Thermogravimetric investigations of new γ - γ' cobalt-based superalloys

Damian Migas¹ · Grzegorz Moskal¹ · Marta Mikuśkiewicz¹ · Tomasz Maciąg²

Received: 1 November 2017 / Accepted: 25 May 2018 / Published online: 5 June 2018

© The Author(s) 2018

Abstract

The aim of the study is characterization of high-temperature oxidation behavior of new Co-based superalloys by thermogravimetry (TG). The following alloys have been taken into account: Co–9Al–9W, Co–20Ni–7Al–7W, Co–10Al–5Mo–2Nb and Co–20Ni–10Al–5Mo–2Nb (at.%). The thermogravimetric analysis was carried out in the temperature range 40–1200 °C of heating rate 5° min^{−1}. The investigation was performed using the thermal analyzer NETZSCH STA 449 F3 Jupiter. TG–DTG plots showed oxidation behavior up to 1200 °C and indicated the temperatures of further isothermal oxidation examinations. The oxidation behavior of basic Co–9Al–9W (at.%) alloy was compared to W-free Co–10Al–5Mo–2Nb and Co–20Ni–10Al–5Mo–2Nb (at.%) alloys. The obtained data showed different oxidation behavior dependably on the type of alloying elements. Moreover, the effect of Ni addition on oxidation performance was determined. The scales grown on Co-base superalloys after thermogravimetry were evaluated by means of scanning electron microscopy and energy dispersive spectroscopy.

Keywords W-free γ - γ' cobalt-based superalloys · Co–Al–Mo–Nb superalloy · Co–Al–W superalloy · Thermogravimetry

Introduction

Ni-based superalloys have come to dominate the high-temperature applications such as blades and disks in aircraft engines and industrial steam turbines [1]. Unfortunately, the possibility to develop temperature capability of these superalloys by increasing the fraction of γ' phase, solvus temperature or by addition of refractory elements is now limited; hence, the alloy system is increasingly being viewed as mature. Moreover, due to limited corrosion properties, these alloys require usage of technologically challenging bond-coats in order to protect substrate material [2]. The recently discovered Co-based superalloys [3] have gained substantial interest as potential new generation of superalloys, alternative to commercial Ni-based superalloys in near future. Due to the γ - γ' microstructure, these

alloys resemble Ni-based superalloys; furthermore, owing to excellent properties at high temperature, the new group of superalloys may surpass the performance of analog Ni-based alloys, which are composed of 10–12 alloying elements and are capable of operating to 1150 °C [4, 5]. Due to inferior creep resistance compared to that of Ni-base alloys, the conventional Co-based superalloys are limited to static applications, such as vanes and combustors [6]. The remarkable creep resistance of alloys based on Ni–Al system is an effect of coherent cuboidal γ' (L_{12}) precipitates dispersed in a γ (fcc) matrix. The γ' -strengthened Co-based superalloys are potentially less prone to freckling than Ni-based superalloys [7] and possess higher melting temperatures [8, 9]. Nevertheless, they still exhibit poorer creep resistance due to a lower temperature of the γ' phase dissolution. Further development of the new generation of superalloys requires substantial efforts dedicated to improvement in thermal stability, γ/γ' lattice mismatch, volume fraction of the γ' , which contributes to the development of the mechanical properties at elevated temperatures. Many authors have focused on influence of alloying elements on stability and distribution of γ and γ' phases in Co-based superalloys [10–15]. The Cr, Mn, Fe or Re dissolve in γ and decrease the *solvus* temperature. On the

✉ Damian Migas
damian.migas@outlook.com

¹ Institute of Materials Engineering, Silesian University of Technology, Krasinskiego 8 str, 40-019 Katowice, Poland

² Department of Extractive Metallurgy and Environment Protection, Silesian University of Technology, Krasinskiego 8 str, 40-019 Katowice, Poland

other hand, Ti, Ta, Nb, Mo and V are elements promoting γ' phase.

Despite discussed high temperature properties, the oxidation resistance of these alloys remains a concern. Recent efforts of several authors have focused on the oxidation behavior of alloys based on the Co–Al–W system [16–19]. These alloys suffer from inferior oxidation resistance relative to that of commercial Ni-base superalloys. During the oxidation of Co–Al–W alloys, a brittle non-protective Co-based oxide is formed. This type of external layer is prone to spallation during high temperature exposure [8, 17]. The known way to improve oxidation resistance of ternary Co–Al–W alloys is addition of Cr and Si, although the γ' -phase stability steadily decreases with increasing content of these elements [11, 16, 20]. The deleterious effect of Cr and Si on the γ – γ' microstructure may be neutralized by Ni addition, whose occurrence in the alloy improves the γ' stability [21]. The newest data show detailed analysis of Co–Al–W alloys oxidation, including role of γ and γ' phases in initial stage of oxidation [22]. Despite the oxidation properties, alloys based on Co–Al–W system have other limitations, resulting from W occurrence, i.e. high density and insufficient creep properties [23, 24], wherefore attempts of W-replacement in Co-based superalloys have been performed [25–29]. The new solutions are based on Mo and Nb addition to Co–Al system; these elements promote formation of γ' -Co₃(Al, Mo) phase. Alloys based on Co–Al–Mo system are characterized by better creep resistance compared to that of Co–Al–W alloys; nonetheless, papers concerning the oxidation properties of the newly developed W-free superalloys are limited. The insufficient data concerning oxidation resistance of Co–Al–Mo–Nb alloys and information regarding these alloys at all were motivation of this paper. The aim of the study is introduction to oxidation resistance studies of new γ – γ' Co-based alloys using thermogravimetry. This method was utilized in order to investigate the oxidation behavior of new superalloys under non-isothermal conditions. The another goal of study is to evaluate influence of Ni on the oxidation performance of Co–Al–W and Co–Al–Mo–Nb alloys.

Experimental

Materials

Four as-cast Co-based superalloys were chosen for the present work: Co–20Ni–7Al–7W, Co–10Al–5Mo–2Nb, Co–20Ni–10Al–5Mo–2Nb (at.%) alloys and reference Co–9Al–9W (at.%) alloy. The investigated Co-based superalloys were melted using induction vacuum furnace and casted into cold graphite molds under protective gas (Ar).

The compositions of investigated superalloys were analyzed by EDS method. The chemical composition details of all four Co-based superalloys are shown in Table 1.

The ingot was subjected to turning, the specimens were cut from ingot base. Taking into account the microstructure, all investigated alloys were characterized by dendritic structure typical for metals solidifying under conditions of fast and directional heat dissipation. More detailed data concerning microstructure of base alloy is available [30]. The satisfactory chemical homogeneity was obtained for all ingots, however, in case of alloys containing Mo, tiny precipitates rich in Mo and Nb were observed. X-ray diffraction showed that these precipitates are Co₃Mo and Co₃Nb.

Methods

The thermogravimetric analysis of as-cast alloys under non-isothermal conditions was performed on NETZSCH STA 449 F3 Jupiter thermal analyzer from 40 to 1200 °C. The specimens used in thermogravimetric investigation were ground using SiC paper down to 1200 grid. The Oxidation of 5 × 5 × 10 mm samples contained in Al₂O₃ crucibles was carried out in air at heating rate 5 °C min^{−1}. The specimens were cooled to room temperature and weighted in order to evaluate spallation of grown scale. Afterward, the surfaces of oxidized samples were investigated by SEM/EDS method. The analysis of grown scale was carried out Scanning Electron Microscope Hitachi S-4200N equipped with an energy dispersive spectrometer.

Results and discussion

Thermogravimetry

Figure 1 shows the TG and DTG curves related to the oxidation of as-cast Co–9Al–9W (at.%) alloy from 40 to 1200 °C. TG plot corresponding to this alloy was slightly growing till 930 °C and subsequently shot up. The gain of

Table 1 Nominal and measured chemical composition of investigated alloys

Nominal composition/at.%	Measured chemical composition/at.%					
	Co	Ni	Al	W	Mo	Nb
Co–9Al–9W	81.7	–	9.1	9.2	–	–
Co–20Ni–7Al–7W	67.2	18.4	7.3	7.1	–	–
Co–10Al–5Mo–2Nb	84.9	–	8.5	–	4.6	2.0
Co–20Ni–10Al–5Mo–2Nb	66.4	18.5	8.3	–	4.7	2.1

Fig. 1 TG–DTG profiles of oxidation of Co–9Al–9W (at.%) alloy

specimen mass at 930 °C was 0.17%, whereas the final mass change at 1200 °C reached almost 1%. Downward arrows indicate peaks present on the DTG curve. The first one, relatively indistinct peak occurred between 660 and 705 °C. The occurrence of the peak is connected with an acceleration of oxidation and subsequently slowing down, what could be attributed to a formation of new type of oxide on the surface. The literature data show that below 700 °C, the scale grown on pure Co is mainly composed of Co_3O_4 oxide; however, the authors reported the formation of CoO at the expense of Co_3O_4 from 700 to 900 °C [31, 32]. The Co_3O_4 oxide is not stable above 900 °C; therefore, at higher temperatures, transition of dual-phase scale composed of Co_3O_4 and CoO into single-phase CoO oxide film occurs. The investigated Co-based superalloys exhibit changes in the oxidation behavior at temperatures close to those of described in the literature, whereas the differences are result of different character of oxidation of alloys and pure metals.

The TG–DTG curves corresponding to Co–20Ni–7Al–7W (at.%) alloy examined in the temperature range 40–1200 °C are shown in Fig. 2. The mass change plot shows a slight gain of mass to 670 °C. In this case also occurred peaks, which have been indicated by downturn arrows. The peak between 670 and 690 °C detected in DTG curve implies the enhancement and subsequent slowing down of the oxidation rate. This phenomenon may be also attributed to selective CoO formation, discussed in the previous example. From 690 °C, the TG plot was increasing; nonetheless, the maximum of another peak of DTG curve was observed at approx. 857 °C. Afterward, the rate of oxidation slowed down, what may be observable as an visible threshold on the mass change profile and is implied by the DTG peak. In this case, it may be also explained by the formation of another type of oxide, namely by transition of Co_3O_4 to CoO oxide, which is

more stable over 900 °C [22–31]. The TG plot shot up after exceedance of 920 °C at which increase in mass reached 0.21%. At 1200 °C, the change of mass was 0.81%, what was slightly lower in comparison with that of basic Co–9Al–9W (at.%) alloy.

Figure 3 shows the TG and DTG curves of Co–10Al–5Mo–2Nb (at.%). The first stage of oxidation occurred between 40 and 660 °C with 0.16% of mass gain that is attributed to initial scale growth. The DTG curve showed the peak corresponding to that of previous case, where possibility of Co_3O_4 oxide formation was discussed. The peak occurred in the temperature range 660–688 °C with the maximum at 670 °C. In the analogous way, the another peak has been indicated. The second one was present between 820 and 855 °C, which may be corresponding to Co_3O_4 into CoO transition, discussed in the previous examples. Above 910 °C at which mass gain was 0.44%, the rate of oxidation substantially improved resulting in the final mass change equal 2.25%.

The TG and DTG curves (Fig. 4) attributed to the oxidation of as-cast Co–20Ni–10Al–5Mo–2Nb (at.%) alloy have comparable profile to that of Ni-free Co–10Al–5Mo–2Nb (at.%). The TG plot related to the investigated alloy was slightly growing, resulting in 0.07% of mass increase at 670 °C. The similar peaks those of previous examples were noticed. The DTG curve implied acceleration of the oxidation rate above 670 °C. In this case also occurred, the threshold on the mass changes profile at 830 °C. The mass was growing up to 910 °C, at which the mass change was approx. 0.27%; afterward, the TG plot shot up due to considerable acceleration of oxidation. At 1200 °C, the gain of mass reached 1.5%, considerably lower compared to that of Ni-free Co–20Ni–10Al–5Mo–2Nb (at.%) alloy.

The temperature range 600–950 °C is of interest for potential applications of Co-based superalloys. Illustration of mass changes corresponding to all investigated alloys is

Fig. 2 TG–DTG profiles of oxidation of Co–20Ni–7Al–7W (at.%) alloy

Fig. 3 TG–DTG profiles of oxidation of Co–10Al–5Mo–2Nb (at.%) alloy

Fig. 4 TG–DTG profiles of oxidation of Co–20Ni–10Al–5Mo–2Nb (at.%) alloy

Table 2 Results of chemical composition analysis in areas and points marked in Figs. 4 and 5

Temp./°C	Mass gain/%			
	Co-9Al-9W	Co-20Ni-7Al-7W	Co-20Ni-10Al-5Mo-2Nb	Co-10Al-5Mo-2Nb
600	0.06	0.06	0.05	0.13
650	0.07	0.07	0.06	0.15
700	0.08	0.09	0.08	0.19
750	0.09	0.11	0.11	0.22
800	0.11	0.13	0.15	0.27
850	0.13	0.17	0.21	0.34
900	0.16	0.20	0.25	0.41
950	0.20	0.25	0.35	0.57

Fig. 5 Losses of mass related to spallation of oxides under cooling

shown in Table 2. The highest scale growth as a function of temperature was observed for Co-10Al-5Mo-2Nb (at.%) alloy. From 600 to 900 °C, the changes of mass between Co-9Al-9W, Co-20Ni-7Al-7W and Co-20Ni-10Al-5Mo-2Nb (at.%) alloys were comparable; however, W-free alloys was characterized by higher gain of mass, contributed to oxidation. In case of oxidation of alloys, oxygen also reacts with alloying elements resulting in formation of oxides rich in Al, Nb, Mo, W or complex oxides [31].

Figure 5 shows losses of samples mass, attributed to the spallation of the scale from cooled specimens. The W-free alloys had considerably poorer resistance in this regard. In case of Co-9Al-9W (at.%), roughly 3% of the scale spalled as a result of cooling from 1200 °C to room temperature. Reduction of the scale mass was almost three times lower in case of Co-Al-W alloy with Ni. Approx. 5.8% of oxidized layer peeled off from Co-10Al-5Mo-2Nb (at.%) alloy surface due to cooling. In case of W-free alloys, the Ni content also caused better adhesion of scale under cooling conditions, resulting in 4.5% of the scale mass drop.

Surface condition

The topography of the scale grown on different alloys after thermogravimetric investigations are shown in Fig. 6,

whereas the chemical composition of these areas is shown in Table 3. The scale grown on Co-9Al-9W (at.%) alloy (Fig. 6a) is highly porous and chemically varied. The light contrast confirms the occurrence of elements with various atomic number, namely Co, Al, W and O, what is confirmed by the chemical composition analysis (Table 3). The occurrence of Al, W and O implies the formation of mixed oxides within the scale, which was discussed by consideration of thermogravimetric plots. The scale observed on Co-9Al-9W (at.%) does not include the top external layer, which spalled due to the cooling to room temperature. The another investigated alloy (Fig. 6b) was covered by a compact, smooth oxide film as a result of oxidation under non-isothermal conditions. In case of Co-20Ni-7Al-7W (at.%) alloy, the spallation occurred in a small extent; therefore, the outer layer has maintained. The external oxide coating was characterized by grain morphology and consisted of Co and O; thus, probably was CoO oxide, which is thermodynamically more stable above 900 °C than Co₃O₄. Chemical homogeneity of external layer does not exclude the occurrence of mixed oxides underneath. Furthermore, Ni oxidized to NiO tends to formation of CoO-NiO solid solutions at high temperatures, what may influence on protective properties of the scale [31, 33]. Moreover, another possible phenomenon is Al-oxidation to Al₂O₃ and subsequent reaction with CoO

Fig. 6 SEM images showing the oxidized surface morphologies of alloys. **a** Co-9Al-9W; **b** Co-20Ni-7Al-7W; **c** Co-10Al-5Mo-2Nb; **d** Co-20Ni-10Al-5Mo-2Nb

Table 3 EDS chemical composition analysis at the surface areas of Fig. 6

Alloy	Al	Co	Ni	Nb	Mo	W
Elements/at. %						
Co-9Al-9W	29.9	64.9	–	–	–	5.2
Co-20Ni-7Al-7W	–	100	–	–	–	–
Co-10Al-5Mo-2Nb	11	58.7	–	–	30.3	–
Co-20Ni-10Al-5Mo-2Nb	25.4	48.3	8.5	7	10.8	–
Elements/mass %						
Co-9Al-9W	14.5	68.5	–	–	–	17
Co-20Ni-7Al-7W	–	100	–	–	–	–
Co-10Al-5Mo-2Nb	4.4	51.9	–	–	43.7	–
Co-20Ni-10Al-5Mo-2Nb	12	49.7	8.7	11.4	18.2	–

resulting in formation of CoAl_2O_4 spinel [34]. The scale of another investigated alloy (Fig. 6c) suffered from spallation the most. The SEM image shows an uncovered area of scale grown on Co-10Al-5Mo-2Nb (at.%) alloy. The chemical composition analysis (Table 2) shows the occurrence of Co, Al, Mo and O within the investigated area, hence the scale is composed of the different types of oxides. Furthermore, the formation of cobalt aluminates and molybdates may occur as well [34, 35]. The scale grown on Co-20Ni-10Al-5Mo-2Nb (at.%) alloy morphologically differs from that of previous example (Fig. 6d). In this case, also the image has been taken from the uncovered area of scale, whereas despite Co, Al, Mo and O, the occurrence of Nb and Ni was detected via EDS chemical composition analysis. The occurrence of many elements in the scale confirms the complex structure, which may be composed of oxides rich in Co, Al, Mo, Nb; moreover, it may contain the different types of complex

oxides. In this case, also, formation of NiO and subsequent solution in CoO is possible.

Conclusions

The oxidation behavior of Co-9Al-9W, Co-20Ni-7Al-7W, Co-10Al-5Mo-2Nb and Co-20Ni-10Al-5Mo-2Nb (at.%) alloys under non-isothermal conditions was determined. The Co-20Ni-7Al-7W (at.%) was characterized by higher gain of mass as a function of temperature in comparison with that of Co-9Al-9W (at.%) in the temperature range 600–950 °C. However, adding of 20 at.% of Ni to Co-10Al-5Mo-2Nb (at.%) slowed down oxidation rate over whole temperature range. Furthermore, Ni influenced on adhesion of the oxide scale in terms of cooling to room temperature. The spallation of oxides occurred in less extent for alloys with 20 at.% of Ni. In most of cases, the DTG curve showed two characteristic peaks at about, respectively, 650 and 850 °C. The collation of obtained information with the literature data implies, that peaks are corresponding to formation of two-phase oxide layer composed of Co_3O_4 and CoO (700 °C) and transformation of Co_3O_4 to CoO (900 °C). The literature data concerning oxidation of pure Co was the base for consideration of oxides formation with increasing temperature, implied by thermogravimetry; however, it is worth noticing that oxidation behavior of discussed alloys may differ from pure Co due to occurrence of alloying elements. Generally, all investigated alloys suffered from accelerated oxidation over 900 °C. The substitution of W by Mo and Nb caused the cobalt-based superalloys to be more prone to the oxidation and spallation of oxide layer under cooling to room temperature. Further investigations should contain thermogravimetric analysis of Co-based superalloys under isothermal condition in the temperature range 700–900 °C.

Acknowledgements This work was supported by Institute of Materials Science of Silesian University of Technology, as a part of Statutory Research no BK-225/RM3/2017.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

1. Sims CT, Hagel WC. The superalloys. New York: Wiley; 1972.
2. Moskal G, Jasik A. Thermal diffusivity characterization of bond-coat materials used for thermal barrier coatings. J Therm Anal Calorim. 2016;126:9–17.

3. Sato J, Omori T, Oikawa K, Ohnuma I, Kainuma R, Ishida K. Cobalt-base high-temperature alloys. Science. 2006;312:90–1.
4. Reed RC. The superalloys fundamentals and applications. Cambridge: Cambridge University Press; 2006.
5. Condruz MR, Matache G, Paraschiv A, Pușcașu C. Homogenization heat treatment and segregation analysis of equiaxed CMSX-4 superalloy for gas turbine components. J Therm Anal Calorim. 2018. <https://doi.org/10.1007/s10973-018-7085-2>
6. Davis JR. Nickel, Cobalt and their Alloys. 1st ed. Ohio: ASM Intl; 2000.
7. Tsunekane M, Suzuki A, Pollock TM. Single-crystal solidification of new Co–Al–W-base alloys. Intermetallics. 2011;19:636–43.
8. Pollock TM, Dibbern J, Tsunekane M, Zhu J, Suzuki A. New Co-based γ - γ' high-temperature alloys. JOM. 2010;62:58–63.
9. Bauer A, Neumeier S, Pyczak F, Singer RF, Göken M. Creep properties of different γ' -strengthened Co-base superalloys. Mater Sci Eng A. 2012;550:333–41.
10. Ooshima M, Tanaka K, Okamoto NL, Kishida K, Inui H. Effects of quaternary alloying elements on the γ' solvus temperature of Co–Al–W based alloys with fcc/L12 two-phase microstructures. J Alloy Compd. 2010;508:71–8.
11. Bauer A, Neumeier S, Pyczak F, Göken M. Microstructure and creep strength of different γ/γ' -strengthened Co-base superalloy variants. Scr Mater. 2010;63:1197–200.
12. Cui C, Ping D, Gu Y, Harada H. A new Co-base superalloy strengthened by γ' phase. Mater Trans. 2006;47:2099–102.
13. Bauer A, Neumeier S, Pyczak F, Göken M. Creep strength and microstructure of polycrystalline γ' -strengthened cobalt-base superalloys. In: Proceedings of the 12th international symposium on superalloys, Pennsylvania. 9–13, IX, 2012. p. 695–703.
14. Omori T, Oikawa K, Sato J, Ohnuma I, Kattner UR, Kainuma R, Ishida K. Partition behavior of alloying elements and phase transformation temperatures in Co–Al–W-base quaternary systems. Intermetallics. 2013;32:274–83.
15. Meher S, Yan H-Y, Nag S, Dye D, Banerjee R. Solute partitioning and site preference in γ/γ' cobalt-base alloys. Scr Mater. 2012;67:850–3.
16. Klein L, Bauer A, Neumeier S, Goken M, Virtanen S. High temperature oxidation of γ/γ' -strengthened Co-base superalloys. Corros Sci. 2011;53:2027–34.
17. Yan HY, Vorontsov VA, Dye D. Effect of alloying on the oxidation behaviour of Co–Al–W superalloys. Corros Sci. 2014;83:382–95.
18. Klein L, von Bartenwerffer B, Killian MS, Schmuki P, Virtanen S. The effect of grain boundaries on high temperature oxidation of new γ' -Strengthened Co–Al–W–B superalloys. Corros Sci. 2014;79:29–33.
19. Klein L, Killian M, Virtanen S. The effect of nickel and silicon addition on some oxidation properties of novel Co-based high temperature alloys. Corros Sci. 2012;69:43–9.
20. Klein L, Shen Y, Killian MS, Virtanen S. Effect of B and Cr on the high temperature oxidation behaviour of novel γ/γ' -strengthened Co-base superalloys. Corros Sci. 2011;53:2713–20.
21. Shinagawa K, Omori T, Sato J, Oikawa K, Ohnuma I, Kainuma R, Ishida K. Phase equilibria and microstructure on γ' phase in Co–Ni–Al–W system. Mater Trans. 2008;49:1474–9.
22. Weiser M, Eggler YM, Spiecker E, Virtanen S. Early stages of scale formation during oxidation of γ/γ' strengthened single crystal ternary Co-base superalloy at 900 °C. Corros Sci. 2018;135:78–86.
23. Chen M, Wang CY. First-principles investigation of the site preference and alloying effect of Mo, Ta and platinum group metals in γ' -Co₃(Al, W). Scr Mater. 2009;60:659–62.
24. Povstugar I, Choi PP, Neumeier S, Bauer A, Zenk CH, Goken M, Raabe D. Elemental partitioning and mechanical properties of Ti- and Ta-containing Co–Al–W-base superalloys studied by atom probe tomography and nanoindentation. Acta Mater. 2014;78:78–85.
25. Xue F, Li ZQ, Feng Q. Mo effect on the microstructure in Co–Al–W-based superalloys. Mater Sci Forum. 2010;654–656:420–3.
26. Makineni SK, Samanta A, Rohjirunsakool T, Alam T, Nithin V, Singh AK, Banerjee R, Chattopadhyay K. A new class of high strength high temperature Cobalt based γ - γ' Co–Mo–Al alloys stabilized with Ta addition. Acta Mater. 2015;97:29–40.
27. Makineni SK, Nithin B, Chattopadhyay K. A new tungsten-free γ - γ' Co–Al–Mo–Nb-based superalloy. Scr Mater. 2014;98:36–9.
28. Makineni SK, Nithin B, Chattopadhyay K. Synthesis of a new tungsten-free γ/γ' cobalt-based superalloy by tuning alloying additions. Acta Materialia. 2015;85:85–94.
29. Yao Q, Shang SL, Hu YJ, Wang Y, Wang Y, Zhu YH, Liu ZK. First-principles investigation of phase stability, elastic and thermodynamic properties in L12 Co₃(Al, Mo, Nb) phase. Intermetallics. 2016;78:1–7.
30. Mikuszewski T, Tomaszewska A, Moskal G, Migas D, Niemiec D. Primary microstructure characterization of new type γ - γ' Co–Al–W cobalt-based superalloys. Mater Eng. 2017;5:217–23.
31. Mrowiec S, Werber T. Korozja gazowa metali (gas corrosion of metals). Katowice: Slask; 1975.
32. Ellet AJ. Oxidation permeation and thermo-chemical stability of oxygen separation membrane materials for the oxyfuel process. Aachen: Rhenisch-Westfälische Technische Hochschule; 2009.
33. Barry C, Norton Grant. Ceramic materials: science and engineering. Berlin: Springer; 2007.
34. Duan X, Pan M, Yu F, Yuan D. Synthesis, structure and optical properties of CoAl₂O₄ spinel nanocrystals. J Alloy Compd. 2011;509:1079–83.
35. Lipsch JMJG, Schuit GCA. The CoO–MoO₃–Al₂O₃ catalyst: I. Cobalt molybdate and the cobalt oxide molybdenum oxide system. J Catal. 1969;15:163–73.