Surface morphology analysis of oxide layers formed on 10CrMo9-10 steel used in the power industry

Monika Gwoździk¹, Mirosław Bramowicz² and Sławomir Kulesza³

¹ Faculty of Production Engineering and Materials Technology, Czestochowa University of Technology, Armii Krajowej 19, 42-201 Częstochowa, Poland
² Faculty of Technical Sciences, University of Warmia and Mazury in Olsztyn, Oczapowskiego 11, 10-719 Olsztyn, Poland
³ Faculty of Mathematics and Computer Science, University of Warmia and Mazury in Olsztyn, Słoneczna 54, 10-710 Olsztyn, Poland

E-mail: monika.gwozdzik@pcz.pl

Keywords: oxides, fractal analysis, steel for power industry, SEM, AFM

Abstract
The knowledge about high-temperature corrosion of steels operating at elevated temperatures is important due to the durability of power equipment. The paper demonstrated the fractal analysis of oxide layers formed on 10CrMo9-10 steel under the operating temperature of 545 °C for 200 000 h employed in the power industry. The studies were carried out on elements taken from the inner and outer surface of the tube wall on the outlet both on the fire and counter-fire side of the tube wall surface. Thorough examinations of the oxide layer comprised microscopic examinations using scanning electron microscopy and atomic force microscopy. The fractal geometry of oxidized surfaces was characterized by providing the fractal dimension D. Using the methods of numerical analysis of the surface, the texture anisotropy ratio Str was also determined. The corner frequency τ and grain size dg were also determined. The obtained results of performed fractal analysis showed that the studied surface on the tube wall outside was more developed as compared with the inside. In addition it was shown that directly on the flue gas inflow side (the fire side) the oxides/deposits layer was built of densely arranged spherical deposits, which formed an unfavourable barrier between the component (tube) and the atmosphere surrounding it.

1. Introduction
The studies on the kinetics of metals and alloys oxidation were initiated by Tamman in 1920, when the author started the research related to the influence of iodine vapours on metals, and to changes of steel depending on time and temperature [1]. Tamman and Köster in 1922 [2] carried out studies into effect of the oxygen, hydrogen sulphide, and halides action on surfaces of metals. And so, in 1923 Pilling and Bedworth [3] started studies on metals oxidation at high temperatures.

Metal’s resistance to oxidation at high temperatures depends on the development of an oxide phase, and hence on maintaining its protective properties. Stresses originating in such a layer can cause fracturing followed by spalling, which directly affects the protective properties of such layer. Two types of stress are generally responsible for such cases of damage. The first consists in stresses formed in the layer due to the oxide layer growth, and the second, so-called thermal, is related to the difference in the thermal expansion between the oxide layer and the metal (substrate). The exact origin of existing stresses is still being studied and not ultimately learnt. It was found that stresses depend both on the metal and oxide volume, on their crystalline structures, as well as on the mechanism of oxide growth. When the oxide forms on the metal/oxide joint, the volume change due to the oxide formation can be expressed by means of Pilling-Bedworth (PBR) relationship (1) [3–6].

\[
PBR_{metal} = \frac{\text{volume of oxide}}{\text{volume of metal}}
\]
Therefore the topic of materials oxidation is still a current issue. Many research centers performs research related to the oxidation of materials [7–20], especially metallic materials [21–24]. Corrosion is an issue of high interest to scientists [25–30]. In particular, the problem of high-temperature corrosion is particularly important in the case of long-term elements operation in power stations or combined heat and power stations [9, 21, 31–39]. Niu et al [21] discussed primarily the main problems associated with ash during combustion, such as: alkali-induced slagging, silicate melt-induced slagging (ash fusion), agglomeration, and customized countermeasures including additives, co-firing, and leaching. Next, researchers characterized the mechanism of corrosion and discussed corrosion countermeasures, influence factors and also the issue of ash utilization. The causes and mechanism of corrosion of the external surfaces of boiler tubes were investigated in paper [32]. The obtained results showed that the sulfur content in the corrosion products was higher on the fire side. This element in the corrosion products existed in the form of SO₄²⁻ sulphate, which caused corrosion on the external surfaces of boiler tubes. Qi et al [33] investigated the behavior of damage in the oxide layer formed on the superheaters from T91 steel using a uniaxial stress test at room temperature and elevated temperature. Sludge created on heat exchange surfaces in water circuits in power plants negatively affects the reliability and efficiency of the power plant, causing enormous economic consequences and thus increasing the cost of electricity [35]. Therefore, investigating the deposition mechanism on energy-generating surfaces is defined as a high priority in the power industry [35]. These sediments mainly consist of iron oxides, which are corrosion products of steel. Magnetite (Fe₃O₄) is the dominant and most abundant compound found in the water and steam cycles of all types of power plants [35].

Atomic force microscopy AFM [40–45] and scanning electron microscopy SEM [42–44, 46] are widely used to study surface topography and fractal analysis [45, 46]. Researchers evaluated the hierarchical surface topography by means of determining the fractal dimension and power spectral density (PSD) of surface topography recorded by atomic force microscopy (AFM) [45]. The local fractal dimension was obtained using the triangulation method. The PSDs of all samples were fitted to the ABC model valid for a self-affine surface topology. The ABC model (k-correlation model) is an alternative to describing the PSD of a pure thin film [47, 48]. Goray and Lubov [49] analyzed the variation of roughness of the film by the power spectral density (PSD) function S(\(f_s, t\)) with a spatial frequency \(f_s\); then \(\sigma\) was calculated. Three correlation models are used in this study to decompose PSD functions calculated numerically: the ABC model, the Shifted-Gaussian model and the Fractal model. The sample morphology analyzing based on SEM or AFM technique and obtaining structural functions and fractal dimensions in micro and nano scales is a systematic and informative way to investigate surface structure [46, 30, 51]. The paper [50] contains results of fractal analysis of oxide layers formed on steels used in the power industry. The studies were carried out on elements taken from three steel grades: 13CrMo4–5 (T = 470 °C, t = 190 000 h), 10CrMoVNb9–1 (T = 535 °C, t = 75,000 h), 10CrMo9–10 (T = 575 °C, t = 100 000 h). The obtained results of studies show that the fractal analysis results are affected by operational parameters and by the type of formed oxide layers. Kargoz et al [5] concentrated on studying nanoscale metal oxide films used for chemical mechanical planarization (CMP) applications. The studies were carried out on thin metal oxide layers formed chemically from tungsten in the environment of a CMP suspension. Tungsten oxides were characterised in terms of thickness, density and surface topography. It was found that the topography of tungsten wafers’ surface tends to change depending on the oxidising agent concentration and it was also found to affect the wettability, total surface energy and consequently the material removal rate and the surface quality responses [5]. The examination of materials’ surface topography is one of main tests used to study the surface layers. Authors of paper [42] developed a method characterising the interphase roughness of laminar materials. This method was used to study internal oxidation of Si₃N₄—TiN composite/thermal barrier coatings upon thermal ageing. The roughness was studied via the image analysis on the image cross-section. The study consisted in making a few continuous images-areas on a specified length at an appropriate enlargement and resolution. The image analysis algorithms were developed to separate profile (y) of the surface or the surface layer based on the microstructure difference. The obtained data was then mathematically processed to determine parameters describing the roughness. The paper was aimed at determination of fractal parameters of oxide layers formed on steels used in the power industry.

In this study, the fractal analysis was carried out on 10CrMo9–10 steel long term operated at an elevated temperature. Morphological properties, fractal and statistical metrics of surface geometry of steel samples derived from SEM and AFM images were analyzed and discussed.

2. Materials and experimental methods

The material studied comprised specimens of 10CrMo9–10 steel taken from a pipeline operated at T = 545 °C during t = 200,000 h. The oxide layer was studied on a surface at the inner and outer surface of the tube wall on
the outlet both on the fire and counter-fire side of the tube wall surface. The oxide layer surfaces were studied using a Jeol JSM-6610LV scanning electron microscope (SEM) and an Vecco atomic force microscope (AFM).

Fast and accurate identification of specific arrangement patterns of spatial features on residual surfaces of solids is of great importance in materials engineering as it can be connected with the dynamics of surface phenomena. In this paper a simple though comprehensive method is used to extract non-random patterns from data series regardless of their origin: SEM and AFM images, and interpret obtained characteristics in a consistent manner [46, 50, 52, 53]. To start with the routine, autocorrelation map $R$ need to be computed according to the formula (2):

$$R_{mn} = \frac{1}{2S^2} \sum_{k=1}^{N-n} \sum_{l=1}^{N-m} (z(x + m, y + n) \cdot z(x, y))$$

where: $(m, n)$ defines discrete steps between original image and its shifted copy, $S$—root-mean-square roughness, and $N$—number of height samples along each side. The use of the autocorrelation is twofold. Firstly, it might serve to express angular differences in surface geometry in terms of anisotropy ratio $S_a$ (3) [54]:

$$S_a = \frac{S_{a1}}{S_{a2}}$$

where: $S_{a1}$ and $S_{a2}$—are smallest and largest autocorrelation decay lengths, respectively. Secondly, arithmetic average of extreme half-widths at half maxima (HWHM) of the autocorrelation peak ($w_{a1}$ and $w_{a2}$, respectively) can be taken as a measure of specific size of dominant bumps on the surface $d_g$ (4):

$$d_g = w_{a1} + w_{a2}$$

In order to find out more sophisticated measures of the surface complexity, higher-order mutual relationships between pairs of height samples can be explored, which leads to so-called fractal description. In this paper fractal descriptors are derived from the structure function also known as the height-height correlation function $S$, which is directly related to the autocorrelation function through the formula (5) [54]:

$$S(\tau) = 2S^2(1 - R(\tau))$$

Sayles and coworkers demonstrated that the structure function exhibits specific allometric invariance to scaling in $\tau$ (6) [55]:

$$S(\tau) = K\tau^{21D-D}$$

where: $D$—is the fractal dimension, and $K$—pseudo-topothesy.

3. Results

Figure 1 presents SEM images (210 $\mu$m long and 145 $\mu$m wide) taken on the residual surfaces of the steel specimens under investigation. In general, the inner surfaces at both ends of the pipeline turn out to be very rough and made of irregular, aggregated bumps several micrometers in size. Unlike that, however, SEM images reveal the presence of spherical, regular grains of various diameters on both outer surfaces with much higher concentration on the fire side of the tube. More specifically, the inner surface of the high-temperature side of the pipeline shown in figure 1(a) was found composed of a large number of irregular, although similar bumps 20 nm in diameter, which are riddled with small holes not larger than few micrometers. The bumps contribute to large height variations in this sample, but the surface itself remains smooth except for very small secondary nuclei. In turn, figure 1(b) presents the outer surface on the fire side of the cylinder, where a large number of spherical particles with diameters spread on the spectrum from hundreds of nanometers to tens of micrometers are easily recognized. The obtained image reveals a dense cover of homogeneously distributed spheres that neither aggregate nor tend to form any higher-order alignment pattern. The surface on the inner side of the pipe opposite to the fireplace shown in figure 1(c) appears lumpy and rough due to a large number of irregular clusters of particles similar to figure 1(a), except for the lack of the riddles. Another difference is the higher concentration of secondary nuclei seen in figure 1(c), randomly grown and oriented on the surface. Finally, figure 1(d) exhibits the outer surface on the counter-fireplace end of the tube, which appears to be a mixture of previously described structures. Apart from numerous spherical grains, also well separated irregular particles can be seen, leading to a structure void of any significant morphological characteristics.

Figure 2 shows AFM images of the same surfaces, although taken at higher magnification than using SEM. The scan length is 5 $\mu$m, hence the scan areas are comparable with those of main topographical features revealed by SEM. As long as the largest particles are considered, both methods yield similar results: all surface structures are composed of grains few micrometers in size that differ in habits and degree of secondary nucleation. An abundance of very small precipitates of tens of nanometers in diameter covering the surfaces of these samples.
cause that their faces are blunt and blurred. However, sample b sticks out from the rest, because of sharp, well developed crystalline faces without any secondary overgrowth.

Example plots of profile structure functions are shown in figure 3, where D and K govern relative and absolute changes in height variations, respectively. However, the above allometricity ultimately vanishes at a certain threshold referred to as the corner frequency $\tau_c$.

In order to get an insight into detailed structure of the residual surfaces, fractal parameters were established in this paper in two different ways, namely in the form of directional and averaged characteristics. The former were derived from profiles of the autocorrelation function taken along directions of its extreme decay ($a_1$ and $a_2$), whereas the latter were computed from the radial profile obtained by averaging of the autocorrelation function around its origin. The only difference is expected to be the range of possible fractal dimensions. Parameters computed from single curves define allometricity of the samples along arbitrary directions, hence they fall somewhere between 1.0 and 2.0. On the other hand, parameters obtained from averaged data express height variability in two dimensions, therefore they are higher than the previous ones.

Figure 1. Low-magnification SEM images of oxides formed on 10CrMo9–10 steel after long-term operation at elevated temperatures: (a) inner surface on the fire wall, (b) outer surface on the fire wall, (c) inner surface opposite to the fireplace, (d) outer surface opposite to the fire wall.

Figure 2. High-magnification AFM images of oxides formed on 10CrMo9–10 steel after long-term operation at elevated temperatures: (a) inner surface on the fire wall, (b) outer surface on the fire wall, (c) inner surface opposite to the fire wall, (d) outer surface opposite to the fire wall.
Fractal dimension provides a statistical index of complexity comparing how a detail in a pattern changes with the scale at which it is measured. On the other hand, geometric objects in Euclidean space scale are directly proportional to L^{−1} (curves), L^{−2} (surfaces) and L^{−3} (volumes), where L defines characteristics scale length, and the numbers in exponents define Euclidean space dimension. In this picture, fractals are intermediate objects with specific space-filling capacity that scale differently and are more developed than the space they are embedded in.

Table 1 summarizes results of statistical and fractal analyzes of images presented in figures 1 and 2, which were performed to find out how spatial features grown on oxidized steel surfaces correspond to specific measures of geometric organization. Results derived from SEM images describe surface geometry at larger ranges, around tens of micrometers, whereas those from AFM images define shapes of two orders of magnitude smaller. The main difference between both pictures relies on the degree of fractality of the structures, i.e. apparent tendency towards aggregation of smaller particles into larger hyper-units seen as higher-order arrangement patterns regardless of the source data (directional profiles versus averaged profiles). As a rule, large-area SEM images exhibit bifractal (aggregated) structures, while small-area AFM data mostly reveal monofractal structures.

The analysis of directional profiles from SEM images demonstrates significant isotropy of spatial characteristics since the lower fractal dimension D₁ fluctuates within a narrow range from 1.23 to 1.36 below the threshold limit 700–750 nm (corner frequency τ₁ roughly equal to the grain diameter), and the upper fractal dimension D₂ remains constant at 1.54–1.55 up to the corner frequency τ₂ (roughly equal to the cluster size). Averaged profiles yield similar results concerning the difference in higher dimension of source data. Lower fractal dimension is found to vary between 2.26 and 2.35 for the wavelengths limited by 700–800 nm, while the upper fractal dimension fluctuates from 2.57 up to 2.62 until the wavelength rises to 2850–4000 nm. What is
interesting, mean grain diameters estimated from averaged data correspond to the upper fractal dimension, but are systematically smaller (less than 20 per cent), which agrees well with the proposed schematic morphology of oxidized steel samples seen as a network of interpenetrating blocks of otherwise separated sub-units. Also the anisotropy ratio proves high spatial isotropicity as it is found higher than 0.7.

On the other hand, since lower corner frequencies obtained from high-magnification AFM scans are nearly equal to those from SEM images, it is reasonable to assume that they define elements of spatial organization within single blocks solely. Directional characteristics demonstrate monofractal nature of all samples, and the same conclusion can be drawn from averaged parameters. Note that obtained characteristics are consistent: fractal dimensions slightly vary around 1.38 and 1.45, while corner frequencies set up the cut-off limits somewhere between 400–600 nm and 460–810 nm, for $a_1$ and $a_2$ axes, respectively. Parameters from averaged data bring nearly identical results. Compared to SEM images, however, there are a few distinct differences. First of all, the samples appear moderately anisotropic according to low values of anisotropy ratio, below 0.6. In addition, grain diameters turn out to be twice the values of the corner frequencies. Such a result suggests that the contribution of single profiles to mean characteristics of anisotropic structures comes with a variable weight, which affects the length of horizontal correlation, but not the scale exponent. Moreover, the records of long-wavelength structures further limit sensitivity of the method towards small elements increasing the decay length, and hence the dimensions of particles.

The surface topography plays an important role in materials engineering, in particular in the case of oxidised surfaces. Because of that some parameters as amplitude, ordering, or directionality provide significant information on the surface condition of a material used in the power industry. Numerical methods, mainly the fractal analysis, are important tools to characterise structures of oxide layers and their properties after long-term operation at elevated temperatures. The type of flowing medium (blue gas side, steam side) has a significant impact on the nature and degree of development of formed oxide layers. A significant degree of surface development has an unfavourable effect on further operation of power equipment components. Results of fractal analysis of the studied steel showed the greatest degree of surface development on the fire side at the tube wall outside. A very large amount of spherical deposits, densely covering the proper oxides layer, has an unfavourable impact on further operation of power equipment. This results in an increase in the tube temperature due to formation of an insulating oxides/deposits layer between the tube wall surface and the atmosphere. Moreover, the oxides/deposits layer causes diminishing of the tube wall thickness. However, not only the type of flowing medium but also the chemical composition of steel and parameters of power equipment operation affect the topography of oxidised surfaces [50]. The studies carried out on three different steel grades used in the power industry ($13CrMo4–5$, $10CrMo9–10$, $X10CrMoVNb9–1$) showed diversified morphology of the formed oxide layers [50]. The studies were carried out both on the inside and outside of tube walls operating at diversified temperature and time parameters. The obtained results $S_n$ showed that the studied surfaces presented a high variability of anisotropy, falling within the range from 0.33 (an anisotropic surface) to 0.99 (a perfectly isotropic surface). In the case of oxides on the inside a trend of growing isotropy was shown with increasing operating temperature (an increase from 0.33 to 0.78). However, the layer of oxides on the outside formed on low-chromium steels was highly isotropic, while that formed on high-chromium steels perfectly anisotropic. The majority of analysed layers turned out to be monofractal structures, meaning that in the entire studied range of length intervals relative and absolute changes of surface heights could be described with only one exponent of the scale, i.e. a single value of fractal dimension $D$. The obtained $D$ values ranged between 2.28 and 2.43, which proves a moderate development of the studied surfaces.

Taking into account the values of corner frequency $\tau_c$, hence the length of autocorrelation shift, for which the exponential scaling law transforms into a constant function, a trend of decreasing values of this parameter with increasing temperatures for the tube outside (from 787 to 488 nm) was noticed [50]. The applied fractal analysis method enables the assessment of oxide layers surface condition, which is very important for the power industry development. Using methods based on this analysis it is possible to assess in detail the condition of the top layer of steels used in the power industry.

4. Summary

The obtained results of studies show that:

- On the fire side, on the inner surface there is a large amount of irregular but similar bumps twenty micrometres in diameter, which are filled with small holes not bigger than a few micrometres. The bumps cause large height fluctuations in this specimen, but the surface itself remains smooth, with the exception of very small secondary nuclei.
• The surface on the inside, on the counter-fire side, seems uneven and rough due to a large number of irregular clusters of particles similar to the fire side, except for the lack of riddles. Another difference consists in a higher concentration of secondary nuclei, random grown and oriented on the surface.

• On the outside there are spheroidal grains of oxide/sediment, which in a more intensiﬁed form exist on the fire side. On this surface there are densely arranged particles with diameters ranging from hundreds of nanometres to tens of micrometres.

• The analysis of directional proﬁles from SEM images shows signiﬁcant isotropy of spatial characteristics.

• The average values of D1 and D2 obtained from the analysis of SEM images showed that the fire side shows higher values of this parameter. The same relationship was observed by analyzing the AFM images for parameter D2.

• Analysis of SEM images showed the lowest values of parameter dg on the inner side of the pipe wall: 2580 nm and 3180 nm for the fire and opposite ﬁre side respectively. Whereas the highest value dg was characterized on a layer of oxide from the fire side on the outside of the pipe wall. Values lower by 70 units were shown on the opposite ﬁre wall.

**ORCID iDs**

Monika Gwoździk [https://orcid.org/0000-0002-4297-5821](https://orcid.org/0000-0002-4297-5821)

**References**

1. Tamman G 1920 Z. Anorg. Allg. Chem. 111 78
2. Tamman G and Köster W 1922 Z. Anorg. Allg. Chem. 123 196
3. Pilling N and Bedworth R J 1923 J. Inst. Metals 29 529
4. Xu C and Gao W 2000 Mater. Res. Innov. 3 231
5. Karagöz A, Craciun V and Basim G B 2015 ECS J Solid State Sci P1
6. Bahadur A and Mohanty O N 1991 Mater Trans 32 1053
7. Hussin M H and Lah N A C 2017 JMES 11 2743
8. Gwoździk M 2015 Arch. Metall. Mater. 60 1783–8
9. Gwoździk M 2016 Arch. Metall. Mater. 61 987–92
10. Mrowec S 1982 Kinetyka i mechanizm utleniania metali. Katowice, Wydawnictwo Śląsk
11. Kuiry S C, Seal S, Bose S K and Roy S K 1994 ISIJ Int. 34 599
12. Bing wei L, Jia Z, Peng peng B, Shu qi Z, Teng A and Xiang li W 2017 Int J Min Met. Mater. 24 646
13. Shariff N A, Othman N K and Jalar A 2014 Procedings AIP Conf. 1571 (AIP Publishing LLC) p 59
14. Story M E and Wohlers B A 2017 ISIJ Int. 57 1468
15. Labisiz K, Konieczny J, Wierzbicki L, Cwiw J and Bator A 2018 Transport Problems 13 111
16. Hou D, Jiang Z H, Dong Y W, Geng W, Cao Y L and Cao H B 2017 ISIJ Int. 57 1400
17. Ng J H, Almubarak T and Nasr-El-Din H A 2018 Spec Prod Oper. 33 131
18. Zheng Z, Sun W and Liu Z 2018 Rare. Metal Mat. Eng. 47 2717
19. Pan H, Huang X, Zhang R, Wang D, Chen Y, Dunan X and Wen G 2019 Chem. Eng. J. 358 1253
20. Xu Y, Luo G, Pang Q, He S, Deng F, Xu Y and Yao H 2019 Chem. Eng. J. 358 1454
21. Niu Y, Tan H and Hui S 2016 Prog. Energy Combust. Sci. 52 1
22. Moon J, Kim S, Park W D, Kim T Y, Mcalpine S W, Short M, Kim J H and Bahn C B 2019 J. Nucl. Mater. 513 297
23. Zhou Y, Wang S, Chen W, Jiang W, Wang L, Chen K and Cui X 2018 P. I. Mech. Eng. J.-J. Eng. 232 1569
24. Zhong X, Xia S, Xu J and Shoji T 2018 J. Nucl. Mater. 511 417
25. Summers K L and Chidambaran D 2017 J. Electrochem. Soc. 164 H5357
26. Zhong X, Lu W, Yang H, Liu M, Zhang Y, Liu H, Hu J, Zhang Z and Zeng D 2019 J. Petrol. Sci. Eng. 172 162
27. Kochek P K and Wang C J 2018 Oxid. Met. 90 713
28. Guo X, Lai P, Tang L, Chen K and Zhang I 2018 Wear 414 194
29. Chen J, Song X, Wang H and Liu J 2018 Rare. Metal Mat. Eng. 47 2642
30. Fernandez A G, Munoz-Sanchez B, Nieto-Maestre I and Garcia-Romero A 2019 Renew. Energ. 130 902
31. Zhu Z, Qiao Y, Wang N and Cao J 2018 Appl. Therm. Eng. 128 1159
32. Pan L, Xie X, Shen J, Li Z, Wang R, Yang Y and Peng K 2013 Progress in Industrial and Civil Engineering II, PTS 1-4 405-408 3253
33. Qi J, Zhou K, Huang J and Si X 2018 Appl. Therm. Eng. 128 244
34. Goyal K, Singh H and Bhatia R 2018 Anti-Corros. Method. M. 65 646
35. Vidojkovic S M and Rakin M F 2017 Adv. Colloid Interface Sci. 245 108
36. Aguero A, Gonzalez V, Mayr P and Spradek-Hahn K 2013 Mater. Chem. Phys. 141 432
37. Gwoździk M and Nikielwicz Z 2013 Sol. Phen. 203-204 121
38. Gwoździk M and Nikielwicz Z 2014 Arch. Civ. Mech. Eng. 14 335
39. Gwoździk M 2016 Acta Phys. Pol. A 130 935–8
40. Tadaev P O, Bobkov A A, Borodzyula V F, Lamkin I A, Mikhailov I I, Moshnikov V A, Permyakov N V, Solomonov A V, Sudar N T and Tarasov S A 2017 In: International Conference Journal of Physics: Conf. Series 929 012048
41. Bobkov A A, Borodzyula V F, Lamkin I A, Mikhailov I I, Moshnikov V A, Solomonov A V and Tarasov S A 2018 Glass Phys. Chem 44 480
42. LeRoux S, Deschaux-Beaume F, Cutard T and Lours P 2015 J. Eur. Ceram. Soc. 35 1063
[43] Birdeanu M, Fagadar-Cosma G, Sebarchievici I, Birdeanu A V, Taranu B, Taranu I and Fagadar-Cosma E 2016 J. Serb. Chem. Soc. 81 163
[44] Singh A R and Deshpande V D 2016 Bull. Mater. Sci. 39 167
[45] Ponomareva A A, Moshnikov V A and Suchaneck G 2013 In: 2nd International Conference on Competitive Materials and Technological Processes. IOP Conf. Series: Materials Science and Engineering 47 012052
[46] Naseri N, Solaymani S, Ghaderi A, Bramowicz M, Kulesza S, Ţălu Ş, Pourreza M and Ghasemi S 2017 RSC Adv. 7 12923
[47] Church E L, Takacs P Z and Leonard T A 1989 Scatter from optical components ed J C Stover Proc. SPIE 1165, 136
[48] Ferré-Borull J, Duparré A and Quesnel E 2001 Appl. Opt. 40 2190
[49] Goray L and Lubov M 2015 Opt. Express 23 10703
[50] Gwoźdźik M, Kulesza S and Bramowicz M 2017 METAL 2017: 26th Int. Conf. on Metallurgy and Materials (Ostrava) (TANGER) p789
[51] Gwoźdźik M, Bramowicz M and Kulesza S 2018 METAL 2018: 27th Int. Conf. on Metallurgy and Materials (Ostrava) (TANGER) p1114
[52] Kulesza S and Bramowicz M 2014 Appl. Surf. Sci. 293 196
[53] Solaymani S Ţ Ş, Bramowicz M, Kulesza S, Ghaderi A, Shahpouri S and Elahi S M 2016 J. Mater. Sci.—Mater. El. 27 9272
[54] Dong W P, Sullivan P J and Stout K J 1994 Wear 178 45
[55] Sayles R S and Thomas T R 1977 Wear 42 265