Temperature-Dependence of Hardness and Wear Resistance of Stellite Alloys

S. Kapoor, R. Liu, X. J. Wu, M. X. Yao

Abstract—A group of Stellite alloys are studied in consideration of temperature effects on their hardness and wear resistance. The hardness test is conducted on a micro-hardness tester with a hot stage equipped that allows heating the specimen up to 650°C. The wear resistance of each alloy is evaluated using a pin-on-disc tribometer with a heating furnace built-in that provides the temperature capacity up to 450°C. The experimental results demonstrate that the hardness and wear resistance of Stellite alloys behave differently at room temperature and at high temperatures. The wear resistance of Stellite alloys at room temperature mainly depends on their carbon content and also influenced by the tungsten content in the alloys. However, at high temperatures the wear mechanisms of Stellite alloys become more complex, involving multiple factors. The relationships between chemical composition, microstructure, hardness and wear resistance of these alloys are studied, with focus on temperature effect on these relations.

Keywords—Stellite alloy, temperature, hardness, wear resistance

I. INTRODUCTION

STELLITE alloy is a group of cobalt-based superalloys designed for wear resistance applications involving unlubricated systems or elevated temperatures. It contains chromium and may also contain tungsten or molybdenum and a small amount of carbon [1]. The chief difference among the individual Stellite wear-resistant alloys is carbon content and, thus, carbide volume fraction in the materials. Stellite alloys can conventionally be categorized as high-carbon alloys designed for wear service; low-carbon alloys for high temperature service; and low-carbon alloys to combat corrosion or simultaneous corrosion and wear.

Addition of chromium, usually between 20-30 wt%, is known to be highly resistant to corrosion and erosion. Chromium has a dual function in Stellite alloys. It is firstly, the predominant carbide former, through the formation of metal carbides M_7C_3 and $M_{23}C_6$. Secondly, it is the most important alloying element in the matrix, where it provides added strength, as a solute, and resistance to corrosion and oxidation. Mo and W have similar effects on the alloys. The effects of Mo (up to 28 wt%) and W (between 4 ~ 17 wt%) are known to contribute to the solid-solution hardening and also add to the strength of the material by forming primarily M_6C carbides along with MC carbides and inter-metallic phases, such as $Co_3(Mo,W)$ [1]. Most of the W remains in solid solution. W and Mo add strength due to their large atomic size which impedes dislocations and slips.

S. Kapoor is with Carleton University, Ottawa, ON, K1S 5B6, Canada (e-mail: samitkis@gmail.com).

R. Liu is with Carleton University, Ottawa, ON, K1S 5B6, Canada (phone: 613-5202600-8397; fax: 613-5205715; e-mail: rliu@mae.carleton.ca).

X. J. Wu is with National Research Council Canada, Ottawa, ON, K1A 0R6, Canada (e-mail: Xijia.Wu@nrc-cnrc.gc.ca).

M. X. Yao is with Kennametal Stellite, Belleville, ON, K8N 5C4, Canada (e-mail: myao@stellite.com).

Other elements are also added to Stellite alloys for providing special features. For example, addition of Ni promotes the stability of the face-centred cubic (fcc) structure of the solution matrices [2], and addition of B can decrease the melting point of the alloys, which favors homogenization of the powder metallurgy (P/M) products in the sintering process [3].

Owing to their wide range of applications, Stellite alloys have been extensively studied. For example, Frenk and Wagnière [4] conducted dry-sliding wear test on Stellite 6, using a pin-on-disc tribometer, aiming to explore the wear mechanisms of Stellite 6 against a hard metal counterface. Frenk and Kurz [5] investigated the influence of microstructure on the wear properties of Stellite 6. Cavitation erosion behavior of Stellite 3, Stellite 6 and Stellite 20 was studied by Heathcock *et al.* [6]. The tribological behavior of Stellite alloys at high temperatures was also studied. Wang, Li and Radu investigated the effects of yttrium additive on the high-temperature wear behavior of Stellite 6 [7], Stellite 21 [8] and Stellite 712 [9]. The effect of silicon addition to Stellite 6 on its hardness and wear resistance at elevated temperatures was also investigated [10]. However, previous research failed to address some of the key issues about Stellite alloys: (1) The effects of chemical composition on the high-temperature properties of Stellite alloys are important for optimizing alloy composition for high-temperature applications, but they were not systematically investigated and studied. (2) Hardness is considered as an important material property for Stellite alloys because it is often used to correlate to wear resistance of materials. Stellite alloys are multi-phase alloys, but the hardness values of individual phases of Stellite alloys were not obtained. Without these data material engineers cannot design the compositions of Stellite alloys with respect to the influence of alloying elements on the overall hardness of Stellite alloys. (3) Although it is well known that hardness plays an important role in wear resistance of Stellite alloys, there are no enough data to ascertain the correlation of hardness and wear resistance at high temperatures. Particularly, the temperature-dependence variations of these critical properties are not understood. The lack of knowledge in these aspects seriously limits the development of Stellite alloys for demanding applications at high temperatures and in severe environments which tend to push engineered materials to their limits, therefore a better understanding of these relationships involving chemical composition, microstructure, hardness, wear, and temperature for Stellite alloys is crucially required and is the emphasis of this research.

The present research was aimed to investigate the high-temperature hardness and wear resistance of Stellite alloys, with focus on the effects of chemical composition on their microstructures and such properties. The variations of hardness and wear resistance with temperature were determined, and the correlations between these two properties were studied for both room temperature and elevated temperatures.

The research results are not only beneficial for extending the application of existing Stellite alloys but also provide the

scientific guidance for designing new Stellite alloys to be used in high-temperature severe-wear conditions.

II. ALLOY SELECTION AND MICROSTRUCTURE

A. Chemical Composition

Firstly, considering the main strengthening agent, carbon, which correlates directly to the carbide volume fraction in Stellite alloys, the selected alloys contain a carbon content varying from 1.2 wt% to 2.4 wt%. Secondly, considering the main strengthening element of solid solution, tungsten, these alloys were selected to contain varying levels of tungsten, from 4.5 wt% up to 32 wt%. Thirdly, as the main agent of carbide formation, chromium, usually takes 20-30 wt% in Stellite alloys. Molybdenum was not concerned in this research. According to these considerations, five Stellite alloys were selected in the present research, numbered as alloy 1, alloy 2, alloy 3, alloy 4, and alloy 5, respectively. The chemical compositions (wt%) of these alloys are detailed in Table I.

TABLE I
CHEMICAL COMPOSITIONS (WT%, CO IN BALANCE) OF STELLITE ALLOYS

Element / Specimen	Cr	W	Mo	Ni	Fe	C	B	Si	Mn
Alloy 1	30.5	12.5	0	3.5	5	2.4		2	2
Alloy 2	29	4.5	1.5	3	3	1.2		0.75	0.5
Alloy 3	30	8.3	0	1.5	3	1.4		0.7	2.5
Alloy 4	33.5	19	0	0	0	1.9	1	0	0
Alloy 5	22	32	0	0	0	1.5		0	0

B. Microstructure

The microstructure analysis of the alloy specimens was performed on a Hitachi Model S-570 Scanning Electron Microscope (SEM) with backscatter electron imaging (BEI) and energy dispersive X-ray (EDX) spectrum and the obtained images are shown in Fig. 1. The volume fraction of carbides in the microstructure of a Stellite alloy is proportional to its carbon content. The alloy may have a hypo-eutectic microstructure or a hyper-eutectic microstructure, depending mostly on its carbon content but also on the contents of other elements, for example, tungsten. The type of carbides in the microstructure is controlled by the alloying elements in the solution matrix and their contents.

Alloy 1 contains a high carbon level that increases the volume fraction of carbides. The high carbide phase Cr_7C_3 (dark) is dispersed in a cobalt solid solution matrix (grey), with the lighter spots representing eutectic $(W,Co)_6C$ carbide (in light), see Fig. 1(a), This microstructure is hyper-eutectic. Alloy 2 has a microstructure with less volume fraction of carbides as this alloy has half of the carbon content of Alloy 1. Cr_7C_3 (dark) carbides having a laminar shape are dispersed in a similar solution matrix, as seen in Fig. 1(b). This alloy is hypo-eutectic with primary cobalt dendrites surrounded by a network of eutectic Cr_7C_3 carbide. Alloy 3 has similar carbon content to Alloy 2 and an average tungsten content of alloy 1 and alloy 2. Its microstructure is hypo-eutectic, consisting of primary cobalt solid solution with longitudinal eutectic Cr_7C_3 carbide, as seen in Fig. 1(c). Also, because of the higher tungsten content, this

alloy contains a small amount of eutectic $(W,Co)_6C$. Alloy 4 contains a high level of carbon so that it has a hyper-eutectic microstructure, with primary Cr_7C_3 carbide, and the eutectic mixture of solid solution, $(W,Co)_6C$ and Cr_7C_3 carbides, see Fig. 1(d). Alloy 5 contains the same elements as alloy 4 except that the former does not contain boron. However, since alloy 5 contains a very high level of tungsten and a medium level of carbon, its microstructure is quite different from that of alloy 4. This alloy has a hyper-eutectic microstructure, with $(W,Co)_6C$ carbide as the primary phase. It is seen in Fig. 1(e) that the primary $(W,Co)_6C$ (in light) has a larger size and takes a large volume fraction of its microstructure. The eutectic consists of a mixture of solid solution, Cr_7C_3 carbide and $(W,Co)_6C$ carbide as well.

## III. HARDNESS INVESTIGATION

A. Indentation Test

A Microhardness Tester Unit, Model SMT-X7 Dual Indenter, was employed to investigate the hardness of each individual phase in the microstructures of the five alloys, at both room temperature and elevated temperatures. With a microscope equipped, each individual phase in a microstructure can be identified and selected to measure. To achieve the temperature capacity of 700°C, a Hot-Stage Assembly, was attached to the platform of the Microhardness Tester Unit. A cooling system was also available to maintain the platform unheated for operation. However, the entire system is exposed to air, that is, the test specimen is not in a vacuum environment, thus oxidation of the specimen surface at high temperatures is inevitable, which may affect the accuracy of the hardness result. On the other hand, hardness is only associated with plastic deformation of a material, while oxide films are generally brittle or fragile, with this viewpoint surface oxidation influence on the hardness results may be trivial and can be neglected. A low indentation load of 100 gf was selected, which allowed the indentation to be made on a selected phase, because if the load was too high, the indentation may cover an area with other phases involved. The indentation test for each specimen was conducted at room temperature, 250°C, 450°C and 650°C, respectively, in a heating process, and then for the same specimen, the indentation was successively made at 450°C, 250°C and room temperature, respectively, in a cooling process. The purpose of doing this reciprocal cycle test was to explore any thermal effects on the hardness of these materials by comparing the hardness value tested at the temperature in heating process with that tested at the same temperature but in cooling process. Five indentations were made at each temperature for each specimen and two specimens were tested for each alloy. The hardness value for each test case was an average of the ten test results.

B. Hardness Results

Since Stellite alloys are multi-phase alloys which contain at least two phases, known as cobalt solid solution and carbides, and each phase may exhibit different features including hardness, the micro hardness test was conducted on each phase of the alloys at the temperature cycle. For alloy 1, from its

microstructure in Fig. 1(a), this alloy consists of two types of carbides, M_7C_3 and $(W,Co)_6C$, dispersed in the cobalt solid solution matrix. Attempt was made to conduct the indentation on these three phases respectively. For the solution matrix, it was possible to make the indentation on single solid solution phase, see Fig. 2(a), however, for the carbides, due to their small sizes, especially, for the carbide $(W,Co)_6C$, it was impossible for the indenter to cover a single phase, that is, the area under indentation contained mainly the carbide M_7C_3 but also with $(W,Co)_6C$ and solid solution. Since the amounts of each constituent in the mixture present in the area covered by the indenter would vary in each test; the obtained hardness values on the mixture cannot accurately predict the effects of individual phases on the overall hardness of the mixture. Therefore, the following analysis will be focused on the single phases only but not on the mixtures.

As shown in Fig. 1(b), the microstructure of alloy 2 consists of M_7C_3 carbides dispersed in the cobalt solid solution matrix. It was possible to make the indentation on single solid solution phase, as shown in Fig. 2(b), however, for M_7C_3 carbide, due to the laminar structure, the area covered by the indenter may also contain minor solution phase. Therefore M_7C_3 carbide of this alloy was not concerned in this indentation test.

Eutectic $(W,Co)_6C$

Primary Cr_7C_3

(a)

Cr_7C_3

(b)
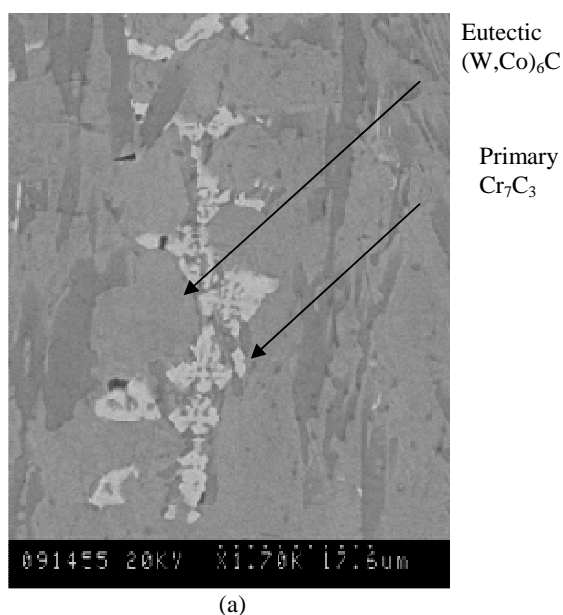
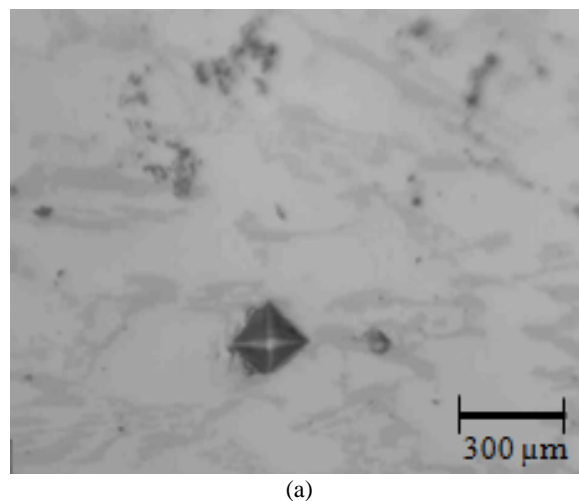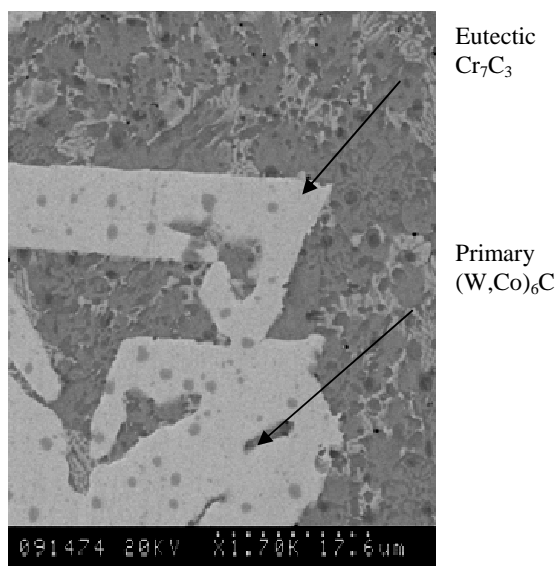

Eutectic $(W,Co)_6C$
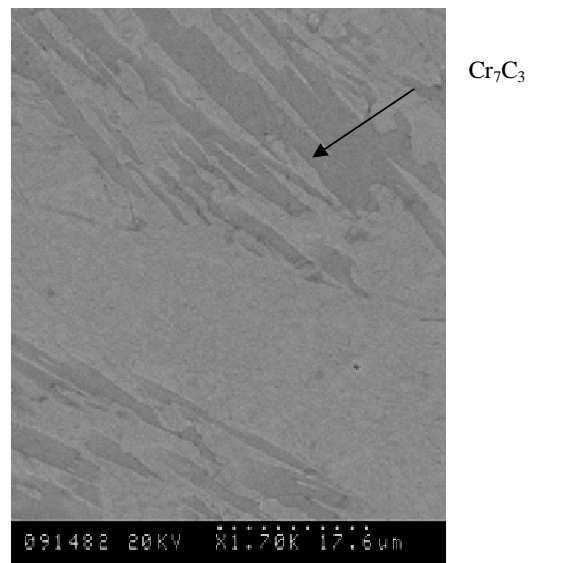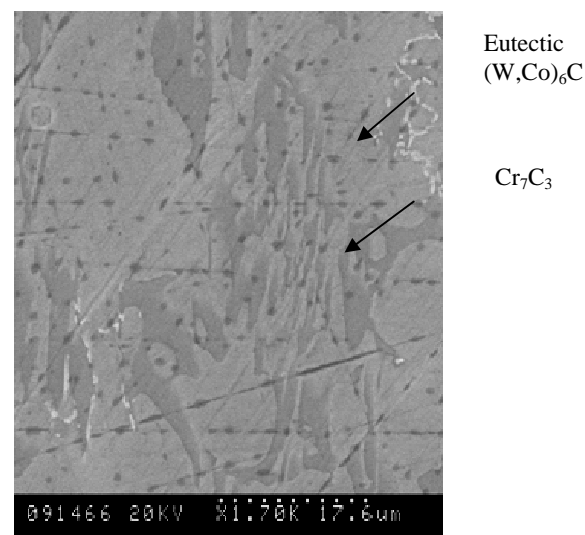
Cr_7C_3

(c)

Alloy 3 has a microstructure consisting of primary solid solution with longitudinal eutectic Cr_7C_3 carbides, as shown in Fig. 1(c). Due to the higher tungsten content, this alloy also contains a small amount of eutectic $(W,Co)_6C$. It was possible to make the indentation on single solution phase, see Fig. 2(c), but for carbides, the area covered by the indenter may also contain minor solution phase. Therefore, $(W,Co)_6C$ and M_7C_3 carbides of this alloy were not concerned in this indentation test. For alloy 4, it has a hyper-eutectic microstructure, consisting of primary Cr_7C_3 carbide and eutectic $(W,Co)_6C$ dispersed in the solid solution matrix, as shown in Fig. 1(d). It was possible to make the indentation on the entire Cr_7C_3 carbide phase because of the large size of the Cr_7C_3 carbides, see Fig. 2(d). However, the solid solution is mixed with $(W,Co)_6C$ and minor Cr_7C_3 so that the indentation could not be made on the single solution phase. Thus, for this alloy, only M_7C_3 carbide was concerned in this indentation test.
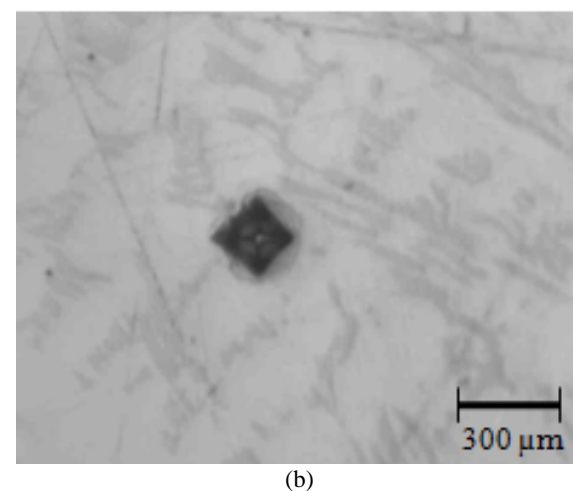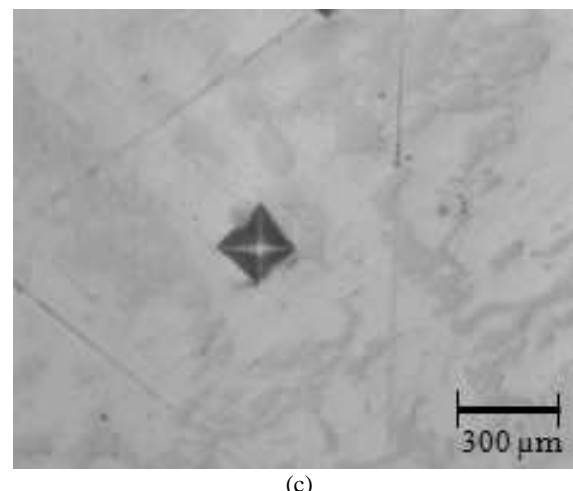
Eutectic (W,Co)$_6$C

Primary Cr$_7$C$_3$

(d)

Eutectic Cr$_7$C$_3$

Primary (W,Co)$_6$C

(e)
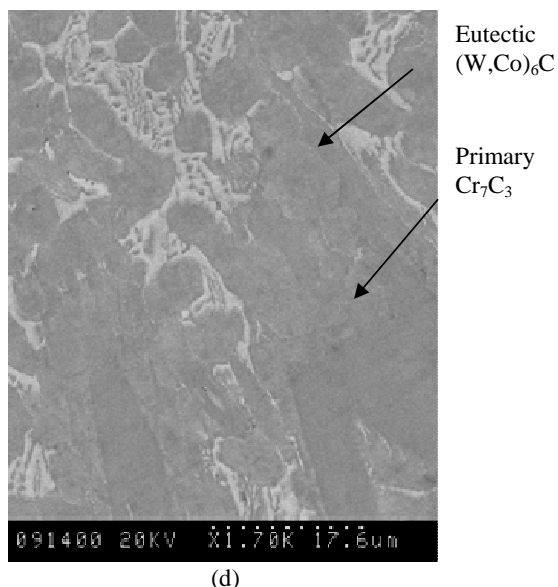
Fig. 1 SEM microstructures: (a) alloy 1, (b) alloy 2, (c) alloy 3, (d) alloy 4 and (e) alloy 5

(a)

(b)

(c)

Alloy 5 has a hyper-eutectic microstructure, consisting of primary (W,Co)$_6$C carbide and eutectic solid solution, Cr$_7$C$_3$ carbide and (W,Co)$_6$C carbide, as shown in Fig. 1(e), owing to the very high tungsten content in the alloy. The (W,Co)$_6$C carbide is large enough to allow the indentation to be made on entire (W,Co)$_6$C carbide phase, as shown in Fig. 2(e). However, the amounts of solid solution and Cr$_7$C$_3$ carbide in this alloy are too small to make the indentation on their single phases. Therefore, for this alloy, only (W,Co)$_6$C carbide was concerned in this indentation test.
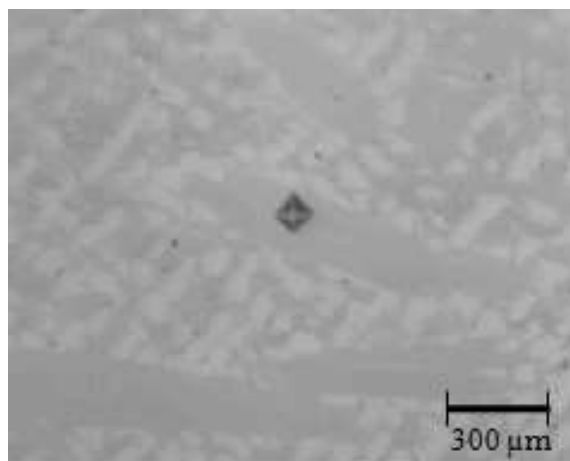
(d)
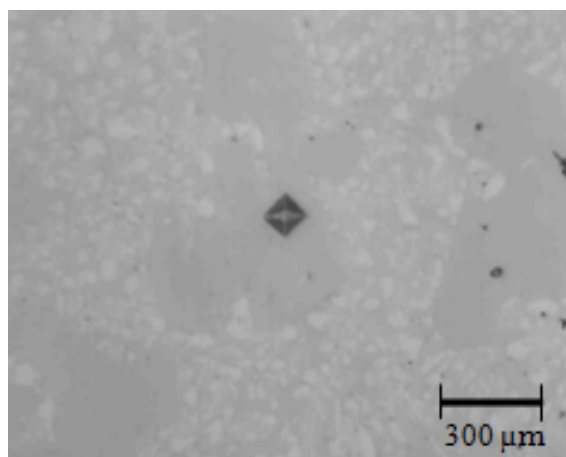
(e)

Fig. 2 Microscopic images of indentation made in the specimens tested at 20°C before heating: (a) alloy 1, (b) alloy 2, (c) alloy 3, (d) alloy 4 and (e) alloy 5

The average hardness values were calculated from the multiple indentation tests for each alloy at each temperature, and the variations of hardness with temperature were plotted, as presented in Fig. 3. To express the temperature-dependence relations of hardness for the solid solutions and carbides of the five alloys, one may linearize the hardness data with respect to temperature to obtain the slopes, as illustrated in Fig. 3, which represent the variation sensitivities of hardness with temperature. The slope results for all the alloys are summarized in Table II. The experimental results show that the hardness values of both solid solution and carbides decrease with temperature, which means that the solid solution and carbides of Stellite alloy can be softened by temperature. The reductions in hardness of solid solution and carbides at 650°C were calculated and the values are presented in Table II. It is also noted that the hardness values of solid solution and carbides are different at the temperatures in heating process and in cooling process, which indicates that the heating/cooling cycle had influence on the hardness of the solid solution and carbides of Stellite alloys.
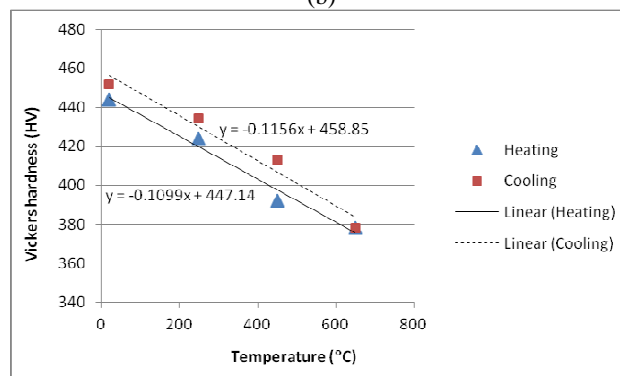
The changes in hardness of the solid solution and carbides at room temperature before and after the heating/cooling cycle were calculated and the results are reported in Table II.
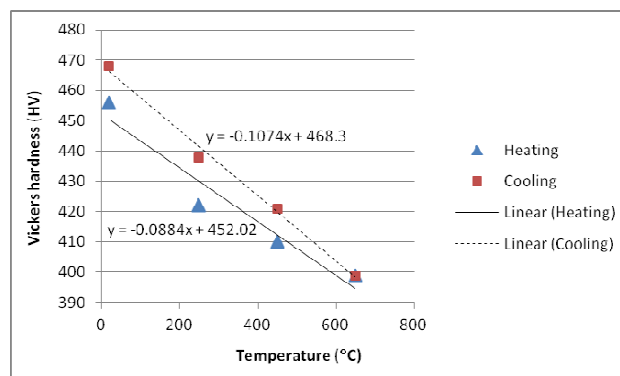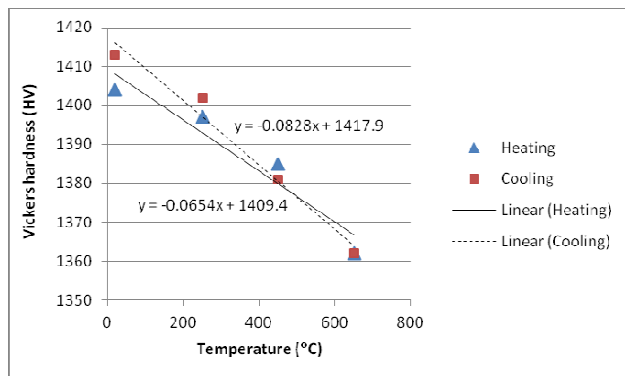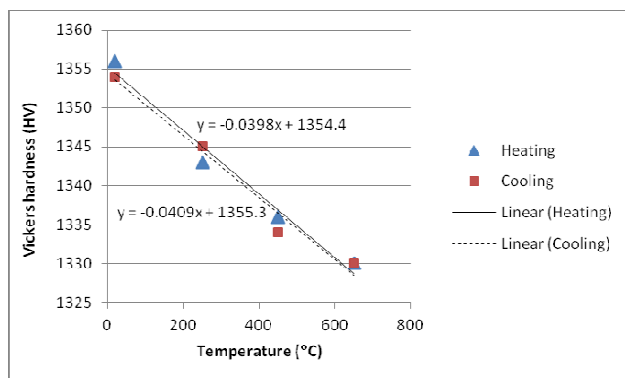

(a)
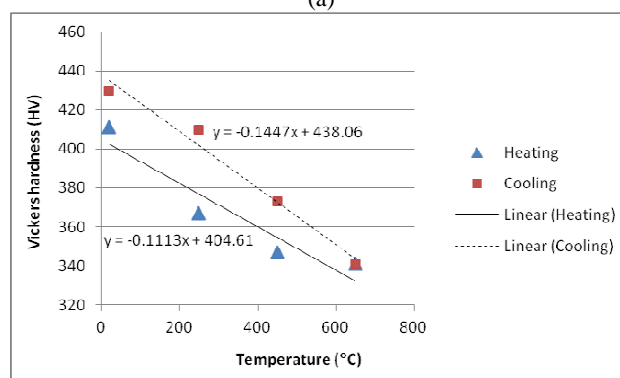
(b)

(c)

According to the data in Table II, both Cr_7C_3 carbide and $(W,Co)_6C$ carbide exhibited much less variation of hardness with temperature than the solid solutions; the small amounts of reduction and change in hardness of the carbides can be considered as the experimental errors, that is, the carbides were almost not affected by this temperature (650°C).

(d)

(e)

Fig. 3 Temperature-dependence of hardness: (a) Co solid solution of alloy 1, (b) Co solid solution of alloy 2, (c) Co solid solution of alloy 3, (d) Cr_7C_3 carbide of alloy 4 and (e) $(W,Co)_6C$ carbide of alloy 5

TABLE II
TEMPERATURE-DEPENDENCE SUMMARY OF HARDNESS FOR SOLID SOLUTION AND CARBIDES

Temperature condition / Phase	Hardness variation sensitivity with temperature in heating cycle (HV/°C)	Hardness variation sensitivity with temperature in cooling cycle (HV/°C)	Reduction of hardness at 650°C	Hardness change at room temperature after heating/cooling cycle
Alloy 1 Solution	0.0884	0.1074	12.5%	2.63%
Alloy 2 Solution	0.1113	0.1447	17%	4.62%
Alloy 3 Solution	0.1099	0.1156	14.9%	1.8%
Alloy 4 Cr_7C_3	0.0654	0.0828	3%	0.64%
Alloy 5 $(W,Co)_6C$	0.0409	0.0398	1.9%	0.15%

For the solid solutions, temperature had more effects on their hardness. Among the three alloys, alloy 1, with the highest content of tungsten (Table I), exhibited the least variation of hardness with temperature, and alloy 2, with the lowest content of tungsten (Table I) exhibited the largest variation. Therefore, it may be concluded that tungsten content is the main factor that affects the high-temperature properties of Stellite alloys. The element, tungsten, is well known for high-temperature properties [1], so that it plays a critical role in stabilizing the properties of the alloys that contain high tungsten at elevated temperatures.

IV. WEAR RESISTANCE EVALUATION

A. Pin-on-disc Wear Test

The wear resistance of the five alloys was evaluated using a Pin-on-Disc Tribometer, according to the testing procedure outlined in ASTM Designation G 99 – 95A Standard Test Method for Wear Testing with a Pin-on-Disc Apparatus. The pin used in this research was a spherical tip having a radius of 2.5 mm and was made of 94% WC and 6% Co with the hardness of HV 1534. The disk with the specimen mounted was a plate (about 5 mm thick) having a flat surface. For elevated temperature tests the pin-on-disc tribometer had a small furnace surrounding the disk, which allowed the pin through a top cover where it made contact with the disk in an almost enclosed environment. This environment was capable of heating the specimen to a maximum temperature of 450°C. Again, this enclosure was not oxidation-protective, therefore, oxidation of materials definitely occurred on the surface of the specimen under wear at high temperatures, resulting in formation of oxides.

During the wear test the pin (ball) was pressed under a compressive force 10 N on the specimen; the latter was spinning at a constant rotational speed 350 rpm. As the result of friction/wear, a wear track or pit was generated on the specimen surface. The wear loss was evaluated by calculating the volume of the wear track after the specimen surface was worn for 2.5 hr. The computation of wear track volume resorted to a D150 Surface Profile Measuring System, which allowed simulating the cross-section profiles of a wear track and computing the cross-sectional areas directly. Three tests were conducted on each alloy at each temperature. For each wear track four locations were selected uniformly along the wear track to calculate the cross-sectional area, and the average value was taken to be multiplied by the periphery length of the wear track (6 mm in diameter) to obtain the volume of the wear track.

B. Wear Loss

The average wear losses (volumes of the wear tracks) of each alloy at room temperature and at elevated temperatures were calculated and the results are illustrated in Fig. 4. At room temperature, in general, the wear resistance of Stellite alloys is controlled by the carbon content in the alloy. Alloy 2, containing the lowest C among the alloys, has the worst wear resistance. However, alloying elements such as W, Mo and Ni also play an important role. For example, alloy 5 has the best wear resistance, but this alloy contains less C than alloy 1. The excellent wear resistance of alloy 5 may be attributed to both high C and high W. Tungsten in satellite alloys not only enhances the solid solution matrix but also participates in the formation of carbides when present in large quantities. Alloy 1, containing the highest C and also containing high W, has better wear resistance than the others except alloy 5. Alloy 4, containing higher W but lower C than alloy 1, has slightly lower wear resistance. Between alloy 2 and alloy 3, the latter has better resistance to wear due to its both higher C and higher W.
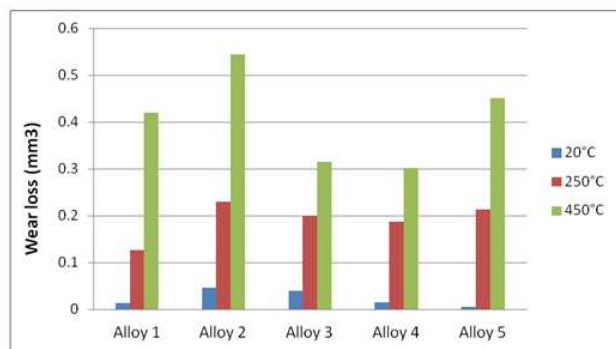
Fig. 4 Wear losses of Stellite alloys under the pin-on-disk wear test

With the increase in the temperature of the specimen to 250°C, the wear resistance of all the alloys decreased, as demonstrated in Fig. 4. The wear resistance of alloy 5 deteriorated significantly at elevated temperatures; it was worse than alloy 1, alloy 3 and alloy 4. Alloy 1 exhibited the best wear resistance among the alloys, followed by alloy 4, at this temperature. Alloy 3 was still better than alloy 2 at this temperature. When further increasing the temperature of the specimen up to 450°C, the wear resistance of these alloys continuously decreased, see Fig. 4. The predominant role of carbon content in the wear resistance of Stellite alloys was lessened by temperature effect. For instance, alloy 1 that contains the highest C exhibited worse wear resistance than alloy 3 and alloy 4. The wear resistance of alloy 5 dropped dramatically with temperature.

V. DISCUSSION

A. Temperature-dependence of Hardness

The hardness tests at elevated temperatures revealed that the solid solutions of Stellite alloys were affected by temperature, but the temperature effect on carbides was trivial and can be neglected. The solid solutions were softened at elevated temperatures; this may be due to the promoted atomic motion and relief of stress. The better performance of carbides may be attributed to their higher melting points. Chromium carbides have a melting point 1250°C to 1895°C and tungsten carbides can be as high as 2870°C. The solid solutions of Stellite alloy melt at the temperatures 1000°C to1200°C. The main reasons that caused softening of the solid solutions at the temperatures (250°C, 450°C and 650°C) can be the so-called stress relief anneal. At these temperatures any dislocations and residual stresses induced in the specimen material during the material processing and the specimen manufacturing may be released. It was also found that after experiencing the heating/cooling cycle the solid solutions were hardened. This can be explained as the structures of the solid solutions were homogenized by the heating/cooling cycle (heat treatment), which increased the overall strength of the solid solutions and thus the local resistance to deformation in the indentation test. In addition, it was shown that the higher the tungsten content, the lower the variation sensitivity of hardness with temperature.

The beneficial effect of tungsten on the high-temperature properties of Stellite alloys is owing to its high melting point and excellent high-temperature performance.

B. Temperature-dependence of Wear

The wear behavior of Stellite alloys at elevated temperatures is much complex than that at room temperature, because temperature effect may induce many changes in the factors that are involved in the wear process, for example, the material surface may be oxidized, the synergic effect of temperature and mechanical attack may result in different wear mechanisms. It was demonstrated by the wear test that when the specimen temperature was increased, the wear resistance of all the alloys decreased. This was due to softening of the alloy materials at elevated temperatures, resulting in loss of the strengths. Also, high temperature oxidation was another cause of increase in wear loss, because in room temperature wear oxidation occurred only at the contact surfaces where friction heat was generated due to rubbing of wearing surfaces. However, in high temperature wear the whole specimen was heated, which resulted in oxidation of the specimen surface; under mechanical attack in the wear process the oxide films were broken down, thus adding to the loss of the material.

To further understand the wear mechanisms, the worn surfaces of the specimens were examined using SEM and the images of the specimens tested at room temperature are provided in Fig. 5. For the worn surface of alloy 5 in Fig. 5(e), it is apparently less damaged and looks fairly smooth, compared with the other alloys, which confirms that this alloy has the least wear loss and best wear resistance among the alloys. Alloy 1 has a large volume fraction of carbides and therefore it is more wear-resistant; its worn surface is less cracked and damaged, as seen in Fig. 5(a). Alloy 3 and alloy 4 have a similar morphology of worn surface, see Fig. 5(c) and Fig. 5(d). Their matrices show accumulated plastic deformation resulting from cyclic mechanical attack during the wearing process. Alloy 2 appears differently from the others. As seen in Fig. 5(b), plastic deformation of the matrix is less but particle spallation from the matrix can be observed obviously in this alloy surface, which may be the main reason for larger wear loss than the others.

Further analyzing the worn surfaces of the specimens tested at the high temperature of 450°C, it was found that all the alloys exhibited obvious oxidation at this temperature, but alloy 2 and alloy 3 were better than the others, as shown in Fig. 6. Similar oxidation behavior of these alloys was observed in the indentation test. As shown in Fig. 7, at 650°C, alloy 1, alloy 4 and alloy 5 were seriously oxidized, but alloy 2 and alloy 3 were almost not oxidized.
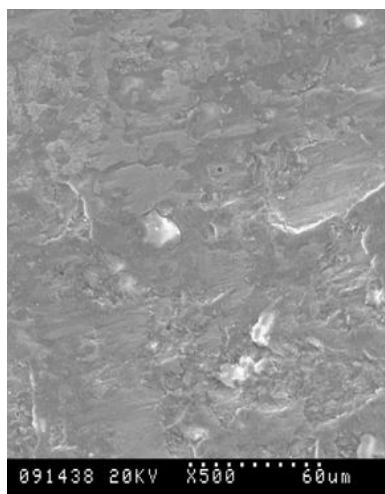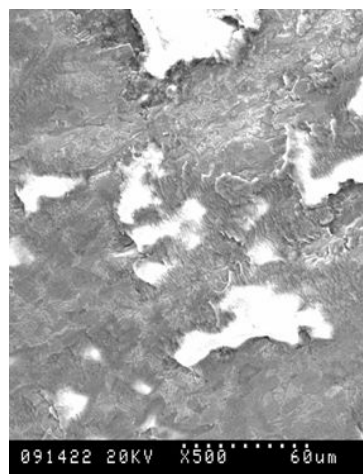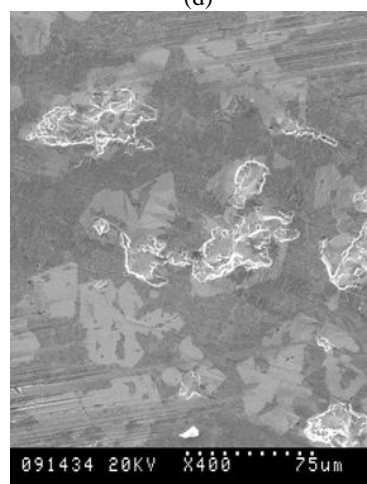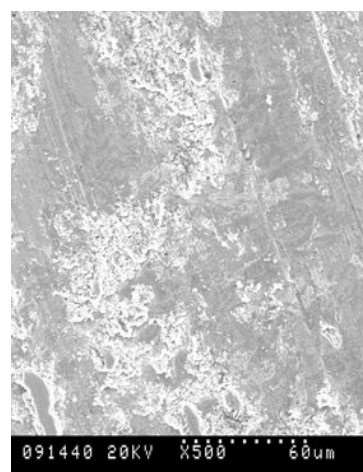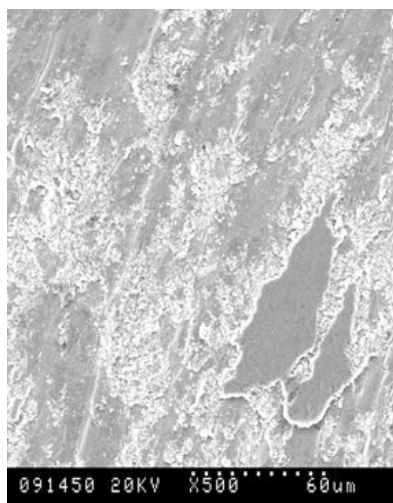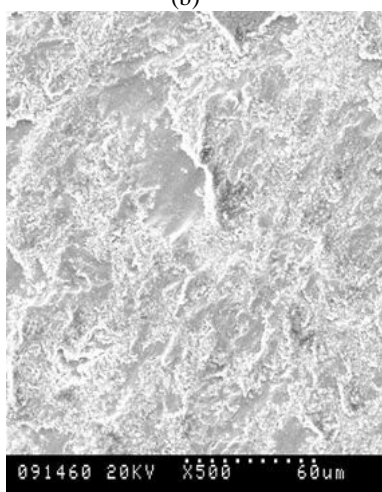
(a)
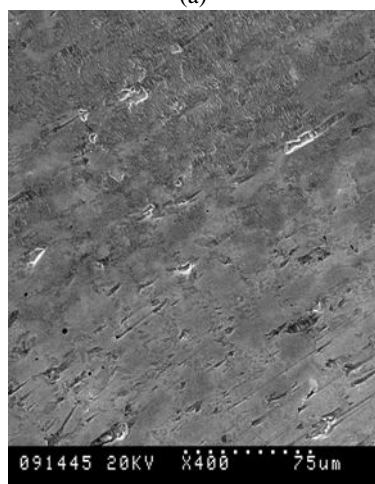
(b)
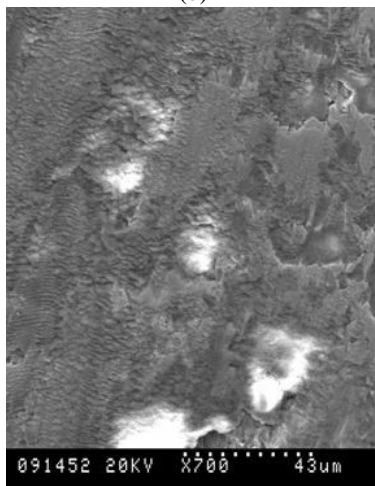
(c)

(d)

(e)

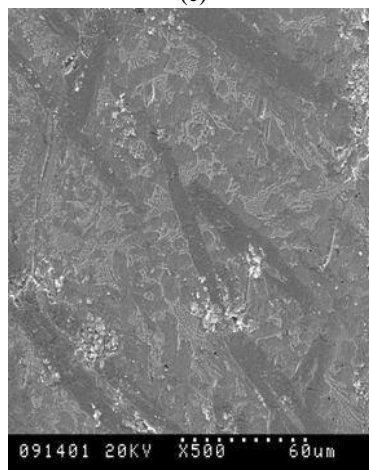Fig. 5 Worn surfaces of specimens tested 20°C: (a) alloy 1, (b) alloy 2, (c) alloy 3, (d) alloy 4 and (e) alloy 5
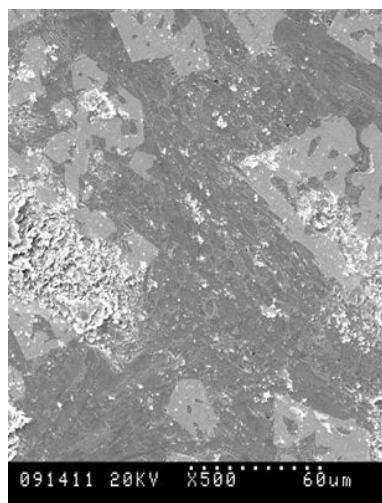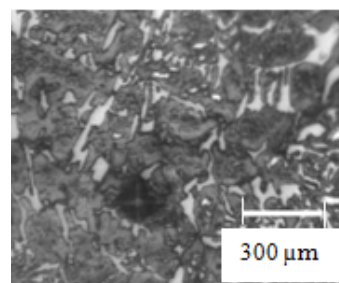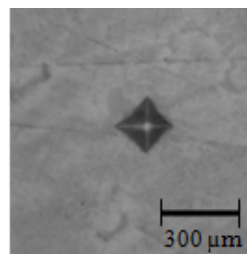

(a)

(b)

(e)
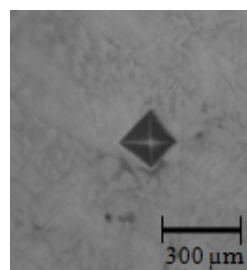
Fig. 6 Worn surfaces of specimens tested at 450°C: (a) alloy 1, (b) alloy 2, (c) alloy 3, (d) alloy 4 and (e) alloy 5
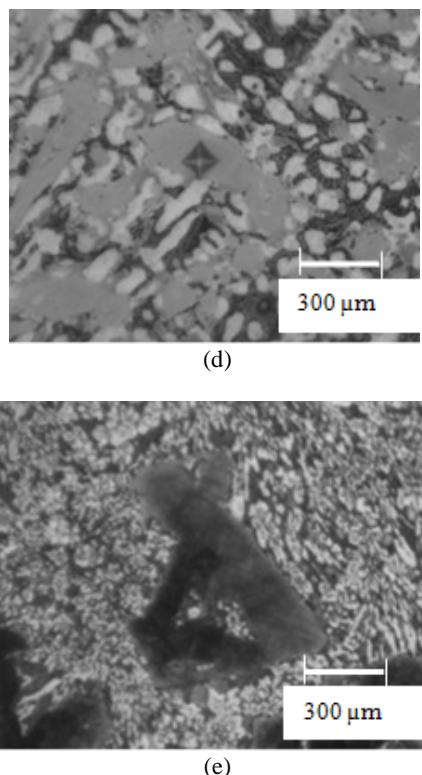

(c)

(a)

(b)

(d)

(c)

(d)

(e)

Fig. 7 Microscopic images of indentation left in specimens tested at 650°C: (a) alloy 1, (b) alloy 2, (c) alloy 3, (d) alloy 4 and (e) alloy 5

If relating the oxidation behavior of these alloys to their microstructures, the alloys that were heavily oxidized all have a hyper-eutectic microstructure, with carbides as the primary phase. Alloy 1 and alloy 4 contain a large amount of Cr_7C_3 carbide, which depletes Cr of the solution matrix thus resulting in severe oxidation of the alloys. Alloy 5 contains the lowest Cr among the alloys and contains a large amount of $(W,Co)_6C$ carbide which is free of Cr, so that this alloy was oxidized significantly at high temperatures, see Fig. 7(e). On the contrary, alloy 2 and alloy 3 exhibited better oxidation resistance at high temperatures. This is because these two alloys have a hypo-eutectic microstructure, with the solid solution as the primary phase that contains a high level of Cr.

Oxidation debris in the worn surface of alloy 5 specimen tested at 450°C is apparently more and larger, which is the main cause to the high wear loss. Obvious oxidation and oxide film breakdown are also observed in the worn surface of alloy 1 specimen. Alloy 2 exhibited the worst wear resistance at 450°C and alloy 4 exhibited relatively good wear resistance. There are two possible reasons for alloy 4 being more wear-resistant at high temperatures; one is that this alloy has the highest chromium content among the alloys, which enhanced its resistance to oxidation; the other is that this alloy also exhibited good resistance to wear at room temperature because of the presence of a large amount of $(W,Co)_6C$ and M_7C_3 carbides. Regarding alloy 2, it contains the least carbon among the alloys. This may be the main reason for the lowest wear resistance of this alloy at both room temperature and at high temperatures.

Comparing between alloy 1 and alloy 3, the latter was worse in wear resistance at room temperature but better at high temperatures. The better oxidation resistance of alloy 3 may be beneficial for the less wear loss at high temperatures.

VI. Conclusion

The solid solutions of Stellite alloys can be softened at elevated temperatures and can also be hardened by the heating/cooling cycle (heat treatment). Increasing the tungsten content of a Stellite alloy can increase the hardness stability of the solid solution of the alloy at high temperatures. However, the carbides of Stellite alloys are more stable; their hardness is almost not affected by temperature/thermal (up to 650°C) effect. The wear resistance of Stellite alloys at room temperature mainly depends on their carbon content; the alloying element, tungsten, also plays an important role in controlling the wear resistance of Stellite alloys.

The tribological behavior of Stellite alloys at elevated temperatures is much more complex than that at room temperature. The carbon content effect on the wear resistance of Stellite alloys is not as significant at elevated temperatures as at room temperature, whereas material oxidation has greater effect on the wear resistance of Stellite alloys at high temperatures. Increase of chromium content enhances the high-temperature oxidation resistance of Stellite alloys and increase of tungsten content enhances the stability of performance at high temperatures of Stellite alloys.

References

[1] J. R. Davis, Cobalt-base alloys, in Nickel, Cobalt, and Their Alloys, ASM International, Materials Park, 2000.
[2] K. Ando, T. Omori, J. Sato, Y. Sutou, K. Oikawa, R. Kainuma and K. Ishida, 2006, Effect of alloying elements on fcc/hcp martensitic transformation and shape memory properties in Co Al alloys, Mater. Trans., 47(9), 2006, 2381-2386.
[3] I. Campos, G. Ramirez, U. Figueroa and C. Velazquez, Paste bonding process: Evaluation of boron mobility on borided steels, Surf. Eng., 23(3), 2007, 216 222.
[4] A. Frenk and J. D. Wagnière, Laser cladding with cobalt-based hardfacing, J. Phys. IV France, 1(C7), 1991, 65-68.
[5] A. Frenk and W. Kurz, Microstructural effects on the sliding wear resistance of a cobalt based alloy, Wear, 174(1-2), 1994, 81-91.
[6] C. J. Heathcock, A. Ball and B. E. Protheroe, Cavitation erosion of cobalt-based Stellite alloys, cemented carbides and surface-treated low alloy steels, Wear, 74(1), 1981, 11 26.
[7] L. C. Wang and D. Y. Li, Effects of yttrium on microstructure, mechanical properties, high temperature wear behaviour of cast Stellite 6 alloy, Wear, 255(1-6), 2003, 535 544.
[8] I. Radu, D. Y. Li and R. Llewellyn, Tribologocal behaviour of Stellite 21 modified with yttrium, Wear, 257(11), 2004, 1154-1166.
[9] I. Radu and D. Y. Li, The wear performance of yttrium-modified Stellite 712 at elevated temperatures, Tribo. Inter., 40(2), 2007, 254-265.
[10] H. Celik and M. Kaplan, Effects of silicon on the wear behaviour of cobalt-based alloys at elevated temperature, Wear, 257(5-6), 2004, 606-611.