A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 60 2015 Issue 3
DOI: 10.1515/amm-2015-0297

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THE INFLUENCE OF TEMPERATURE GRADIENT ON STEREOLOGICAL PARAMETERS OF CARBIDE PHASE ON CROSS-SECTION OF ABRASIVE WEAR RESISTANT CHROMIUM CAST IRON

WPŁYW GRADIENTU TEMPERATURY NA PARAMETRY STEREOLOGICZNE FAZY WĘGLIKOWEJ NA PRZEKROJU ODLEWU Z ŻELIWA CHROMOWEGO ODPORNEGO NA ZUŻYCIE ŚCIERNE

In the paper analysis of temperature gradient and parameters of structure on casting cross-section of abrasive wear resistant chromium cast iron at carbon content of 2,5%wt. and chromium 17%wt. with nickel and molybdenum additives are presented. The castings were made with use of special tester ϕ100mm (method of temperature gradient and derivative analysis) with temperature recording in many points from thermal centre to surface (to mould) of casting. Registered cooling curves were used to describe the temperature gradient on cross-section of analyzed casting. On the basis of determined curves of temperature gradient measurement fields were selected to make the quantitative studies of structure. The results of studies show significant influence of temperature gradient on quantitative parameters of chromium cast iron structure. Moreover was affirmed that exists a critical temperature gradient for which is present rapid change of quantitative parameters of chromium cast iron structure.
Keywords: casting, chromium cast iron, crystallization, TGDA, structure;

W artykule przedstawiono analizę gradientu temperatury i parametrów struktury lanej na przekroju odlewu wykonanego z żeliwa chromowego odpornego na zużycie ścierne o zawartości węgla ok. 2.5% i chromu ok. 17% z dodatkami niklu i molibdenu. Odlew wykonano w specjalnym próbniku ϕ100mm (metoda analizy gradientu temperatury i derywacyjna) z pomiarem temperatury w wielu punktach odlewu od jego centrum cieplnego do powierzchni (do formy odlewniczej). Zarejestrowane krzywe stygnięcia wykorzystano do opisu gradientu temperatury na przekroju analizowanego odlewu. Badania ilościowe struktury wykonano na wybranych przekrojach odlewu. Analizowane przekroje wybrano na podstawie wyznaczonych krzywych gradientu temperatury. Badania wykazały istotny wpływ gradientu temperatury na parametry ilościowe struktury żeliwa chromowego. Stwierdzono występowanie krytycznego gradientu temperatury, dla którego następuje skokowa zmiana parametrów ilościowych struktury badanego żeliwa chromowego.

1. Introduction

The chromium cast iron is foundry material, which is widely use on parts working in the conditions of abrasive and corrosive wear. Therefore chromium cast iron is applied in industry of extractive, mineral processing, power engineering etc., mainly on components (castings) working at mining, crushing, grinding, transport etc. of minerals [1-6]. These castings during working are subject to destruction mainly due to the wear process, but sometimes it must also be resistant to momentary increase of load or impacts. Therefore for these working conditions are applied hypoeutectic chromium cast iron contains proper matrix with usually about 30% of carbides of M_7C_3 grade.

The decisive influence on increasing of wear resistance has amount of hard carbides phase in austenite matrix, mainly M_7C_3 (where M represents Cr or Fe), which is created at proper amount of carbon and chromium. This diphase structure guarantees high resistance to abrasive wear, which can be further strengthened by heat treatment. Therefore important is introducing into chemical composition of chromium cast iron nickel and molybdenum which guarantees decrease of brittleness at simultaneous increase in suitability to heat treatment [1, 2]. Moreover one of the failures of chromium cast iron massive castings is large quantitative heterogeneity of phases on cross-section, which reveals the formation of a coarse grain structure generating worse mechanical properties. The structure except of chemical composition of alloy is determined by the conditions of casting cooling, which depends of its design and accepted technology.

Therefore presented paper describes influence of cooling conditions represented by temperature gradient on quantitative parameters of abrasive wear resistant chromium cast iron structure.

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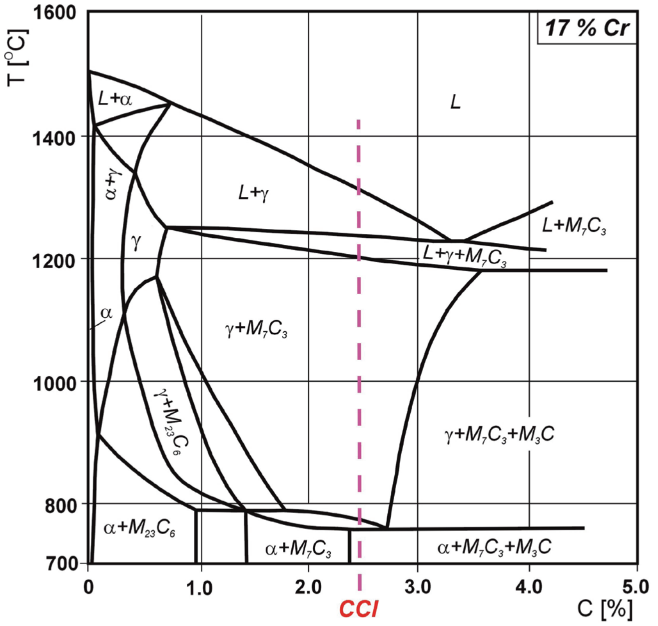
2. The range of studies

On figure 1 polythermic section of phase equilibrium system of Fe-C-Cr alloy at constant concentration of chromium 17%wt. and chemical composition of studied alloy is presented. On presented system theoretical path of crystallization of studied alloy (CCI - chromium cast iron) was indicated. The additional chemical elements which are present in studied alloy move characteristic points and lines of equilibrium system mostly in direction of the smaller content of carbon and the lower temperatures. Moreover the larger cooling rate of studied alloy in the relation to cooling rate of alloy from equilibrium system influences the lowering of phase transformation temperatures.



C	Cr	Si	Mn	Mo	Ni	P	S	Nb	V	Ce	La	N
% weight												ppm
2.63	16.89	0.62	0.31	1.86	1.27	0.050	0.016	0.22	0.13	0.009	0.004	657

Fig. 1. Polythermic section of phase equilibrium system of Fe-C-Cr alloy at constant concentration of chromium 17%wt. and chemical composition of studied alloy

The experimental melts were made in the inductive crucible furnace with inactive lining and capacity of 20 kg. The metallic charge was composed of typical materials applied in foundry engineering. The pouring temperature was set on 1480°C.

In the studies of crystallization process methods enabling analysis of temperature gradient and its first derivative in time was applied. In this method called TGDA (Thermal Gradient and Derivative Analysis) is used a special tester of ϕ 100 mm. During the designing process of this tester the assumptions of similar testers used in the classic TDA method (Thermal and Derivative Analysis) were used [5, 6] and the widened TDA-K3 method (Thermal and Derivative Analysis with 3 testers of different solidification module).The final version of tester ϕ 100 mm results from its applying mainly to the wear resistance studies of materials [7-9]. Moreover a diameter of model casting ϕ 30 mm makes easier carry out further metallographic studies. On figure 2 the tester applied in TGDA method with layout of thermocouples is presented. In studies was assumed equal distance (10mm) between the thermocouples.

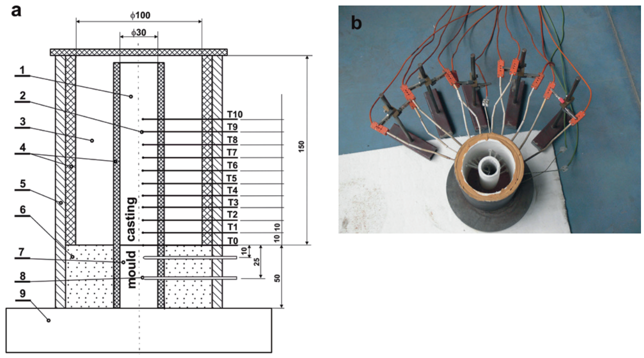


Fig. 2. The tester ϕ100 mm (a) and its view prepared to studies (b): 1 - model casting,

2 - PtRh10-Pt thermocouple, 3 - thermal insulator, 4 - material isolating SIBRAL 300,

5 - steel pipe, 6 - quartz sand mould, 7 - steel model mould, 8 - NiCr-Ni thermocouple,

9 - bottom plate, T0÷T10 - PtRh10-Pt thermocouples in quartz shields placed in model casting

On figure 3 cooling curves of studied chromium cast iron, which were used to develop a curves of temperature gradient on cross-section of model casting are presented. The average value of temperature gradient between measuring points, for example 2 and 3 can be calculated as follows:

$$GT2{,}5 = \frac{T3 - T2}{d_{2-3}} \ \text{[K/cm]} \tag{1}$$

where:
T2, T3 - temperature in point 2 and 3, °C,
d_{2-3} – distance between measuring points 2 and 3, cm.

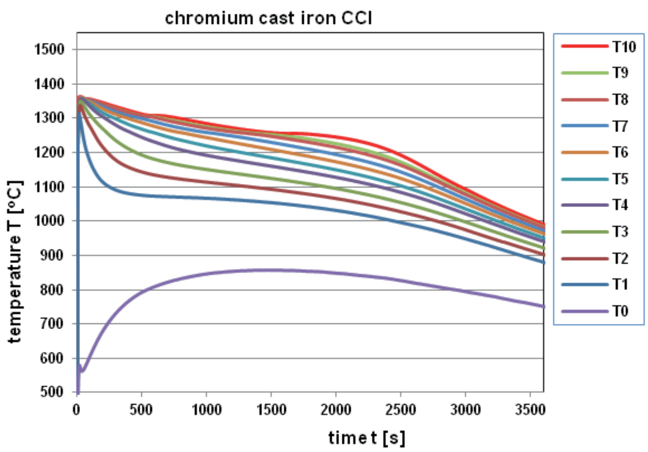


Fig. 3. The cooling curves of studied chromium cast iron CCI

The samples for metallographic studies were cut at 5, 10, 15, 25, 35, 45, 55, 65, 75, 85 and 95mm from the surface (mould) of model casting ϕ 30 mm. The samples to quantitative studies were prepared by grinding, polishing and etching with use of nitrohydrochloric acid. The quantitative studies were made at magnification from 200x to 600x on ten measuring areas for each sample using NIS ELEMENTS BR 3.10 software. This software consists of two applications, first to capture images from the camera and second to calculate of stereological parameters (amount of precipitates, shape factors, length, area and volume, etc.). Typical image processing was based on the extraction of information from color image.

3. The results of studies

3.1. The analysis of temperature gradient on cross-section of model casting

The temperature gradient for the area adjacent to the mould (GT0,5) achieves the maximum value about 700 K/cm and then strongly decreases to about 10 K/cm in direction to thermal centre of casting (GT8,5). On figure 4 temperature gradient curves on cross-section of chromium cast iron model casting only in the range of primary crystallization are presented.

Such a large difference of value of temperature gradient has significant influence on primary structure of casting, mainly on its refinement.

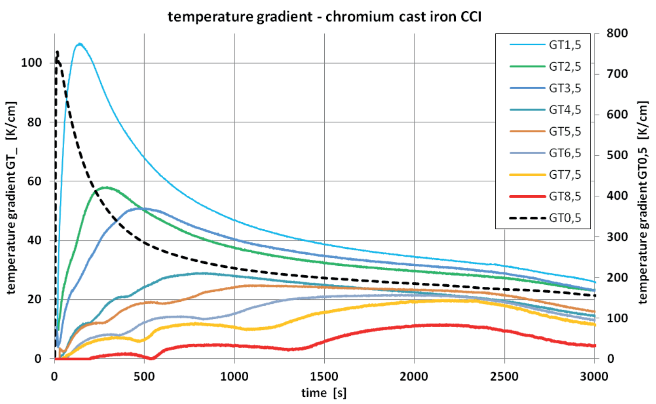


Fig. 4. Temperature gradient on cross-section of studied chromium cast iron CCI

On the basis of temperature gradient curves and characteristic parameters of TDA (Fig.5) graph concerning changes of temperature gradient in the range of primary crystallization on cross-section of model casting in time of its cooling down was developed (Fig.6). On figure 6 were marked curves representing the value of temperature gradient in time of obtaining the liquidus temperature (curve GT_TL), the eutectic temperature (curve GT_TE) and temperature of the end of primary crystallization (curve GT_TH) on selected cross-section of model casting (distance d from the mould surface). In the case of analyzed chromium cast iron in area distant of 35 mm from the surface of mould the temperature gradient does not exceed 35 K/s in the whole range of primary crystallization.

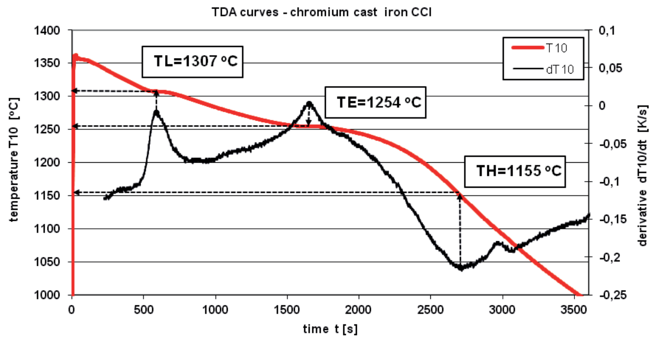


Fig. 5. The TDA curves of studied chromium cast iron CCI

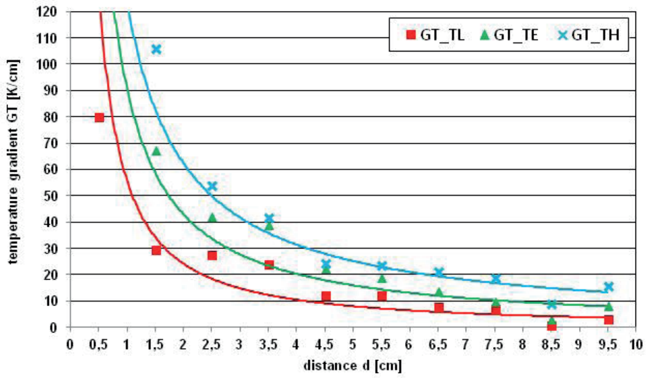


Fig. 6. The change of temperature gradient on cross-section of chromium cast iron CCI in the range of primary crystallization

3.2. The analysis of structure on cross-section of model casting

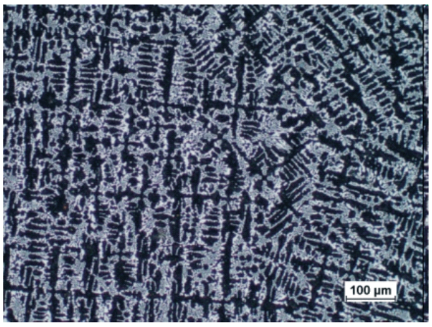
The quantitative description of chromium cast iron structure brought to description of carbide phase similarly as in the work [10]. The results of carbides measurements were used to develop the histograms of amount of carbides belonging to different classes per 1 mm2. Then the obtained histograms were described by following relationship (2) [11]:

$$Na(A) = \frac{U\,Z\,exp\{Z[\overline{lnA} - ln(A)]\}}{\{1 + exp[Z(\overline{lnA} - ln(A))]\}^2} \qquad (2)$$

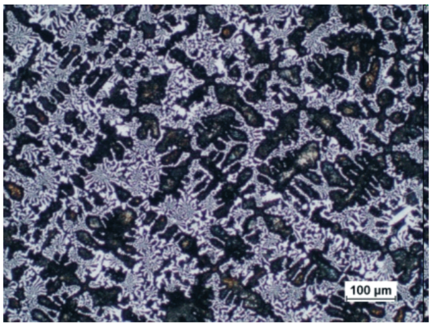
where:
Na(A) – amount of carbides per unit area, $1/mm^2$,
A – area of carbides, μm^2,
U – index of carbides total amount, $\mu m^2/mm^2$,
$\overline{lnA}$ – logarithmic average size of carbides, μm^2,
Z – diversification of carbides size, $1/\mu m^2$.

On figure 7 are presented view of structures in analyzed areas of model casting together with the set parameters U, $\overline{lnA}$ and Z of function, which describes distribution of carbides amount in dependence of their area A. The quantitative analysis of carbides revealed no significant change in the volume fraction of carbides in the casting cross-section (about 24%).

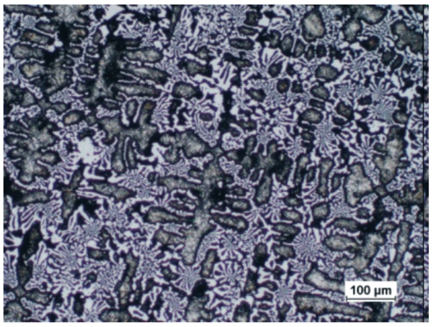
On figure 8 all set functions, which quantitatively describe the carbide phase on cross-section of chromium cast iron casting are presented. Analyzed functions show that there



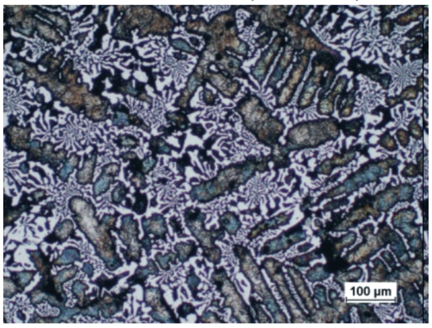
d=0,5 cm
U= 5135 $\overline{lnA}$=2,23 Z=0,93



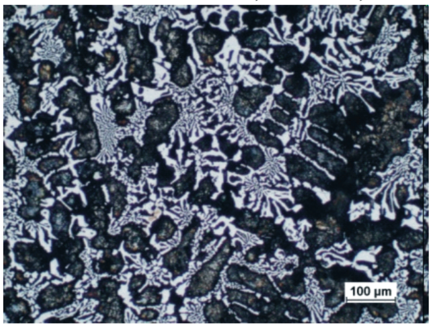
d=1,5 cm
U= 3186 $\overline{lnA}$ =2,64 Z=0,88



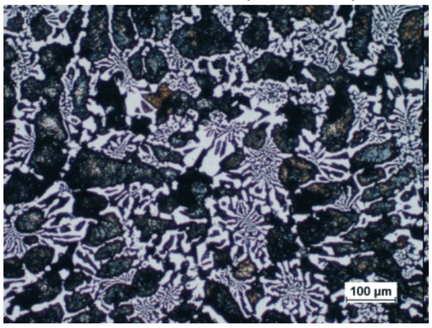
d=2,5 cm
U= 2203 $\overline{lnA}$=2,91 Z=0,87



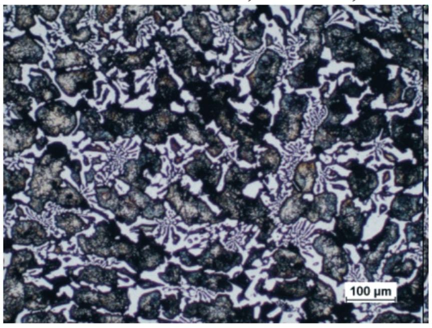
d=3,5 cm
U= 1281 $\overline{lnA}$=3,54 Z=0,92



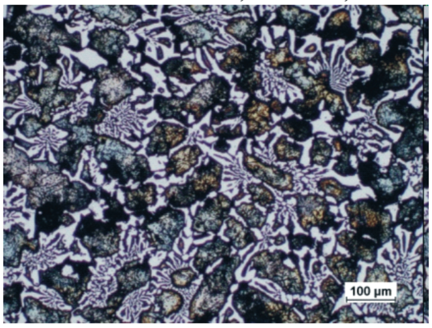
d=4,5 cm
U= 980 $\overline{lnA}$=3,82 Z=0,84



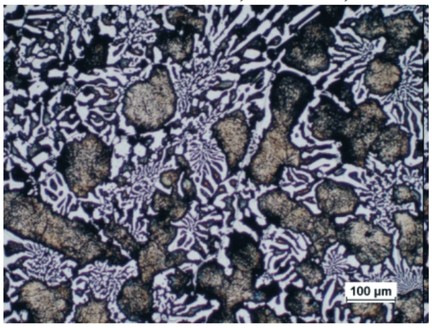
d=5,5 cm
U= 776 $\overline{lnA}$=3,92 Z=0,72



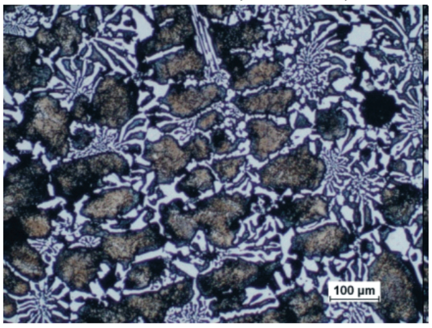
d=6,5 cm
U= 683 $\overline{lnA}$=4,09 Z=0,69



d=7,5 cm
U= 741 $\overline{lnA}$=3,57 Z=0,65



d=8,5 cm
U= 710 $\overline{lnA}$=3,59 Z=0,67



d=9,5 cm
U= 658 $\overline{lnA}$=3,63 Z=0,62

Fig. 7. Structure of chromium cast iron on cross-section of model casting together with value of parameters U, $\overline{\text{lnA}}$ and Z

are decrease of carbides amount and increase of their size in direction to thermal centre of casting.

On figure 9 change in the parameters of function depending on the distance from the mould surface was shown. Significant changes concern the parameter U, which stabilizes its value after falling to about 1000 at a distance of 35mm from the surface of casting. In the same place also stabilizes parameter $\overline{\ln A}$, which is connected to carbides size. The parameter Z describing diversification of carbides size is systematically decreasing, what indicating increasing the dimensional heterogeneity of carbides crystallizing near the thermal center of casting.

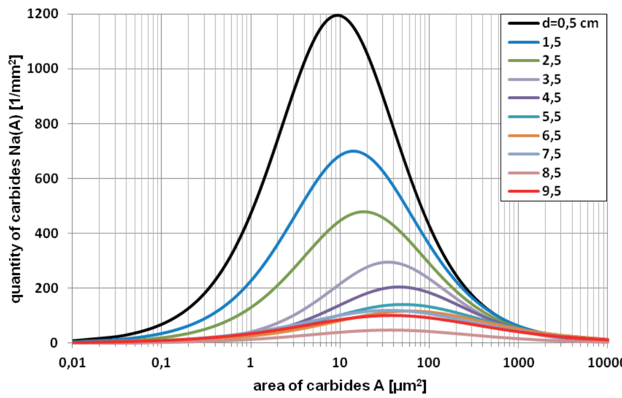


Fig. 8. Distribution function of carbides quantity Na(A) in dependence on their area A

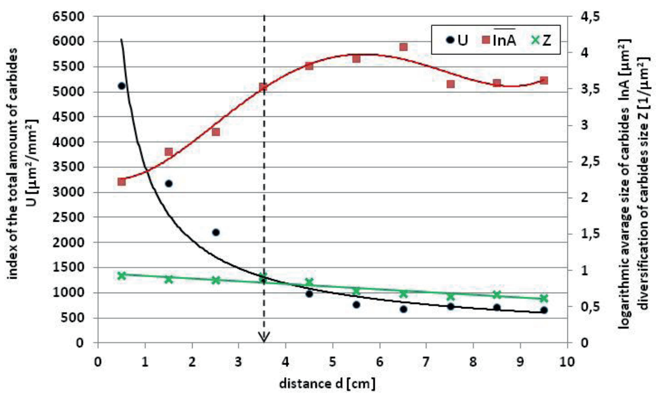


Fig. 9. The change in the parameters U, $\overline{\ln A}$, Z of function Na(A) depending on the distance from the mould surface

3.3. The influence of temperature gradient on structure

In the aim of connection of temperature gradient with stereological parameters of carbides on cross-section of casting, was assumed value of characteristic temperatures of primary crystallization determined on the basis of TDA graph (Fig.5) and corresponding values of the temperature gradient (Fig.6). On the basis of data presented on figure 10 representing the influence of temperature gradient on stereological parameters of carbide phase was affirmed that exists the critical gradient which if exceeded is visible (rapid) refinement and homogenizing of the size of carbides. In the case of studied chromium cast iron the temperature gradient in time of crystallization of primary austenite should exceed about 30K/cm, what result in higher temperature gradient in time of crystallization of next phases (Fig.10a). The extension of critical temperature gradient in time of cooling down of chromium cast iron casting guarantees obtaining a favourable parameters of function of carbides distribution, what results in higher utility properties (Fig.10b, 10c).

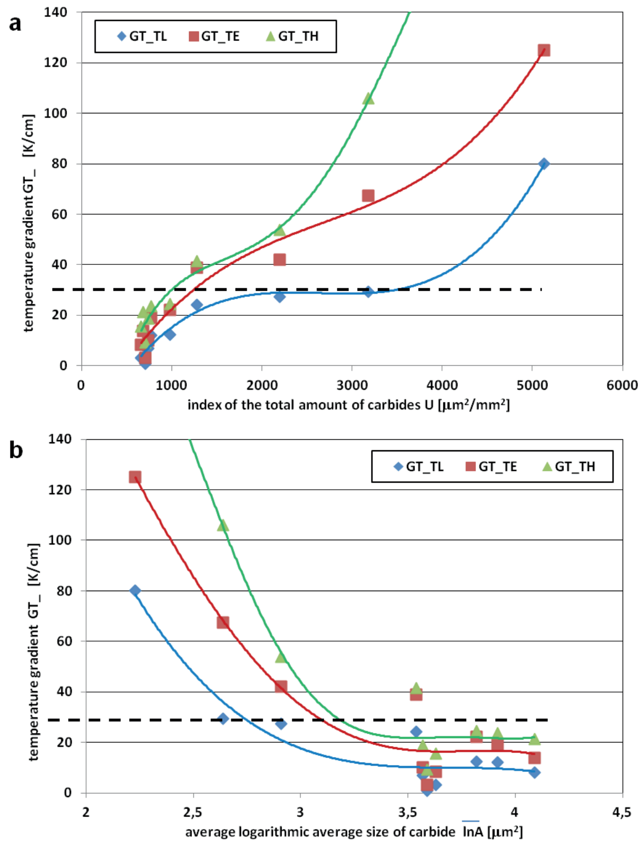


Fig. 10. The parameters U (a), $\overline{\ln A}$ (b) and Z (c) of distribution function of quantity carbides Na(A)and critical temperature gradient in the range of primary crystallization of studied chromium cast iron

4. Conclusions

Based on conducted studies the following conclusions have been formulated:

1. On the basis of TGDA method was affirmed that the eutectic temperature of studied chromium cast iron equals 1254°C.
2. The analysis of temperature gradient shows its strong influence on geometrical parameters of structure. In near surface area of casting high temperature gradient is present, which results in fine grained structure, whereas in thermal center of casting its small value results in coarse grained structure.
3. The change of temperature gradient in the range of primary crystallization has a strong influence on structure on cross-section of studied resistant to abrasive wear resistant chromium cast iron castings. In consequence was affirmed that for studied chromium cast iron exists

critical temperature gradient equals 30K/cm, which if exceeded is rapid change in stereology of carbide phase.

Acknowledgements

The work was made thanks to funding by Polish Ministry of Science and Higher Education as own research and development project No. NR507 0054 10

REFERENCES

[1] W. Sakwa, S. Jura, J. Sakwa, Wear resistance iron alloys. Part I: Cast iron, ZG STOP Publication, Kraków, (1980).

[2] C. Podrzucki, Cast iron, ZG STOP Publication, Kraków, (1991).

[3] D. Kopyciński, M. Kawalec, A. Szczęsny, R. Gilewski, S. Piasny, Analysis of the structure and abrasive wear resistance of white cast iron with precipitates of carbides, Arch. Metall. Mater. **58**, 973-976 (2013).

[4] T. Wróbel, Characterization of bimetallic castings with an austenitic working surface layer and an unalloyed cast steel base, J. Mater. Eng. Perform. **23** (5), 1711-1717 (2014).

[5] J. Gawroński, J. Szajnar, Z. Jura, A. Studnicki, Profesor Stanisław Jura twórca teorii i zastosowań przemysłowych diagnostyki oraz zużycia metali i stopów. Archives of Foundry **4**, 1-74 (2004).

[6] J. Szajnar, Progresses in theory and casting practice, PAN Publication, Katowice, (2009).

[7] A. Studnicki, Badanie procesu krystalizacji odlewniczych materiałów odpornych na ścieranie, Archives of Foundry **2**, 257-264 (2002).

[8] A. Studnicki, The temperature gradient on section of casting in process of primary crystallization of chromium cast iron, Archives of Foundry Engineering **8**, 149-153 (2008).

[9] A. Studnicki, Temperatury krystalizacji żeliwa chromowego w funkcji szybkości stygnięcia odlewu, Archives of Foundry **5**, 371-378 (2005).

[10] A. Studnicki, J. Jezierski, Stereological parameters of carbides in modified wear resistant Fe-C-Cr alloys, 21st International Conference on Metallurgy and Materials, Metal 2012, May 23-25.2013, Brno, Czech Republic, 795-802.

[11] J. Cybo, S. Jura, The functional description of isometrical structures in metallography, Silesian University of Technology Publication, Gliwice (1995).

Received: 20 October 2014.