



The effect of nickel on sliding wear behaviour of cobalt-based hardfacing alloy at elevated temperature

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ABSTRACT

Purpose: To investigate the effect of addition of nickel on the microstructure, hardness and tribological properties of cobalt-based hardfacing alloy (Stellite 12) deposited by plasma transferred arc (PTA) welding technique.

Design/methodology/approach: Microstructural characterization was carried out on deposited layers by utilising X-ray diffractometer and energy dispersive X-ray (EDX) equipped scanning electron microscope (SEM). Mechanical properties of the coatings were determined by hardness measurements and sliding wear tests. Hardness of the deposited layers was evaluated in HV scale. Wear tests were conducted under normal load of 3 N at room temperature (RT), 300 and 500°C.

Findings: Microstructural studies revealed that addition of nickel into Stellite 12 alloy dominated FCC crystal structure in the cobalt rich solid solution matrix rather than HCP crystal structure. Furthermore, nickel addition reduced the hardness and wear resistance of the deposited layer at room temperature. Nickel containing Stellite12 deposited layers demonstrated better wear resistance as compared to a Stellite12 deposited layer at high temperatures (300 and 500°C) owing to the formation of stable oxide layer on the worn surface.

Practical implications: Determining the sliding wear performance of Stellite 12 alloy deposited layer which nickel is added to enhance the corrosion resistance in harsh environments.

Originality/value: The investigation of high temperature wear performance of Stellite 12 alloy deposited layer upon addition of nickel.

Keywords: Wear resistance; High temperature; Hardfacing coating; PTA

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PROPERTIES

1. Introduction

Stellite12 is a cobalt-based hardfacing alloy extensively used as a surface protector of engineering components in harsh conditions of aerospace, gas turbines, chemical, petrochemical industries and power plants due to its superior wear, corrosion and heat-resistance properties [1, 2]. The hardness of cobalt-based alloys is derived generally from the high hardness of carbides or intermetallic compounds dispersed in the cobalt rich solid solution matrix or dendrite [3]. In these alloys, carbides and intermetallic phases are considered as the primary strengthening agent and solid solution hardeners including chromium, tungsten, and molybdenum are known as the secondary strengthening agent [4]. Tribological properties of Stellite alloys at room temperature depend on strengthening and crystallographic nature of cobalt rich solid solution matrix, type and amount of carbides and intermetallic compounds formed during solidification [5].

From the corrosion standpoint, carbon containing Stellite alloys can be classified into two categories: low-carbon (0.025-0.15%) alloys intended for use in severely corrosive environments or where ductility is an important consideration. High-carbon (1-3%) alloys, which exhibit high hardness and more abrasive and sliding wear resistance, are used in less corrosive environments [5,6]. Examples of high carbon containing wear resistant alloys include Stellite 1, 6 and 12. Unfortunately corrosion resistance of higher carbon containing cobalt base wear resistant alloys exposed to aqueous corrosive environment are limited by grain boundary carbide precipitation and the lack of vital alloying elements in the solid solution phase resulted from formation of carbides. Nickel can be added to these alloys to improve their resistance to mineral acids and stress-corrosion cracking [6].

While the tribological performance of different kind of cobalt-based hardfacing alloys at ambient temperature has been investigated in details, published information on the effect of addition of nickel on the wear behavior of high carbon containing Stellite alloys at high temperatures is scarce.

2. Experimental

Stellite 12 powder having nominal composition as listed in Table 1 were mixed with 2, 6 and 10 (wt.%) of nickel (purity $\geq 99.8\%$) and deposited on AISI 4140 steel by PTA welding machine. The particle size of the Stellite 12 and nickel powders were 53-150 and 48-90 μm , respectively.

The plasma transferred arc deposition process was implemented under constant parameters which were a current of 92 A, a voltage of 32 V and a welding speed of 85 mm/min. Welding procedure was carried out in a single layer with a thickness of 5 mm. After deposition process, the surface of each specimen was ground to make a flat hardfacing layer with a thickness of 2.5 mm for characterization and wear test. Microstructure and phases analysis were examined by X-ray diffractometer (XRD) with Cu-K_α radiation (GBC, Australia) and scanning electron microscope (SFEG SEM, Philips, Holland) equipped with energy dispersive X-ray (EDX) spectrometer.

Table 1.

Nominal composition of Stellite 12 powder (wt.%)

Co	Cr	C	W	Ni	Si	Fe	Mn
Balance	29.5	1.6	8.5	2.2	1.5	2.4	1

Surface of samples for wear and hardness tests was ground with SiC papers and polished with 0.25 μm diamond paste in order to eliminate surface roughness effect. Hardness measurements were conducted on a conventional micro-hardness tester (Shimadzu, HMV2, Japan) with indentation load of 500 g. Ten successful measurements were made on each specimen and the average was the final hardness result. Dry sliding wear tests were performed using a ball on disc type tribometer (CSM High temperature Tribotester, Switzerland) under normal load of 3 N at room temperature (RT), 300 and 500°C. A ball made of alumina (Al_2O_3) with diameter of 6 mm was used to wear samples with a constant sliding speed of 10 cm/s along a circular path of 5.5 mm in radius for the total sliding distance of 500 m. The samples were heated in ambient condition and test was started when the desired temperature was reached. During wear testing, coefficient of friction data was continuously recorded. After the wear tests, wear tracks were analyzed by using a contact profilometer (Dektak- 6M, Veeco, USA) and the worn surfaces were examined by a SEM.

3. Results and discussion

3.1. Characterization

The X-ray diffraction patterns of deposited samples by PTA machine are presented in Fig. 1. X-ray analysis reveals that the microstructures of Stellite 12 and nickel

containing Stellite 12 alloy deposited layers were consisted of Co phase (as α -Co and ϵ -Co phases) and chromium carbides (in the form of Cr_7C_3 and Cr_{23}C_6). It is noticeable that addition of nickel dominated the peaks of α -Co (with FCC crystal structure) rather than the peaks of ϵ -Co (with HCP crystal structure).

Cross-sectional microstructures of the Stellite 12 and Stellite 12+10 (wt.%) Ni deposited layers are shown in Fig. 2. In general microstructures were consisted of matrix and eutectic carbides. The EDX analysis and compositional

evolution of each phase in the microstructures of Stellite 12 and Stellite 12+10 (wt.%) Ni alloys are presented in Table 2. The matrix consists of cobalt rich solid solution that contains chromium, tungsten and nickel and diluted iron. In the Stellite 12+10 (wt.%) Ni deposited layer most of nickel atoms dissolved in the cobalt rich matrix. Eutectic carbides are found to contain the high amount of chromium in accordance with results of XRD analysis (Fig. 1). They were containing cobalt and tungsten in substitution from chromium.

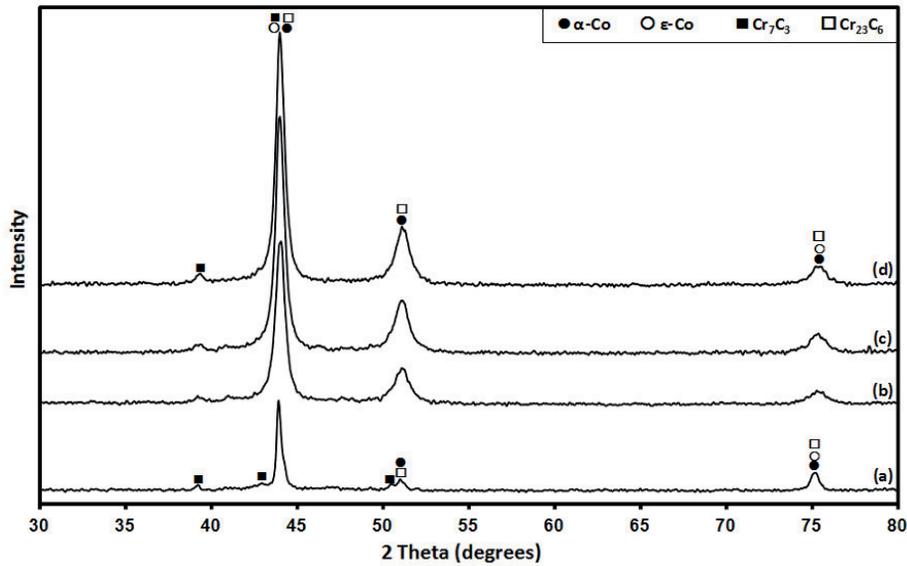


Fig. 1. XRD patterns of PTA deposited layers (a) Stellite12, (b) Stellite12+2 (wt.%) Ni, (c) Stellite12+6 (wt.%) Ni and (d) Stellite12+10 (wt.%) Ni

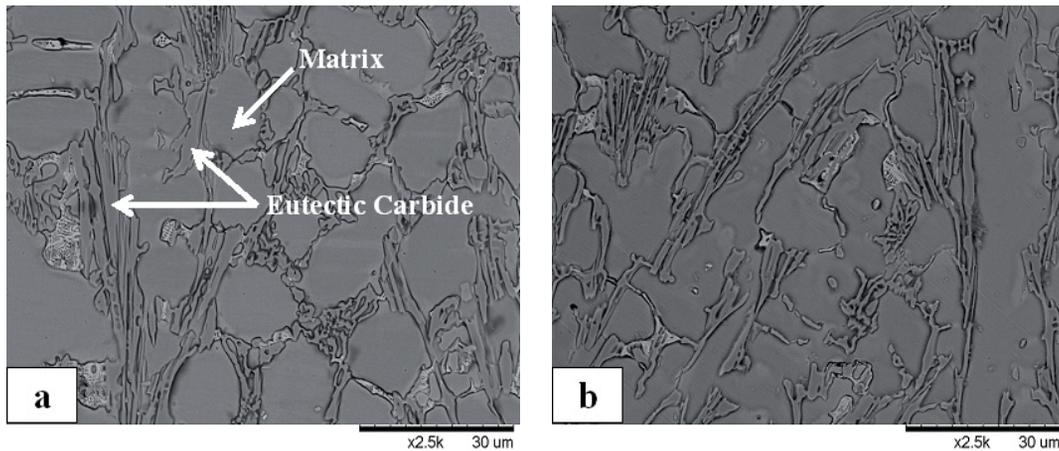


Fig. 2. Cross-section SEM micrographs of PTA deposited layers (a) Stellite 12 and (b) Stellite 12+10 (wt.%) Ni

Table 2.

Compositions of matrix and carbides present in the microstructures of Stellite 12 and Stellite 12+10 (wt.%) Ni deposited layers

		Co		Cr		W		Ni		Fe	
		Wt%	At%	Wt%	At%	Wt%	At%	Wt%	At%	Wt%	At%
Stellite12	Matrix	63.24	63.40	23.87	27.12	5.48	1.76	2.15	2.17	5.26	5.55
	Carbide	21.75	21.01	69.74	76.35	8.51	2.64	---	---	---	---
Stellite12+10wtNi	Matrix	56.60	57.30	21.94	25.18	6.44	2.09	11.98	12.18	3.04	3.25
	Carbide	34.06	34.29	54.29	61.95	11.65	3.76	---	---	---	---

The results of the Vickers microhardness of Stellite 12 and nickel containing Stellite 12 alloy deposited layers are presented in Fig. 3. It is apparent that the hardness value decreases from 490 to 440 Vickers as the content of nickel increases up to 10 (wt.%).

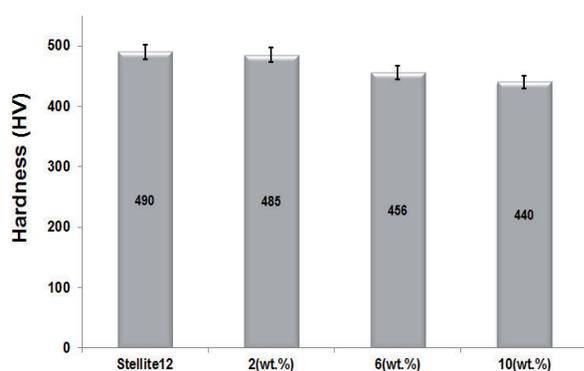


Fig. 3. Variation of hardness of Stellite 12 deposited layers with addition of nickel

There are two allotropic modifications of pure cobalt; a hexagonal close packed (HCP) form, ϵ , stable at temperatures below 422°C, and a face-centered-cubic (FCC) form, α , which is stable between 422°C and its melting point of 1495°C [7]. Presence of alloying elements in cobalt-based alloys affects the transformation temperatures [8]. While tungsten and molybdenum tend to increase the transformation temperature, presence of nickel and iron tend to decrease the transformation temperature and increasing metastable FCC phases in microstructure. However, under most cooling conditions, the transformation tends to be sluggish in a cobalt-based alloy;

therefore the matrix is a mixture of ϵ -Co and metastable α -Co at room temperature. Metastable FCC phase tends to transform to a HCP phase under the action of a mechanical stress (or strain) at room temperature [9]. This transformation is classified as martensitic, arising from the mobility of partial dislocations along the close-packed planes. When nickel is added to the cobalt rich solid solution matrix, the FCC is stabilized therefore martensitic transformation or work hardening under mechanical load is hindered. In this case deformation occurs by twinning or slip rather than by the FCC→HCP phase transformation and consequently hardness decreases [10]. Also increasing intensity of α -Co peaks in XRD pattern reveals that FCC begin more stable by addition of nickel to Stellite12 alloy.

3.2. Tribological properties

The results of the wear tests conducted at RT, 300 and 500°C are presented in Fig. 4 as the wear volume loss of the deposited layers based on the 2D cross-section profiles of the wear tracks. For each wear track, eight different locations were measured by contact profilometer system and the software calculated the cross-sectional area automatically. The average of the eight cross-sectional areas was multiplied by the circular length of the wear track to obtain the wear volume loss.

It is clear from Fig. 4 that, the wear resistance of Stellite 12 and Stellite12+10 (wt.%) Ni deposited layers varied with temperature; they were more wear resistant at room temperature. At 300 and 500°C, the wear resistance of the deposited layers decreased significantly. However, wear resistance of the nickel containing deposited layer is better than Stellite12 layer at 300 and 500°C, unlike RT.

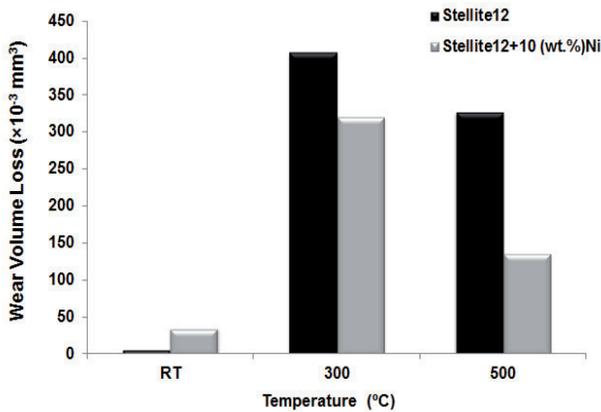


Fig.4. Variations of the wear volume loss of the Stellite 12 and Stellite12+10 (wt.%) Ni deposited layers with wear testing temperature.

Friction curves of Stellite 12 and Stellite12+10 (wt.%) Ni deposited layers are given in Fig. 5. In contrast to Stellite12+10 (wt.%) Ni deposited layer, Stellite 12 shows more fluctuations in the coefficient of friction at 300 and 500°C. As a general trend higher coefficient of friction values were more likely at RT as compared to 300 and 500°C.

Worn surface micrographs of Stellite 12 and Stellite 12+10 (wt.%) Ni deposited layers are shown in Fig. 6. At RT worn surfaces exhibited micro-grooved nature with rugged morphology as the result of repeated mechanical

attack during the sliding wear. On the bases of these observations, room temperature wear resistance of the examined layers can associated with the hardness. Previously contribution of high hardness and Young’s modulus of the matrix and the volume fraction of the eutectic carbides on room temperature wear resistance of Stellite alloys have been reported [11,12]. The strain induced transformation of metastable FCC to HCP of cobalt base matrix during plastic deformation increases the alloy’s work hardening rate, which is reported to be beneficial for sliding wear resistance of Stellite alloys. Presence of nickel in solid solution by increasing stacking fault energy stabilize the FCC phase, thus suppressing the transformation to HCP phase of cobalt and decreasing hardness and wear resistance of Stellite 12+10 (wt.%) Ni alloy at RT [12]. Decreasing of wear resistance with increasing temperature (Fig. 4) can be attributed to material softening [13,14]. Furthermore, oxidation at the worn surface played crucial role on progress of wear at elevated temperatures as well as the level of the friction curve. As can be seen in Fig. 6, more oxidation on the worn surface of the Stellite 12+10 (wt.%) Ni layer than Stellite 12 layer at 500°C is accompanied by better wear resistance and more smooth friction curve. Since low temperatures favors thinner oxide layers, it is suggested that they were inevitably broken under mechanical load and could not prevent the destructive action of the counter-face so that the examined deposited layers exhibited lower wear resistance at 300°C than 500°C.

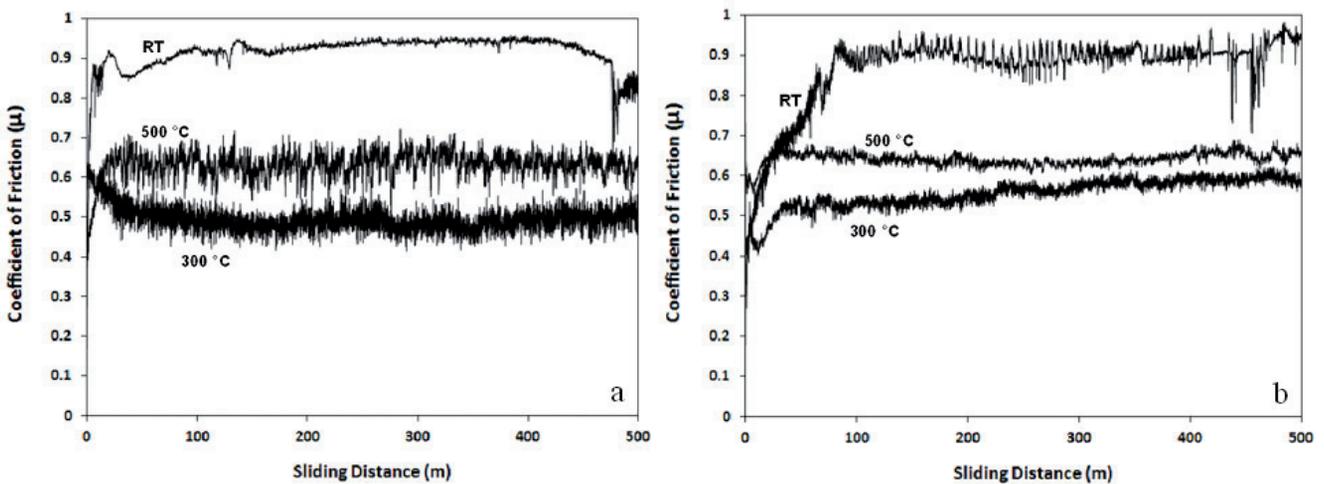


Fig. 5. Friction curves of Stellite 12 and Stellite 12+10 (wt.%) Ni deposited layers tested at RT, 300 and 500°C

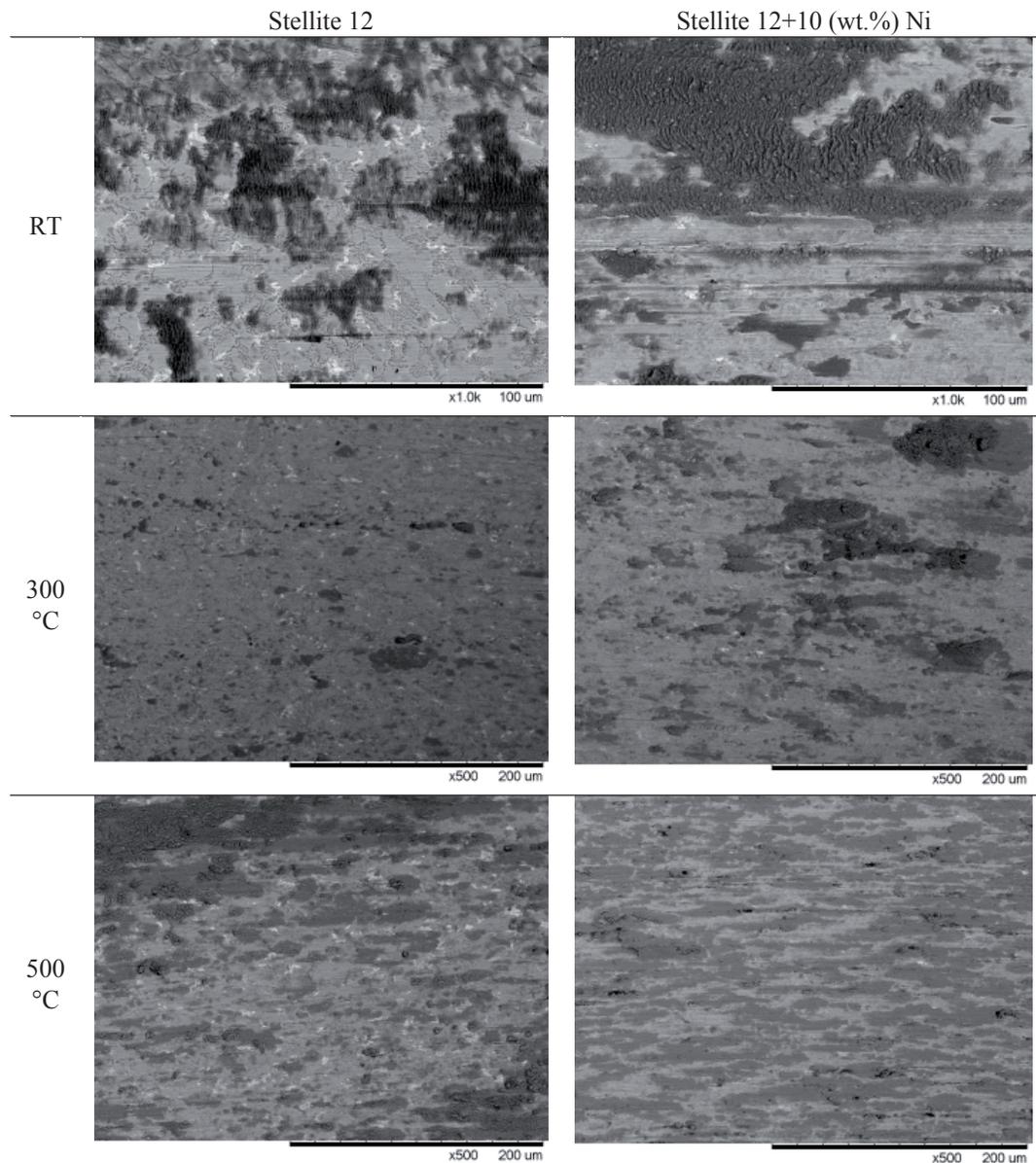


Fig. 6. The worn surface micrographs of the Stellite 12 and Stellite 12+10 (wt.% Ni) deposited layer after testing at RT, 300 and 500°C

4. Conclusions

1. PTA deposited Stellite 12 layer has a microstructure consisting of a matrix (α -Co and ϵ -Co) and eutectic carbides (Cr_7C_3 and Cr_{23}C_6). Addition of nickel up to 10 (wt.%) did not change the microstructure of the Stellite 12 layer due to the complete dissolution of nickel in the matrix as the α -Co stabilizer.
2. Alloying of the Stellite 12 layer with nickel (up to 10 wt.%) did not impose any beneficial effect on hardness and wear resistance at RT.
3. Stellite 12 and Stellite 12+10 (wt.% Ni) deposited layers exhibited lower wear resistance at high temperatures than RT. At a certain temperature (300 or 500°C) Stellite 12+10 (wt.% Ni) layer provided better wear resistance than Stellite 12 layer due to the formation of stable oxides on the worn surfaces.

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Additional information

The presentation connected with the subject matter of the paper will be presented by the authors during the 15th International Materials Symposium IMSP'2014 in Denizli, Turkey on 15th-17th October 2014.

References

- [1] A.P. Wu, J.L. Ren, Z.S. Pang, H. Murakawa, Y. Yudea, Numerical simulation for the residual stresses of Stellite hard-facing on carbon steel, *Journal of Materials Processing Technology* 101 (2000) 70-75.
- [2] V. Kuzucu, M. Ceylan, H.C. Aksoy, Microstructure and phase analyses of Stellite 6 plus 6 wt.% Mo alloy, *Journal of Materials Processing Technology* 69 (1997) 257-263.
- [3] W.C. Lin, C. Chen, Characteristics of thin surface layers of cobalt-based alloys deposited by laser cladding, *Surface & Coating Technology* 200 (2006) 4557-4563.
- [4] A. Khoddamzadeh, R. Liu, M. Liang, Q. Yang, Novel wear-resistant materials – carbon fiber reinforced low-carbon Stellite alloy composites, *Composite Part A* 43 (2012) 344-352.
- [5] H. Yu, R. Ahmed, H. de Villiers Lovelock, A comparison of the tribo-mechanical properties of a wear resistant cobalt-based alloy produced by different manufacturing processes, *Transaction of ASME* 129 (2007) 586-294.
- [6] J.R. Davis, Nickel, cobalt, and their alloys, ASM International, Ohio, 2000.
- [7] T.S.S. Winston, O. Soboyejo, *Advanced structural materials: properties, design optimization, and applications*, CRC Press, New York, 2006.
- [8] I. Radu, D.Y. Li, The wear performance of yttrium-modified Stellite 712 at elevated temperatures, *Tribology International* 40 (2007) 254-265.
- [9] C.D. Opris, R. Liu, M.X. Yao, X.J. Wu, Development of Stellite alloy composites with sintering/HIPing technique for wear-resistant applications, *Materials & Design* 28 (2007) 581-591.
- [10] M.X. Yao, J.B.C. Wu, W. Xu, R. Liu, Metallographic study and wear resistance of a high-C wrought Co-based alloy Stellite 706K, *Materials Science and Engineering A* 407 (2005) 291-298.
- [11] J.C. Shin, J.M. Doh, J.K. Yoon, D.Y. Lee, J.S. Kim, Effect of molybdenum on the microstructure and wear resistance of cobalt-base Stellite hardfacing alloys, *Surface & Coating Technology* 166 (2003) 117-126.
- [12] R. Liu, S.Q. Xi, S. Kapoor, X.J. Wu, Effects of chemical composition on solidification, microstructure and hardness of Co-Cr-W-Ni and Co-Cr-Mo-Ni alloy systems, *International Journal of Research and Reviews in Applied Sciences* 5 (2010) 110-122.
- [13] S. Nsoesie, R. Liu, K. Jiang, M. Liang, High-temperature hardness and wear resistance of cobalt-based triballoy alloys, *International Journal of Material and Mechanical Engineering* 2 (2013) 48-56.
- [14] S. Kapoor, R. Liu, X.J. Wu, M.X. Yao, Temperature-dependence of hardness and wear resistance of Stellite alloys, *Engineering and Technology* 67 (2012) 964-973.