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Computer assisted evaluation of degree of exhaustion of T/P23 (2.25Cr-0.3Mo-1.6W-V-Nb) steel after long-term annealing

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ABSTRACT

Purpose: The method of image analysis and artificial intelligence methods in the evaluation of materials while working in creep conditions were proposed. The application of scanning electron microscopy in the correct assessment of the degree of exhaustion was of a demonstration character.

Design/methodology/approach: For the material after long-term operation in the creep tests microstructure examination was performed in a scanning electron microscope. To assess the degree of exhaustion of the material, the computer program was used.

Findings: The article demonstrates how to assess the state of the material using a computer program as an example of the application of computer methods for materials science. The verification was found to develop methodologies for assessing the correct level of exhaustion while working in steel material creep conditions.

Practical implications: The presented method can be used for evaluation and qualification of structural changes in power station boiler components operating in creep conditions.

Originality/value: The obtained results of changes in the mechanical properties, microstructure and in the precipitation processes are applied to the evaluating the condition of the elements in further industrial service.

Keywords: Image analysis; Steels; long term annealing; T/P23 steel grade

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

In the last fifteen years there was a considerable development of steels for power engineering, particularly through the assuring high strength properties, including temporary creep strength simultaneously with necessary plastic and technological properties, as weldability [1-20].

Therefore, at the end of the last century, two Japanese companies Mitsubishi Heavy Industrie Ltd. and Sumitomo Metal Industries Ltd. developed a new grade of bainitic T/P23 steel, named as HCM2S. It has given adequate mechanical properties - in this: time creep strength simultaneously with maintenance of the necessary plastic and technological properties [10].

T/P23 steel was developed by modifying the chemical composition of the 10CrMo9-10 steel. Increasing competitiveness of developed steel i.e. better application properties was obtained by the addition of elements such as W, V, Nb, B, and reduction of the carbon content, which improved the process of forming and weldability of T/P23. The addition of tungsten in an amount of about 1.6%, while reducing the molybdenum content caused the strengthening of the solid solution with simultaneously delay of the growth of $M_{23}C_6$ type carbides. The addition of alloying elements such as Nb and V resulted in the formation of stable precipitates MX type contributing to the precipitation strengthening of steel.

T/P23 steel has a comparable chromium and silicon content with 10CrMo9-10 steel and therefore the corrosion resistance to oxidation and gas corrosion is close to the base steel up temperature of 550°C. At higher temperature, a marked predominance of T/P23 steel is shown, probably due to theaddition of tungsten. The composition of T/P23 steel is shown in Table 1. The individual influence of elements on the parameters of steel affecting creep process are shown in Table 2. T/P23 steel was originally designed for thin-walled components such as pipe-screen, however, due to high properties is also applied to the coil pipes of steam superheater.

Changes in the microstructure result from the annealing temperature, time and cooling conditions. For steel with strictly required chemical composition it is important to know the ranges of occurrence of martensite, bainite and ferrite and pearlite. It is illustrated by CCT diagram shown in Fig. 1 for the 7CrWVNb9-6 (P23) steel. It allows for the selection of parameters of heat treatment of steel products in order to obtain the expected microstructure and functional properties.

Typical microstructure of the T/P23 steel is a mixture of martensite, bainite or bainite with carbide precipitates of both $M_{23}C_6$ at former austenite grain boundary and MX carbides / nitrides, especially Nb, V and W within the area of the bainite [4].

Table 1.
Material for investigation - T/P23 chemical composition of steel in relation to the requirements of ASTM A213/A213M-99A [10]

Element content [wt.%]												
C	Mn	Si	P	S	Cr	Mo	V	W	Nb	B	Al	N
0.04-0.10	0.10-0.60	max. 0.50	max. 0.03	max. 0.01	1.90-2.60	0.05-0.30	0.20-0.30	1.45-1.75	0.02-0.08	0.0005-0.006	max. 0.03	max. 0.03

Table 2.
The individual influence of elements on the parameters of steel affecting creep process

Element	Positive influence	Negative influence
B	- increase of steel hardenability - increase of creep strenght - stabilization of $M_{23}C_6$ carbides and delay of their growth	- decrease of impact strenght
C	- necessity of creation of $M_{23}C_6$ and NbC carbides	- reduction of plastic properties - reduction of weldability
Cr	- improvement of oxidation resistance - decrease of M_s, - increase of A_1 - main component of $M_{23}C_6$ carbides	- increase of diffusion coefficient
Mn		- increase of diffusion coefficient - decrease of creep strength - decrease of A_1 - stimulate precipitation of M_6C carbides
Mo	- decrease of M_s, - increase of A_1 - solid solution strengthening	- acceleration of the growth of carbides $M_{23}C_6$
N	- necessity of creation of VN	
Nb	- creation of MX carbides - contribution to strenghtening	
V	creation of MX carbides - contribution to strenghtening	
W	- decrease of M_s, - increase of A_1 - delay of $M_{23}C_6$ carbides growth - solid solution strengthening	- acceleration of M_6C carbides precipitation

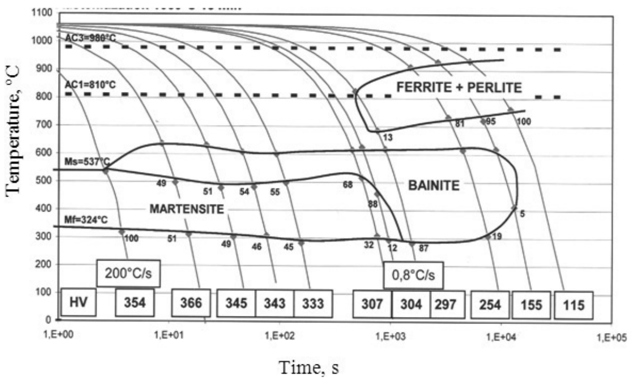

Fig 1. CTP_c diagram for low- carbon bainitic steel T/P23

2. Methodology

There were made the following research:

- analysis of T/P23 steel microstructure before and after exposure to creep conditions using scanning electron microscopy,
- estimating the material state on the base of scheme of microstructure changes during long-term operation in creep condition of low-alloy Cr-Mo microalloyed steel with the microstructure of ferritic - bainitic,
- proposition of a computer aided method for the analysis of changes in the microstructure and the automatic classification of the degree of exhaustion of the material.

3. Results

3.1. The influence of long-term annealing on changes in microstructure

Analysis of the T/P23 steel microstructure in the initial state and after long-term exposition to the creep condition were made with use of the scanning electron microscope [4,5].

For known material states, i.e. with estimated degree of microstructure degradation, developed on the base of the own classification of Institute for Ferrous Metallurgy Institute, a series of reference images of the microstructure by magnification from 500 to 5000x were made. Sample images of the microstructure and the assigned degree of exhaustion on the basis of the own classification Institute for Ferrous Metallurgy Institute (Fig. 2) are shown in Figs. 3 to 6.

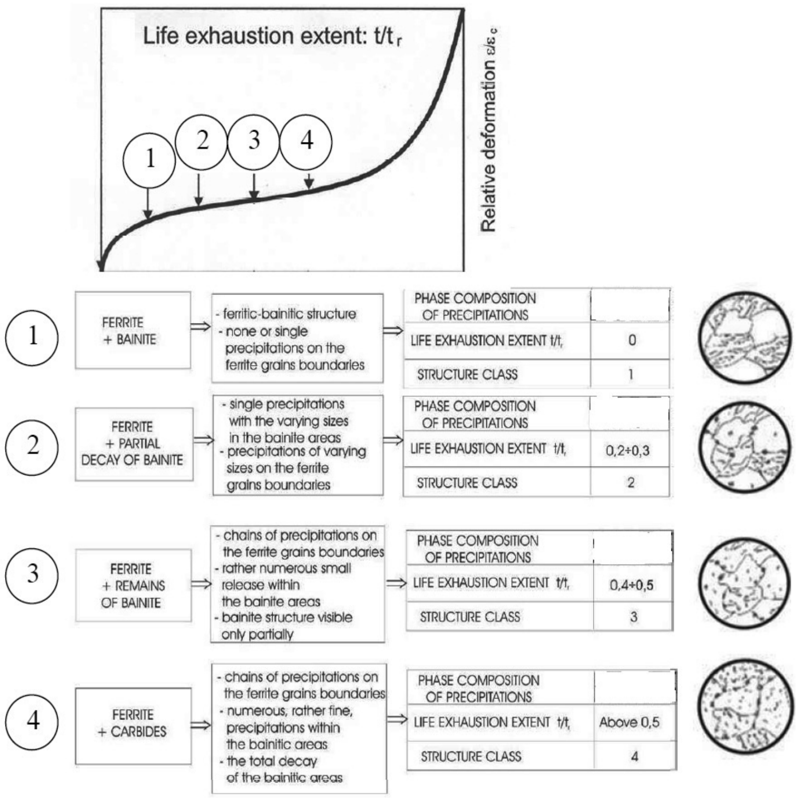

Fig. 2. Scheme of microstructure changes during the long-time creep service of the low-alloy Cr-Mo steel type with micro-additions with the ferritic-bainitic microstructure in the initial state

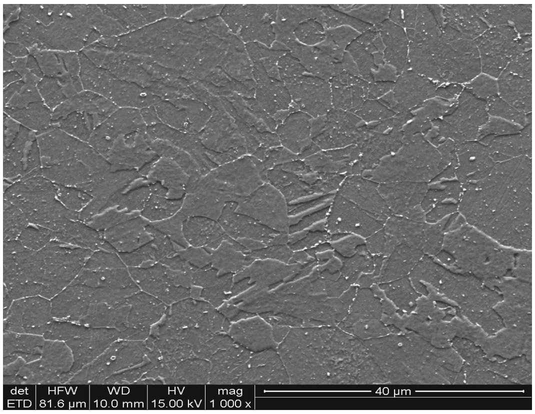

Fig. 3. The microstructure of the initial state of T/P23 steel, Bainitic areas, class 0; precipitation: class 0; Processes of damages in class 0, Material state: CLASS 1; degree of exhaustion: 0

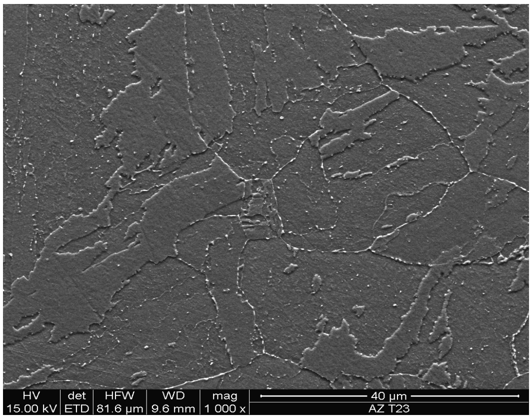

Fig. 4. The microstructure of T/P23 steel after 1000 hours of the annealing in the temperature of 550°C, Bainitic areas, class 0/I; precipitation: class 0/a; Processes of damages in class 1/2, Material state: CLASS 1/2; degree of exhaustion: to 0.2

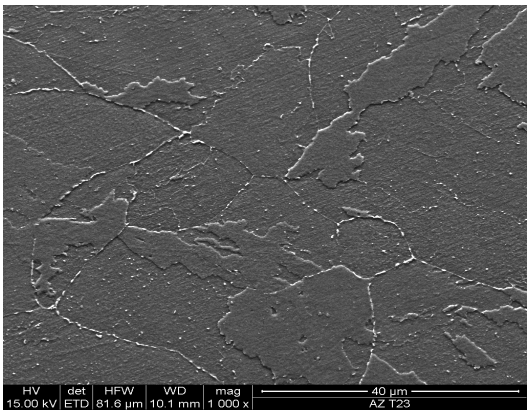

Fig. 5. The microstructure of T/P23 steel after 1000 hours of the annealing in the temperature of 600°C, Bainitic areas, class 0/I; precipitation: class 0/a; Processes of damages in class 0, Material state: CLASS 1/2; degree of exhaustion: 0.2

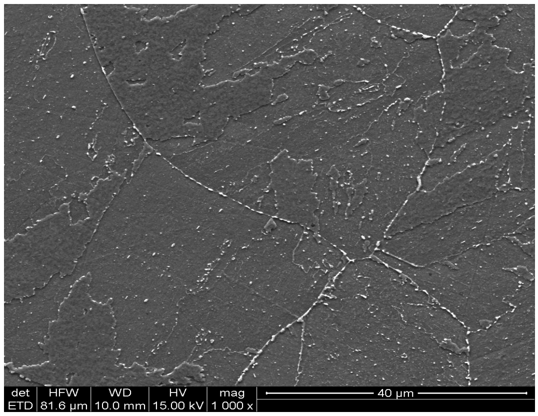

Fig. 6. The microstructure of T/P23 steel after 10000 hours of the annealing in the temperature of 550°C, Bainitic areas, class 0/I; precipitation: class 0/a; Processes of damages in class 0, Material state: CLASS 1/2; degree of exhaustion: 0.2

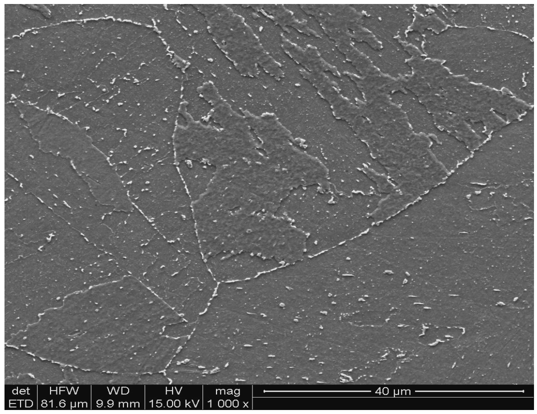

Fig. 7. The microstructure of T/P23 steel after 1000 hours of the annealing in the temperature of 600°C, Bainitic areas, class 0/I; precipitation: class 0/a; Processes of damages in class 0, Material state: CLASS 2; degree of exhaustion: 0.2-0.3

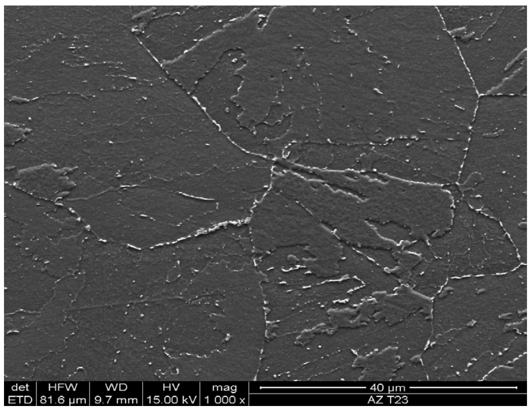

Fig. 8. The microstructure of T/P23 steel after 70000 hours of the annealing in the temperature of 550°C, Bainitic areas, class I; precipitation: class 0/a; Processes of damages in class 0, Material state: CLASS 2; degree of exhaustion: 0.2-0.3

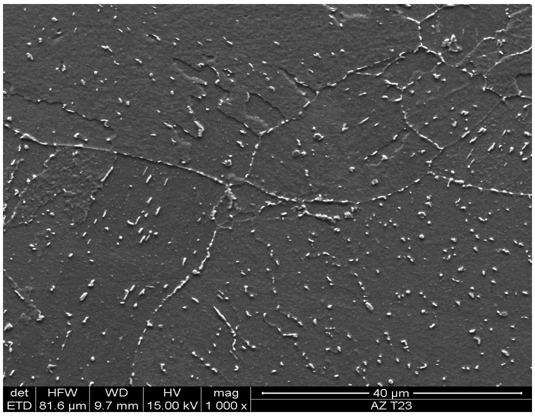

Fig. 9. The microstructure of T/P23 steel after 70000 hours of the annealing in the temperature of 600°C, Bainitic areas, class I; precipitation: class a; Processes of damages in class 0, Material state: CLASS 2/3; degree of exhaustion: 0.3

Microstructure analysis in scanning electron microscope by magnification up to 5000x shows that the annealing up to 70000 hours at temperature of 550°C does not cause important changes in images of the observed microstructures in relation to the initial state. There is visible, slight increase in the amount and size of precipitations inside grains, on the boundaries of the created subgrains and on the boundaries of primary austenite. Long term exposure to the elevated temperature revealed in the bainitic areas after annealing at 550°C only a slight their decay. For T/P23 steel after annealing by 70000h at 550°C a degree of exhaustion around 0.2-0.3 and assigned main class of microstructure number 2 were estimated (Fig. 8).

Annealing of T/P23 steel at 600°C up to 70000h resulted in significant changes in the image of the observed microstructure. The partial loss of bainitic areas with a significant increase in the size of carbides along grain boundaries and within the grains is visible. For T/P23 steel after annealing by 70000h at 550°C one estimated the degree of exhaustion of approximately 0.3 and assigned main class microstructure of 2/3 (Fig. 9).

3.2. Computer aided analysis of the growth of T/P23 steel particle size after exposure to elevated temperature

Registered in the scanning electron microscope reference images of T/P23 steel microstructure were saved as bitmap images with 256 shades of gray and standardized to improve their quality by changing the brightness and contrast. Normalization was performed using a linear function, which extended the scope of the intensity value points to the interval <0, 255>.

Filtration was used to suppress the unwanted noise in the image and remove the defects from the image referred to. Median filter combats all local noise without causing blurring in a wider area very effectively. It is a powerful filter because extreme values deviating from the mean does not have a large impact on the value that the filter passes on its output. Median filtering does not provide the image of any additional value, so after filtering additional scaling is not performed.

Then the process of image segmentation by thresholding the brightness consisting in the fact that the image contains multiple levels of gray turned into a picture whose pixels have only the values 0 or 1 was carried out. Binarization threshold was chosen in an experimental way based on the average magnitudes backgrounds. The next step was used to open operation, which removes the image of small objects and small details (peninsulas, extensions) without changing the way a significant dimension of the principal figures. It can also hang some objects that are locally in contact with each other.

Afterwards the indexation, i.e. assigning to all the pixels of objects identifiers (labels), indicating objects and pixels, which can be commonly assigned was conducted. After passing the whole picture and identifying all objects the bonding array came into being. Then it can be easily used to indexation of incorrectly indexed parts of objects that are thus almost completely eliminated.

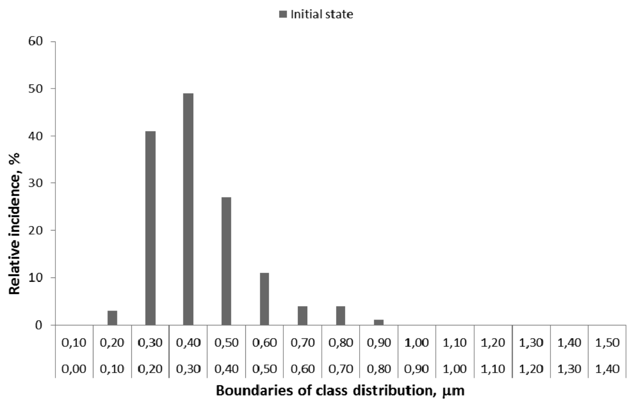

Fig. 12. Chart of empirical distribution of diameters of equivalent particle of the steel in the initial state T/P23

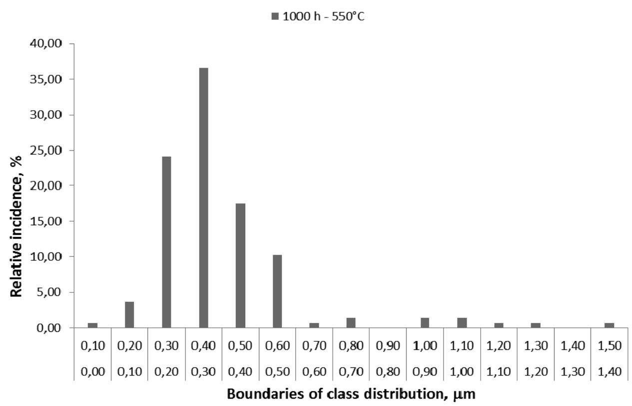

Fig. 13. Chart of empirical distribution of diameters of equivalent particle of T/P23 steel after annealing 1000h/550°C

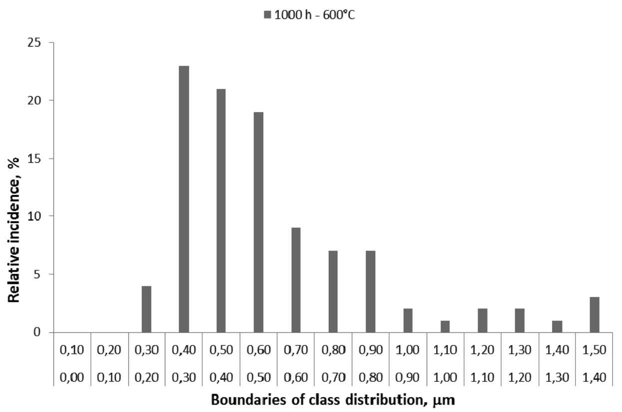

Fig. 14. Chart of empirical distribution of diameters of equivalent particle of T/P23 steel after annealing 1000h/600°C

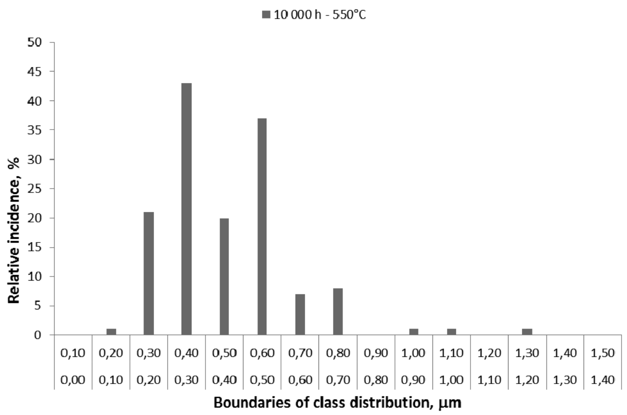

Fig. 15. Chart of empirical distribution of diameters of equivalent particle of T/P23 steel after annealing 10000h/550°C

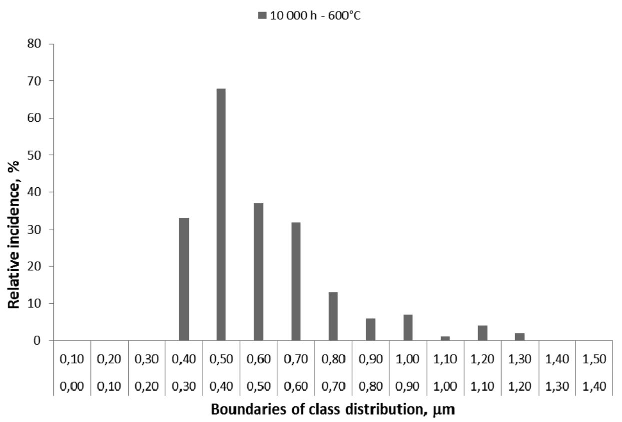

Fig. 16. Chart of empirical distribution of diameters of equivalent particle of T/P23 steel after annealing 10000h/600°C

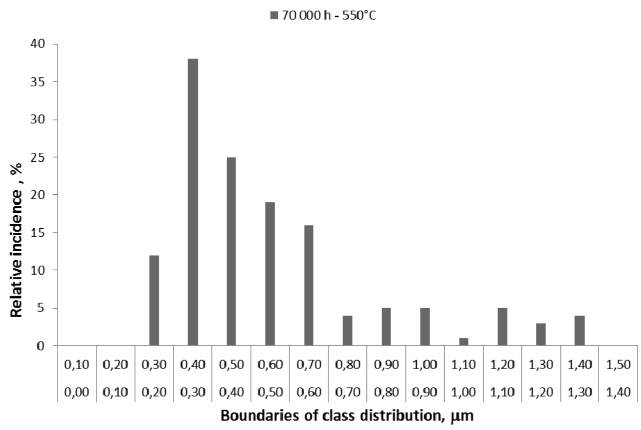

Fig. 17. Chart of empirical distribution of diameters of equivalent particle of T/P23 steel after annealing 70000h/550°C

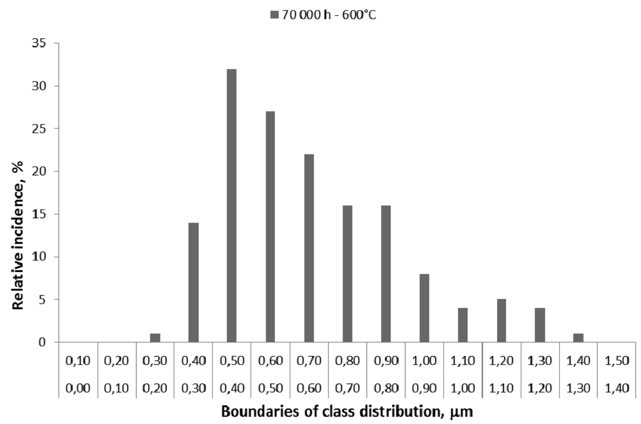

Fig. 18. Chart of empirical distribution of diameters of equivalent particle of T/P23 steel after annealing 70000h/600°C

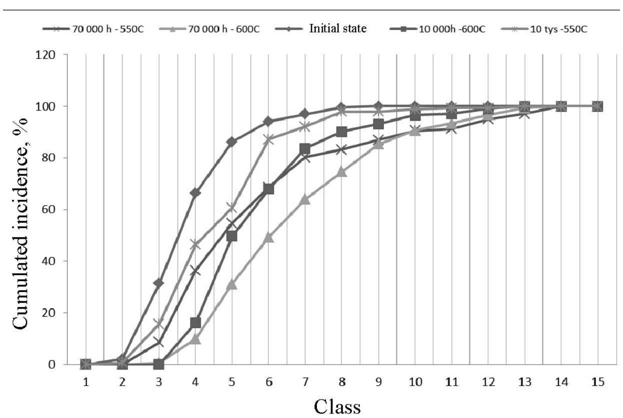

Fig. 19. Specification of cumulative frequency distributions for the precipitates in the steel T/P23

After extracting the contours, measures of the features of each object were made. Values of the coefficients of geometric features were calculated. They were used to determine the diameters of the precipitates occurring.

For registered reference images of T/P23 steel microstructure, both in the initial state and after long term exposure in annealing and creep conditions, the distribution of diameters of occurring precipitates was determined. Results in the form of distributions of equivalent diameters of the precipitates occurring for the states analyzed of investigated steel T/P23 is shown in the diagrams (Figs 12-19). They take into account the empirical relative distributions and cumulative frequency.

Table 3.
Specification of results of particle size measurements with regard to the estimated degree of exhaustion.

Material state	Mean diameter µm	Standard deviation	Min. diameter µm	Max. diameter µm	Exhaust degree
Initial state	0.379	0.127	0.163	0.891	1 0
1000h 550°C	0.356	0.161	0.090	1.197	1/2 to 0.2
1000h 600^0C	0.431	0.144	0.207	1.030	1/2 about 0.2
10000h 550°C	0.387	0.134	0.169	0.970	1/2 max. 0.2
10000h 600°C	0.557	0.187	0.326	1.271	2 about 0.2-0.3
70000h 550°C	0.419	0.146	0.208	1.035	2 about 0.2-0.3
70000h 600°C	0.661	0.244	0.210	1.602	2/3 about 0.3

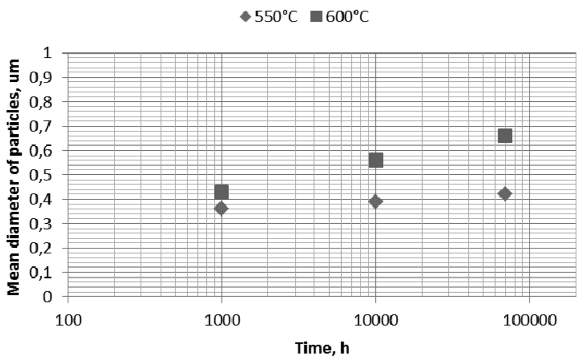

Fig. 20. Diagram of influence of annealing temperature and time on the mean particle diameter of T/P23 steel

The analysis of particle size growth on the example of T/P23 steel in the initial state and after annealing at 550 and 600°C, clearly indicates that the equivalent diameters grow with the increase of temperature and time of annealing. It was observed that the rate of particle growth in annealing temperature of 600°C is much faster than at 550°C (Fig. 20). Comparing the obtained result can be noted that changes in the size of the precipitates after annealing time 1000h/600°C are similar to the results obtained after the time of 70000 hours at 550°C.

4. Conclusions

Research carried out in the study allowed to evaluate changes in the microstructure of T/P23 steel in the initial state and their comparison with the results obtained after long term annealing at 550 and 600°C. Analysis of the microstructure showed that annealing for 70000 hours at 550°C resulted in no significant changes in image microstructure observed in relation to the microstructure of the initial state. For T/P23 steel after annealing by 70000h at 550°C, the estimated degree of exhaustion is around 0.2 - 0.3 and the major class is assigned as microstructure number 2. Annealing of T/P23steel at 600°C until 70000 h resulted in significant changes in the image of the observed microstructure. There is visible, partial loss of bainitic areas with a significant increase observed in the size of carbides along grain boundaries and within the grains. For T/P23 steel after annealing at the temperature of 550°C 70000h exhaustion rate was estimated about 0.3. One assigned the microstructure of the major class 2/3.

The analysis of particle size growth at initial state and after long term annealing clearly shows that the equivalent diameters grow with increasing annealing temperature and time. It was observed that the rise of temperature significantly intensifies the precipitation process in T/P23 steel. The mean particle diameter after annealing for 1000h/600C is close to the average determined for the annealing time 70000h/550°C.

The use of computer-aided evaluation of the degree of exhaustion, by the analysis of the increase of precipitates growth in low-alloy steels of Cr-Mo microalloyed can be a component in assessing the degree of exhaustion of materials after exploitation. It should be noted that the reliability of the results of the evaluation of the size of the precipitates, should be supported by an analysis of a few to several areas of the metallographic sample in terms of area from 1000 to 5000x registered by scanning electron microscope.

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