting technology into a disposable mold. In order to enhance the hardness values and eliminate internal stress, the castings undergo a gradual heating annealing process in a furnace where they are heated between 900 °C to 950 °C and soaked at this temperature for 3 to 4 hours. The castings are then cooled down to 500 °C. The chemical composition of the tested Stellites is shown in Tab. 4.

Tab. 4 *The chemical composition of Stellite 6 and Stellite 12 used for testing*

Element [%]	C	Cr	W	Fe	Ni	Si	Mn	Mo	B	Co
Stellite 6	1.2	27.3	6.1	1.8	0.29	1.4	0.4	0.2	0.02	Balance
Stellite 12	1.6	32.5	10.2	1.7	0.36	1.1	0.29	0.35	0.01	Balance

6 Experimental part

6.1 Measurement methodology

The study involved testing seven samples of each material for their hardness, before and after exposure to liquid nitrogen. The valve seats were submerged in liquid nitrogen for varying durations of 5, 10, 15, 30, 60, and 960 minutes, ensuring the liquid level was always above the samples being examined. To minimize the risk of any changes in structure or properties due to different materials, the same material samples were used throughout the testing.

The samples were subjected to a freezing process using liquid nitrogen, after which the hardness was measured again. The process was carried out carefully to prevent any thermal shock to the material. The valve seats were gradually dipped into liquid nitrogen for short periods of time, and the duration of exposure was gradually increased.

6.2 Prepared samples

A sample of each type was prepared for the experiment, including cast valve seats and semi-finished valve seats after freezing (Fig. 2).

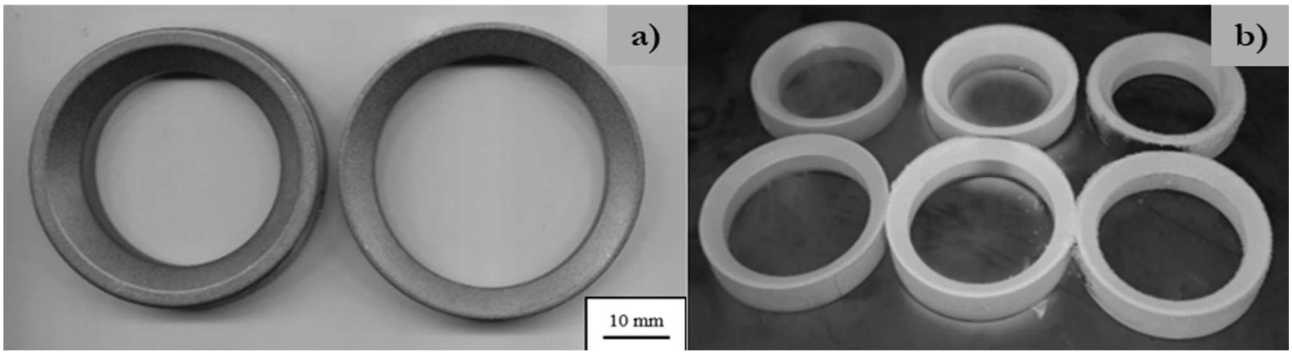

Fig. 2 *Samples used a) cast valve seats, and b) semi-finished valve seats after freezing*

6.3 Tribological experiment

The Pin-on-Disc method was used for the tribological experiment. A Tribometer TRB³ from Anton Paar company was used to evaluate the tribological properties of the surface in both dry and liquid environments. [13, 14, 15]

We conducted an evaluation of the tribological properties of Stellite 6 and Stellite 12 after undergoing cryogenic treatment. To examine realistic material combinations, we used P37S as the overlay material for the intake and exhaust valve, which served as the friction pair of materials. This selection was made to test the functionality and durability of these materials in real-world scenarios.

The valves were modified before the experiment by removing the valve stems using an EDM machine. This was done to fit the valves into the tribometer (Fig. 3a) without any thermal impact on the samples. Actual valve seats were used as "Pin" (counterpart) cylinders. The material variants and their heat treatments are listed in Tab. 6. Fig. 3b shows a CAD model of the valve seat with extracted cylinders on the left side. The same model was used for the EDM machine to remove rollers. On the right side of Fig. 3b, an actual valve seat with extracted rollers can be seen.

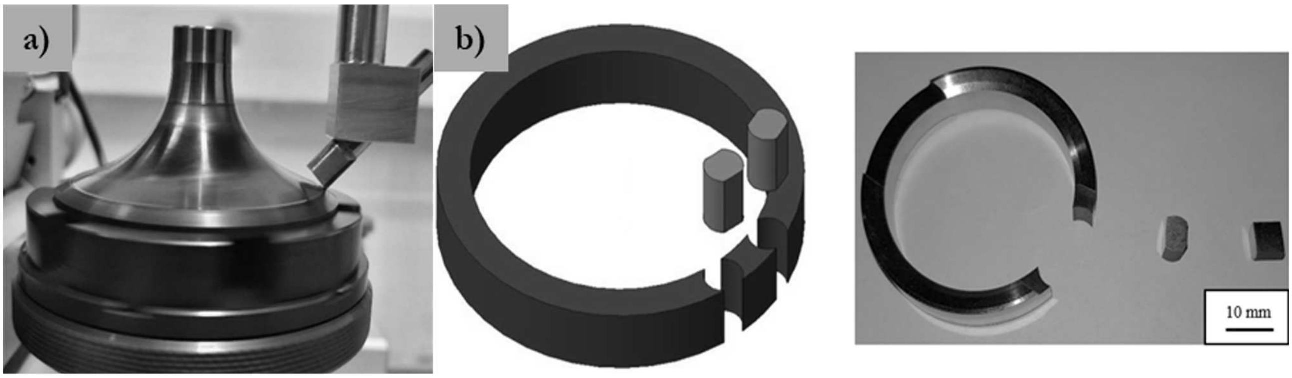

Fig. 3 *Experiment preparation a) example of testing setup and b) prepared cylinders from real valve seat used as a "Pin"*

7 Results and discussion

The semi-finished product's circumference was measured every 45° using the HRC method with a BRIRO VA hardness tester according to EN ISO 6508-1 [16]. Tab. 5 show the measured data of hardness value for Stellite 6 and Stellite 12 before and after freezing in liquid nitrogen. Average Difference Hardness (Δ HRC) refers to the variation in hardness exhibited by a sample before and after freezing. By quantifying the discrepancy in hardness levels pre- and post freezing, Δ HRC serves as a crucial parameter in assessing the material's suitability for applications.

Tab. 5 *Measurements of Stellite 6 and 12 hardness under the exposure to liquid nitrogen*

Material	Sample	Time in cryo [min]	Average hardness HRC	Average diference hardness Δ HRC	Material	Sample	Average hardness HRC	Average diference hardness Δ HRC
Stellite 6	1	0	43.4 ± 0.8	0	Stellite 12	1	50.7 ± 0.5	0
Stellite 6	2	0	44.1 ± 1.7	-0.8 ± 1.6	Stellite 12	2	50.0 ± 0.7	-1.1 ± 1.2
		5	43.3 ± 1.6				48.9 ± 1.5	
Stellite 6	3	0	44.7 ± 1.0	-2.1 ± 0.9	Stellite 12	3	50.7 ± 0.5	-2.7 ± 0.6
		10	42.7 ± 0.7				48.0 ± 0.8	
Stellite 6	4	0	44.2 ± 1.6	-1.6 ± 1.6	Stellite 12	4	50.2 ± 0.9	-2.8 ± 1.1
		15	42.6 ± 1.6				47.4 ± 1.3	
Stellite 6	5	0	43.9 ± 1.2	-1.2 ± 1.2	Stellite 12	5	50.4 ± 1.2	-1.3 ± 0.9
		30	42.7 ± 1.2				49.1 ± 0.5	
Stellite 6	6	0	45.1 ± 1.6	1.0 ± 1.7	Stellite 12	6	51.1 ± 0.7	-0.4 ± 0.9
		60	44.2 ± 1.8				50.7 ± 1.0	
Stellite 6	7	0	44.0 ± 1.6	-0.2 ± 1.4	Stellite 12	7	50.0 ± 0.9	-0.9 ± 0.8
		960	43.8 ± 1.2				49.1 ± 0.8	

*The HRC values have been determined by employing a conversion table in accordance with ASTM E 140–97 [17]

The tribological experiment was conducted at room temperature, with a relative humidity between 30-50 %, and without any lubrication. The valve head being studied was clamped in the holder shown in Fig. 3a. The roller was fixed in a holder above the table without the possibility of rotation, while the counterpart performed sliding friction on the surface of the valve being examined. The holder rotated at a speed of 60 revolutions per minute, with an applied load of 10 N for 1500 cycles. To standardize the testing procedure, the samples were glued to the testing cylinders using Loctite EA 3421 epoxy adhesive. The objective was to replicate the actual contact of the friction pair in an engine as closely as possible. The ASTM G99-95 standard was followed during the tribological measurements. [18]

Throughout the measurement process, the working surfaces were constantly in touch and consistently under load with the counterpart. The valve head and the counterpart were always in contact on the sealing cone of the valve head to ensure that the contact closely resembled the actual operation.

Tab. 6 *Overview of tested friction couples*

Disc	Pin	Test No.
P37S	Stellite 6 -without freezing	1
P37S	Stellite 6 – frozen 5 min	2
P37S	Stellite 6 – frozen 10 min	3
P37S	Stellite 6 – frozen 15 min	4
P37S	Stellite 6 – frozen 30 min	5
P37S	Stellite 6 – frozen 60 min	6
P37S	Stellite 12 – without freezing	7
P37S	Stellite 12 – frozen 5 min	8
P37S	Stellite 12 – frozen 10 min	9
P37S	Stellite 12 – frozen 15 min	10
P37S	Stellite 12 – frozen 30 min	11
P37S	Stellite 12 – frozen 60 min	12

The wear on the valve surfaces was examined using a SENSOFAR S Neox confocal microscope, which allows for non-contact scanning of surfaces using confocal and interferometric methods. Pin wear was assessed using a Leica DVM6 digital microscope. [19]

Fig. 4 depicts the effect of cryogenic temperatures on the coefficient of friction of Stellite 6. The measured data shows a decrease in the static coefficient of friction due to cryogenic temperatures. The untreated Stellite 6 sample had the highest initial static friction coefficient at 0.431. Cryogenic processing resulted in surface strengthening, thought to be due to the formation of new structural phases or changes in dislocations in the material's crystal lattice, enhancing resistance to wear and reducing friction during motion. However, the untreated sample displays stable behavior over time with no gradual increase in the dynamic coefficient of friction.

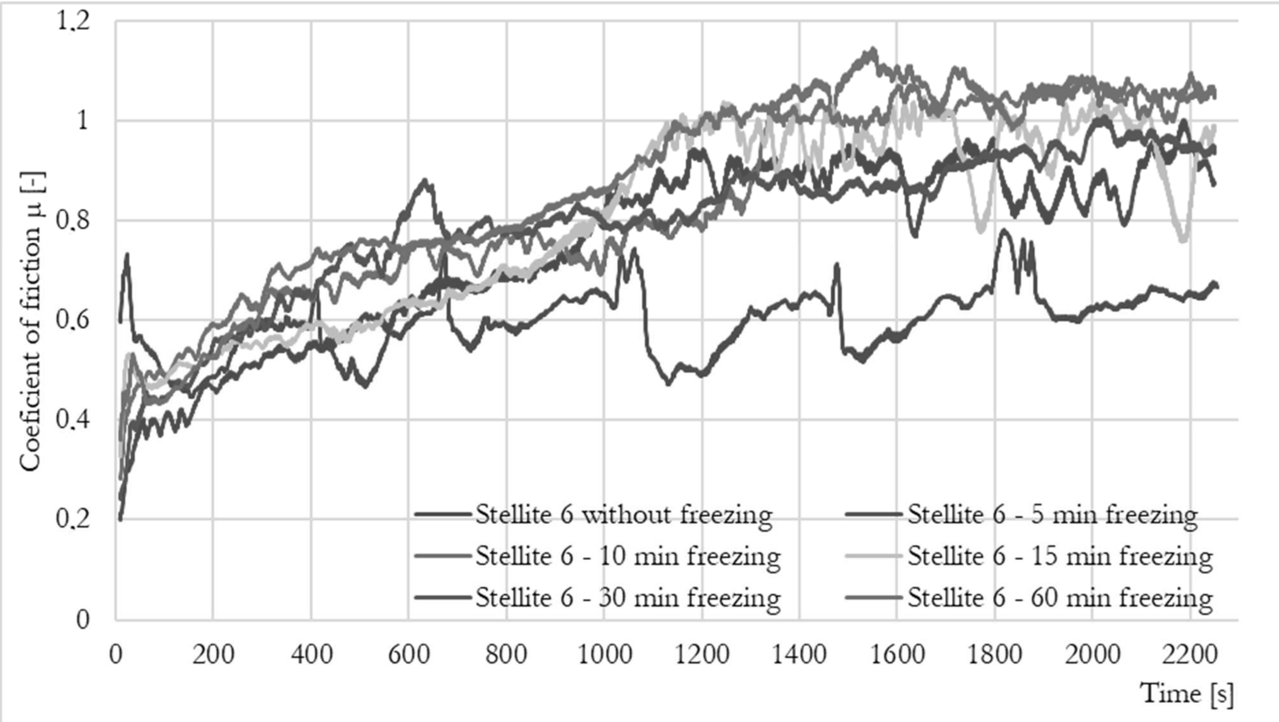

Fig. 4 *Influencing of cryogenic treatment to friction coefficient of Stellite 6*

Fig. 5 illustrates the effect of cryogenic temperatures on the coefficient of friction of Stellite 12. The freezing times of 15 and 60 minutes result in a reduction in the coefficient of static friction. In contrast, the freezing times of 5, 10, and 30 minutes show a slight increase in the coefficient of static friction.

These alterations enhance the surface's resistance to wear, thus reducing resistance during motion or friction. However, the sample without the freezing treatment shows stable behavior over time with no gradual increase in the dynamic coefficient of friction.

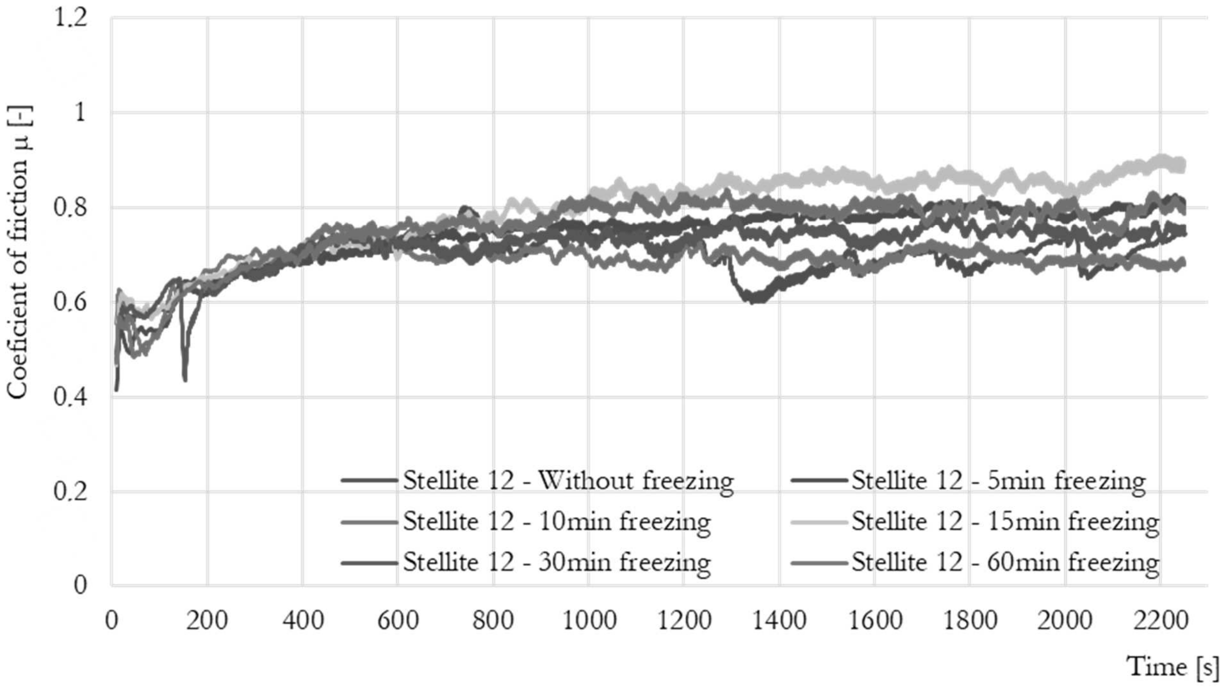

Fig. 5 *Influence of cryogenic treatment to friction coefficient of Stellite 12*

Based on the data collected, it can be concluded that the tribological properties of Stellite 12 are less affected by cryogenic temperatures compared to Stellite 6. The static coefficient of friction of Stellite 12 is influenced by the duration of freezing.

A comparison of the average friction coefficient values is for Stellite 6 in Fig. 6a and Stellite 12 in Fig. 6b.

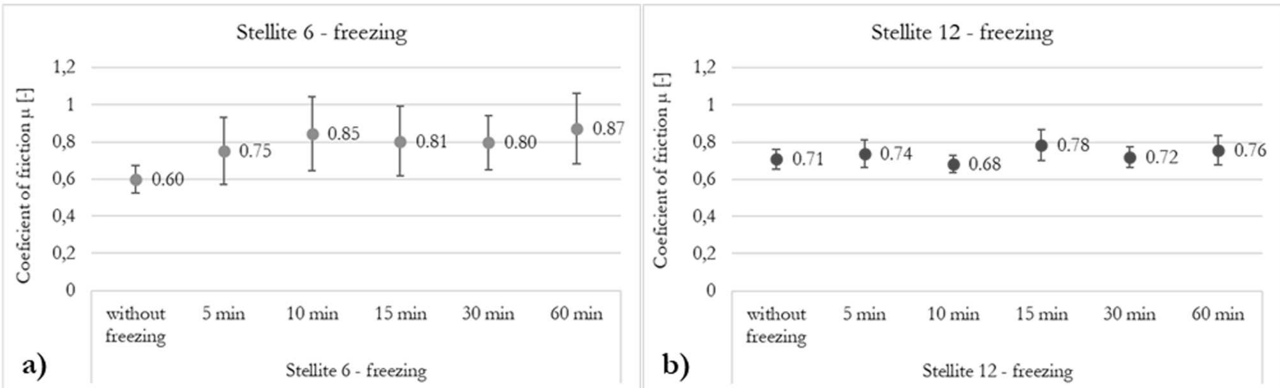

Fig. 6 *Comparison of the average values of the coefficient of friction for the monitored materials*

The composition of Stellite 6 and Stellite 12 consists of cobalt-based alloys with different additives and carbon content. These variations in chemical composition can cause distinct structural changes during cryogenic processing, which can impact their tribological properties. The microstructure of a material, including the arrangement and formation of crystals, plays a vital role in determining its mechanical and tribological characteristics. Cryogenic temperatures can cause phase transformations within the material, which can lead to changes in its tribological properties. Depending on the phases that Stellite 6 and Stellite 12 exhibit at specific temperatures, they may show different reactions. Different wear mechanisms can affect the tribological behavior of materials. Cryogenic temperatures can alter these wear mechanisms, which, in turn, can affect the performance of both Stellite 6 and Stellite 12 materials in tribological applications. The microstructure of the materials can have a significant impact on their tribomechanical properties. Adhesive wear is considered to be the primary wear mechanism of materials, which results from the formation of microwelds between the mating surfaces [20, 21, 22].

Based on our measurements, we recommend using the shortest possible cryogenic treatment time for the intake valve seat (Stellite 6) from a tribological perspective. This means cooling it for up to 5 minutes. Beyond this time, the coefficient of friction begins to increase, and our experiments have shown that hardness changes occur. Specifically, the most significant decrease in hardness occurs after 10 minutes of cooling, which can lead to increased wear of the intake valves.

Based on the measured values, it is recommended to freeze the exhaust valve seats (made of Stellite 12) cryogenically for a duration of 10 minutes. At this duration, the friction coefficient values are the lowest, and the decrease in material hardness does not reach its maximum.

An assessment of wear on the friction pairs was carried out as per the standard ČSN EN 1071-13 [23]

The outcomes are presented in Table 6. The quantity of wear on the disc sample was determined by using the below equation (1), which involves the smallest diameter of the machining track and the diameter perpendicular to it:

$$V_{pin} = \frac{\pi A^3 B}{32D} \quad (1)$$

V_{pin}…Amount of wear on the disc sample [mm³],

A…Smallest diameter of the machining track [mm],

B…Diameter in the direction perpendicular to the smallest diameter [mm],

D…Diameter of the disc sample [mm].

Circular machining marks were left on the flat disc sample after the test. The transverse profile was measured at four different points with 90-degree intervals using the SENSOFAR S Neox confocal microscope.

The damaged surfaces of the valve after the tribological experiment are shown in Figure 7a (Stellite 6) and Figure 7b (Stellite 12).

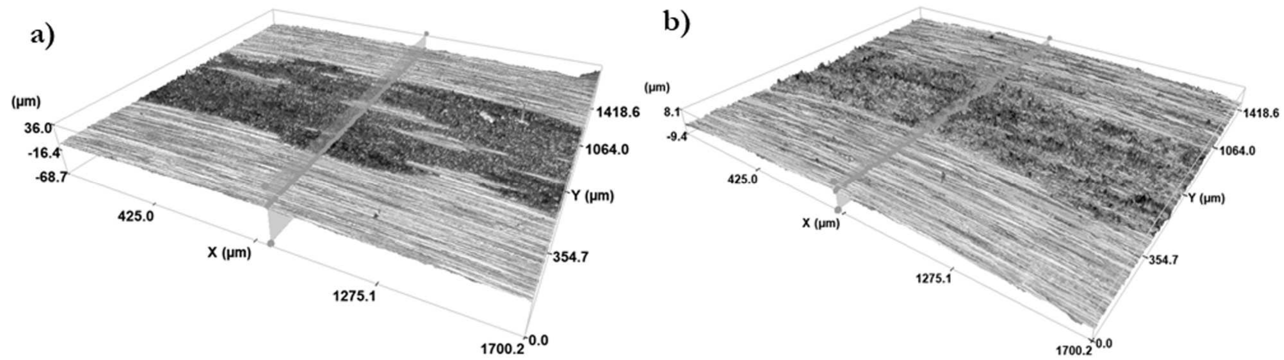

Fig. 7 *Valve surface damage for a) Stellite 6 and for b) Stellite 12*

Figure 8a shows damage to the surface of pins that were in contact with Stellite 6, and Figure 8b shows damage to the surface of pins that were in contact with Stellite 12.

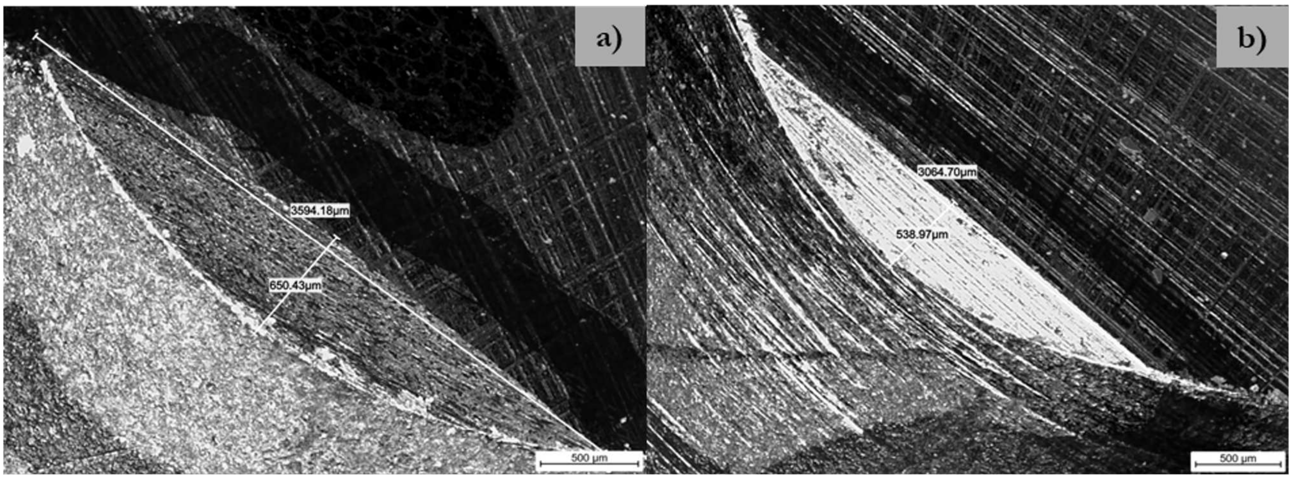

Fig. 8 *Pin surface damage a) pin in contact with Stellite 6 and b) pin in contact with Stellite 12*

Friction pair wear monitoring shows that Stellite 6 samples experience a reduction in valve (disc) wear. After freezing, a reduction in wear of the friction pair was also observed for the Stellite 12 samples. This information can be found in Table 6.

According to Yang [8], cryogenic processing can refine the microstructure in the surface layer and reduce residual stress. Additionally, the study's findings suggest that optical microscopy may not be sufficient to accurately characterize microstructures resulting from different freezing conditions.

Based on the measured values, it is apparent that the technological freezing time of the valve seat needs to be regulated. This is because there is a chance that the freezing time might coincide with the most significant reduction in the hardness of the valve seat material.

Differences in hardness may be smaller than the measurement error, but the experiment revealed discernible trends in the material's hardness changes.

The results obtained from this tribological experiment will help us understand the friction and wear properties of valve-seat systems. Additionally, they will give us a better idea about the feasibility of using alternative materials and surface treatments to enhance the efficiency and cost-effectiveness of such friction pairs.

Tab. 6 *Measured values of tribological testing*

Test No.	Valve (DISC) wear width [μm]	Depth of DISC wear [μm]	Pin wear [mm³]
1. (Stellite 6 -without freezing)	519.27	32.91	0.003
2. (Stellite 6 – frozen 5 min)	721.09	2.31	0.016
3. (Stellite 6 – frozen 10 min)	710.74	4.42	0.016
4. (Stellite 6 – frozen 15 min)	719.15	3.35	0.016
5. (Stellite 6 – frozen 30 min)	840.30	5.20	0.018
6. (Stellite 6 – frozen 60 min)	566.63	3.82	0.005
7. (Stellite 12 – without freezing)	583.13	12.36	0.030
8. (Stellite 12 – frozen 5 min)	527.20	3.94	0.008
9. (Stellite 12 – frozen 10 min)	595.65	7.38	0.009
10. (Stellite 12 – frozen 15 min)	558.75	3.84	0.005
11. (Stellite 12 – frozen 30 min)	534.13	4.72	0.008
12. (Stellite 12 – frozen 60 min)	523.81	5.56	0.007

The Stellite 6 and Stellite 12 materials are made up of alloys based on cobalt, with different additives and carbon content. This results in specific changes in their structure during cryogenic processing. The microstructure, which includes the arrangement and formation of crystals, plays an essential role in determining mechanical and tribological properties. Cryogenic temperatures can cause phase transformations, which may affect tribological characteristics. The wear mechanisms that affect tribological behavior can be altered by cryogenic temperatures, which can impact the performance of both Stellite 6 and Stellite 12 in tribological applications.

8 Conclusion

The hardness values of Stellite 6 and Stellite 12 valve seats were analyzed and it was found that there were specific freezing times at which local minimum hardness values were observed. Specifically, 10 minutes of freezing time for Stellite 6 and 15 minutes for Stellite 12. This discovery led to the creation of a technological regulation that mandates a minimum freezing time of 5 minutes with a tolerance of ± 1 minute during the production of cylinder heads. The goal of this standardized procedure is to increase the service life of cylinder heads and eliminate the variable effects of different freezing times, thus providing more consistent and reliable results. Furthermore, cryogenic treatment did not significantly alter the hardness of valve seats.

Based on the measured values for Stellite 6, it can be concluded that exposure to cryogenic temperatures led to a decrease in hardness. The sample with a freezing time of 10 minutes exhibited the highest impact on hardness.

Based on the measured values for Stellite 12, we can conclude that exposure to cryogenic temperatures resulted in a decrease in hardness for all samples. The sample that was frozen for 60 minutes showed the smallest impact on hardness, while the sample that was frozen for 15 minutes had the highest impact on hardness.

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