



Influence of Melt Properties on the Dendritic Structure of Steel Castings

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Abstract

The paper presents the experimental results on the determination of melt parameters such as the energy of the boundary, contact angle, density and kinematic viscosity of low and medium alloy steels at different temperatures, as well as the dispersion of their dendritic structure in solidified castings. The analysis of the data obtained allowed revealing using mathematical models the influence of the chemical composition and temperature of melts on their properties and the dendritic structure of castings. It was established the variation of the melt parameters depending on the particular chemical elements of steels as C, Si, Mn, O, P, V, Cr. The established analytical dependences shown that increasing density and viscosity contributes to the dispersion of the dendritic structure and viscosity is of the major effect. The derived quantitative patterns allows to evaluate structure formation of cast structural low and medium alloy steels.

Keywords: Steel, Chemical composition, Melt, Dendrite, Viscosity, Density, Energy of boundary, Wetting angle, Irregularities, Crystallization

1. Introduction

It is known [1, 2] that the melt properties depend significantly on its chemical composition, temperature and affect crystallization process.

The chemical composition and thermal treatment of liquid steel have a significant effect on the energy of the boundary, viscosity and density of the melt [3-5]. But the analysis of published results shows the inconsistency. For example, in [6] it is presented that V, Cr, P, Si, Al, C decrease the density of liquid iron, W and Ni increase, and Mn has no effect. At the same time, authors in [7] stated that Mn and Ni decrease the density of the melt. It was shown in [8] that the molar volume of iron practically is not changed when alloyed with Cr and significantly decreases with C increase. In [9] it is indicated that an increase of C content in the melt up to 0.4% wt. decreases the density of the iron melt.

The influence of alloying elements and impurities on the energy of the boundary of liquid iron is also controversially estimated.

Thus, it was shown in [6] that Mo, V, Ti increase this energy, while P, C, Si, Mn, N, S, and O decrease it. However, the authors of [10] believe that elements are arranged in a different order in terms of this energy reduce: Ti, V, C, Si, P, Cr, Mn, As. In contradiction with the results in [11], it was shown that C increases, Si and P do not affect, and As, Sn, N, Sb impurities in a different sequence reduce the energy of the boundary.

It was experimentally shown that, depending of the content of alloying elements and impurities in the melt of ternary systems Fe-Mn-Si, Fe-N-Cr, Fe-N-P, Fe-N-Ni, Fe-N-S the effectiveness of their influence on energy of the boundary changes significantly not only quantitatively, but also qualitatively [12].

It was found in [13] that W, Mo, Ti, Nb, Ta, V increase in this sequence, while Si, Cr, Mn, P, As, C decrease the kinematic



viscosity of liquid iron. At the same time, in [7] a different sequence of the elements is proposed, i.e. Ti, V, Nb, Cr, Mo, W increase, and Si, Co, Ni, Mn decrease the viscosity. The authors in [6] believe that the elements in the following sequence change the viscosity of liquid iron, i.e. S, O, N increase and Cr, Si, Mn, P, C decrease its value. The results are confirmed, particularly for C, in the recent research [14]. Molecular dynamics simulations established that increase in C content results in high-temperature viscosity of iron-carbon melts decrease.

The influence of elements becomes even more complicated in the case of ternary, i.e. Fe - C - element [6] or more complex systems. Analysis of the regularities obtained for the influence of C, O, S, P on the kinematic viscosity of melts containing (wt. %) 0.08 - 1.0 C; 0.004 - 0.1 P; 0.002 - 0.06 S; 0.003 - 0.01 O, shows that the elements change the effectiveness of each other's influence not only quantitatively, but also qualitatively.

The given example shows that even in the Fe-C-O-S-P system, which characterizes carbon steel in the first approximation, it is impossible to predict the change in the viscosity of the melts.

This review shows that the experimental results of various authors are difficult to compare and are not predicted for commercial steels.

To determine the quantitative regularity of the influence of elements on the properties of liquid low- and medium-alloyed structural steels in certain temperature and concentration range it seems most rational to systematically study the polytherm properties of structural steels melts, followed by determining the effectiveness of the influence of each factor by the regression analysis.

The influence of liquid metal properties on the primary structure is implemented mainly through a change in the conditions for the nucleation and grain nucleation patterns during casting solidification.

The equations for the analytical description of the rate of homogeneous and heterogeneous nucleation of crystallization centers [15] contain energy of the boundary between the melt and crystal (σ_{l-s}), as well as the diffusion coefficient in the liquid (D_l) and undercooling around crystallization centers (ΔT), which depend on the properties of the melt. In the case of heterogeneous nucleation of crystallization centers contact angle (Θ) between liquid and solid phases is also of importance.

The energy of the boundary between liquid and solid phases (σ_{l-s}) depends on energy of the boundary between liquid and gas (σ_{l-g}) according following equation [16]:

$$\sigma_{l-s} = 0,33 \cdot \sigma_{l-g}, \quad (1)$$

The dependence of the diffusion coefficient (D_l) on the dynamic viscosity of the melt (η) is as follows [3]

$$D_l = \frac{k \cdot T}{6 \cdot \pi \cdot a \cdot \eta}, \quad (2)$$

where a is the radius of the particle, k - Boltzmann's constant.

Undercooling (ΔT) around crystallization centers depends on the concentration Undercooling (ΔT_c) and thermophysical

solidification conditions (ΔT_{tph}), related to melt density (ρ_l) and energy of the boundary between melt and crystal (σ_{l-s}) by the following relationship [17].

$$\Delta T = \Delta T_{tph} + \Delta T_c = \frac{\sigma_{l-s} \cdot T_l}{r \cdot \rho_l \cdot q_{cr}} + \Delta T_c, \quad (3)$$

where r is the nucleus radius; q_{cr} is the specific heat of crystallization, T_l - liquidus temperature of the melt.

At present, the main mechanisms of crystal growth after their nucleation are known as growth by two-dimensional nucleation, growth by means of dislocations, and continuous growth.

Growth patterns during the formation of two-dimensional nuclei on the growing crystal surface are described in [18, 19]. This mechanism can be realized only when there are no dislocations on the crystal surface. Their presence in a crystal significantly increases the crystal growth rate [19, 20]

The continuous growth rate (V_{cg}) is described by Equation 4 [21].

$$V_{cg} = \frac{D_l \cdot \Delta H \cdot \Delta T}{a \cdot k \cdot T_l^2}, \quad (4)$$

where ΔH - heat of melting.

The dependence of alloys structure on their melts properties is noted in [22].

Therefore, the purpose of this work is to study the effect of chemical composition and temperature on the properties of melts of low and medium alloyed steels and the effect of melt properties on the parameters of the dendritic structure of castings after solidification.

2. Methodology

Low- and medium-alloy structural steels of composition wt. %: 0.06-0.33 C; 0.08 - 1.8 Si; 0.2 - 1.82 Mn; 0.2-1.57 Cr; up to 0.24% V; 0.013 - 0.028 S; 0.005 - 0.025 P; 0.0036 - 0.028 O; 0.012 - 0.034 N were used at the experiments and superheated above the liquidus temperature (ΔT) up to 140 °C. They were melted in IST 016 induction furnace with a basic lining with using industrial ferroalloys. The chemical composition of the steels was determined using an SPAS-05 optical emission spectrometer.

Energy of the boundary (σ) and melt density (ρ) were determined by the drop method in the calibrated beryllium oxide cups [23]. The contact angle (Θ) was determined on polished sintered alumina substrates. The kinematic viscosity (ν) was determined by the method of damped oscillations of a crucible filled with melts [23]. Dynamic viscosity (η) was determined by the formula

$$\eta = \nu \cdot \rho \quad (5)$$

The experiments were carried out in a He atmosphere purified from impurities, water vapor, and oxygen using zeolites and a chromium-nickel catalyst at isothermal exposures during 30 min in the cooling mode. The measurement error of energy of the boundary and contact angle was $f \pm 2.5\%$; density $\pm 1.0\%$, viscosity $\pm 5\%$.

The influence of the chemical composition and overheating over the liquidus temperature (Δt) on the selected parameters σ , Θ , ρ , v and η (denoted below as Y_i) of the studied melts was estimated by determining the coefficients (A_i), correlation (R) and average approximation error (δ , %) of the polynomial of the following form

$$Y_i = A_0 + A_C \cdot [C] + A_{Si} \cdot [Si] + A_{Mn} \cdot [Mn] + A_{Cr} \cdot [Cr] + A_S \cdot [S] + A_P \cdot [P] + A_V \cdot [V] + A_N \cdot [N] + A_O \cdot [O] + A_{\Delta t} \cdot \Delta t, \quad (6)$$

where $[C]$, $[Si]$, $[Mn]$, $[Cr]$, $[S]$, $[P]$, $[V]$, $[N]$, $[O]$ are the content (wt. %) of carbon, silicon, manganese, chromium, sulfur, phosphorus, vanadium, nitrogen and oxygen in the melt, respectively.

The effectiveness of the influence (significance) of the factors of the equations was evaluated by the Student's criterion (t_{st}) at 95% probability [24].

To reduce the error in determining the properties of melts at the liquidus temperature the patterns of change in the polytherms of each alloy was studied. Energy of the boundary (σ), contact angle (Θ) and density (ρ) were approximated by a polynomial of the form

$$Y_i = A_{li} + A_i \cdot \Delta t, \quad (7)$$

where Y_i represents σ_i , Θ_i or ρ_i ; A_{li} and A_i are polynomial coefficients. Coefficient A_{li} represents the values σ_i , Θ_i or ρ_i at liquidus temperature.

Kinematic (v) and dynamic (η) viscosity were approximated by the dependences 8 and 9, respectively.

$$v = \frac{1 \cdot 10^{-7}}{A_0 + A_t \cdot \Delta t}, \quad (8)$$

$$\eta = A \exp(E_\eta / (R \cdot T)), \quad (9)$$

where A , A_t and A_0 – polynomial coefficients; E_η - viscous flow activation energy; R - universal gas constant ($R=8.31$ J/(gram atom·K)); T – temperature.

The values of v_l and η_l at the liquidus temperature were determined by the equations 8 and 9, respectively, at $\Delta t = 0$ and T equal to the liquidus temperature.

The study of the selected parameters σ , Θ , ρ , v and η on the parameters of the steels dendritic structure was carried out on transverse sections of castings with a diameter of 20 mm and a length 150 mm.

The castings were obtained by the investment casting at 1600 °C in ceramic molds. The casting model and gating system were preliminary made from paraffin and stearin in the detachable die molds assembled by soldering. Ceramic shell was formed around the model by the conventional procedure of its immersion into suspension of fireproof mixture with binder. After shell hardening the paraffin model was removed by hot water and the shell was inserted into the flask with sand treated at 1000°C and preheated prior steel pouring. Casting was solidified in mould for 7 hours.

The scheme of casting and gating system is depicted in Figure 1. The thermocouple (5) was installed in the center of riser ball

(2) with a diameter of 100 mm. The liquidus temperature of the steels was measured with recording changes of Pt-PtRh (PPR 6/30) thermocouple and four-channel analog input modules WAD-AIK-BUS through the RS-485 interface. The distance from the axis of the riser to the place where the sample was cut was of 70 mm.

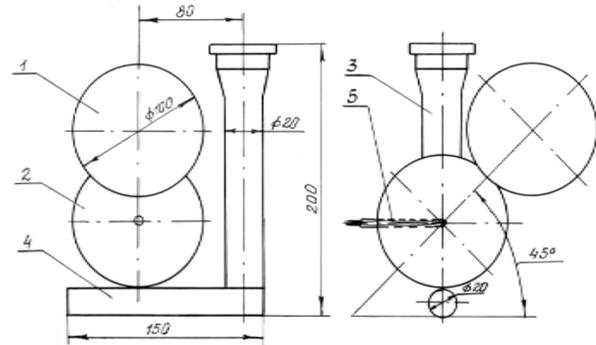


Fig. 1. The scheme of casting and gating system to study the kinetics of castings solidification: 1, 2 – spherical shaped risers (casting heads), 3 – riser, 4 – casting, 5 – thermocouple

The rate of castings crystallization was about $3 \cdot 10^{-4}$ m/s. The dendritic structure was investigated on transverse templates by etching in a reagent containing 10 ml HNO_3 , 30 ml HCl at 100 °C during 10–15 s.

The dendritic length (l_d) and second order branches length (l_2), as well as the secondary dendrite arm space (Δ_2) were determined by analyzing images of the entire cross-sectional area of the castings on a scanning electron microscope JSM-T300 (Jeol, Japan) with image analyzing software "ImageJ". Such parameters were measured in about 60-70 fields of view. Figure 2 shows the most typical fields of each sample. The data given in Table 5 was based on 1255 measurements.

The effectiveness of the influence of the selected parameters σ , Θ , ρ , v and η of melts at liquidus temperature on the average length of dendrites (l_d), l_2 and Δ_2 of the studied steels were estimated by the value of Student's criterion (t_{st}) of the coefficients of the following equation

$$Y_i = A_0 + A_\sigma \cdot \sigma_i + A_\Theta \cdot \Theta_i + A_\rho \cdot \rho_i + A_v \cdot v_i + A_\eta \cdot \eta_i, \quad (10)$$

where Y_i represents l_d , l_2 , Δ_2 ; A_i – polynomial coefficients.

3. Results and discussion

The chemical composition of the studied melts is given in Table 1, the property polytherms are shown in Figure 2. All other parameters as well as coefficients (A_i) of the regression Equation 7 - 9 and correlation coefficients (r_i) are shown in Table 2.

Coefficients (A_i) of the regression Equation 6, multiple correlation (R_i), relative approximation error (δ) and Student criteria (t_{st}) for determining the chemical composition influence on the selected parameters are shown in Table 3.

Analyzing the experimental data it is clear the ambiguity of the direction of influence of alloying elements. S, P, O, Mn naturally increase, and V, Cr, Si decrease the energy of the boundary of the melts. The influence of elements on the contact

angle is similar, except for the insignificant positive influence of P.

At the same time, the influence of elements on the density has a different pattern, i.e. O, Si, V, P and Mn increase, while C and Cr decrease its values.

Even with respect to kinematic and dynamic viscosity, there are different trends. So, if the kinematic viscosity is increased by V and Si, and reduced in the following sequence - O, C, P and Mn, then in the case of dynamic viscosity, other patterns are observed, i.e. V and Si increase, but Cr, P, C, Mn reduce its values.

A more constant influence of overheating above the liquidus temperature is observed. From Figure 2 it can be seen that with an increase of overheating the contact angle increases, and the viscosity and density of the studied steels decrease.

The energy of the boundary varies ambiguously. In the case of steels 4 and 7 (Table 1) the energy of the boundary decreases with

increasing overheating, whereas the other melts show the inverse relationship. This can be explained by the phenomenon of temperature buffering of the energy of the boundary of melts of complex composition [16].

The regular increase of the energy of the boundary with P, O, Mn, as well as its decrease with V, Cr, and Si were revealed. It indicates that the number of atoms or clusters containing P, O, and Mn increases in the volume of the melt, while V, Cr, and Si are placed mainly on the interfacial surface.

This assumption is confirmed by the fact that according to the results of [26], the maximum decrease in the energy of the boundary of iron by oxygen is observed at a content up to $(2 - 3) \cdot 10^{-4}$ % of oxygen, which correspond to the lower limit of the investigated range of element content. It is also noted there that at $2.09 \cdot 10^{-4}$ % oxygen the temperature coefficient $d\sigma/d(\Delta t)$ is negative, then at $3.49 \cdot 10^{-4}$ % it is positive.

Table 1.
The chemical composition and liquidus (t_l) temperatures of the cast steels

No.	Alloy Grade	Content of elements, wt. %									t_l , °C
		C	Si	Mn	Cr	S	P	V	N	O	
1	06L	0.06	0.16	0.30	0.25	0.023	0.005	0	0.012	0.0160	1515
2	06AFL	0.06	0.10	0.25	0.21	0.023	0.005	0.11	0.020	0.0170	1520
3	06AFL	0.06	0.08	0.20	0.20	0.023	0.005	0.21	0.028	0.0280	1525
4	20KhGSAFL	0.21	1.15	1.00	1.00	0.028	0.025	0.09	0.023	0.0049	1491
5	20KhGSAFL	0.20	1.08	1.05	1.12	0.024	0.025	0.19	0.034	0.0068	1498
6	30Kh2G2S2L	0.33	1.75	1.66	1.33	0.012	0.008	0	0.014	0.0036	1480
7	30Kh2G2S2AFL	0.31	1.80	1.72	1.51	0.013	0.009	0.12	0.023	0.0036	1485
8	30Kh2G2S2AFL	0.30	1.80	1.82	1.57	0.013	0.009	0.24	0.032	0.0040	1490

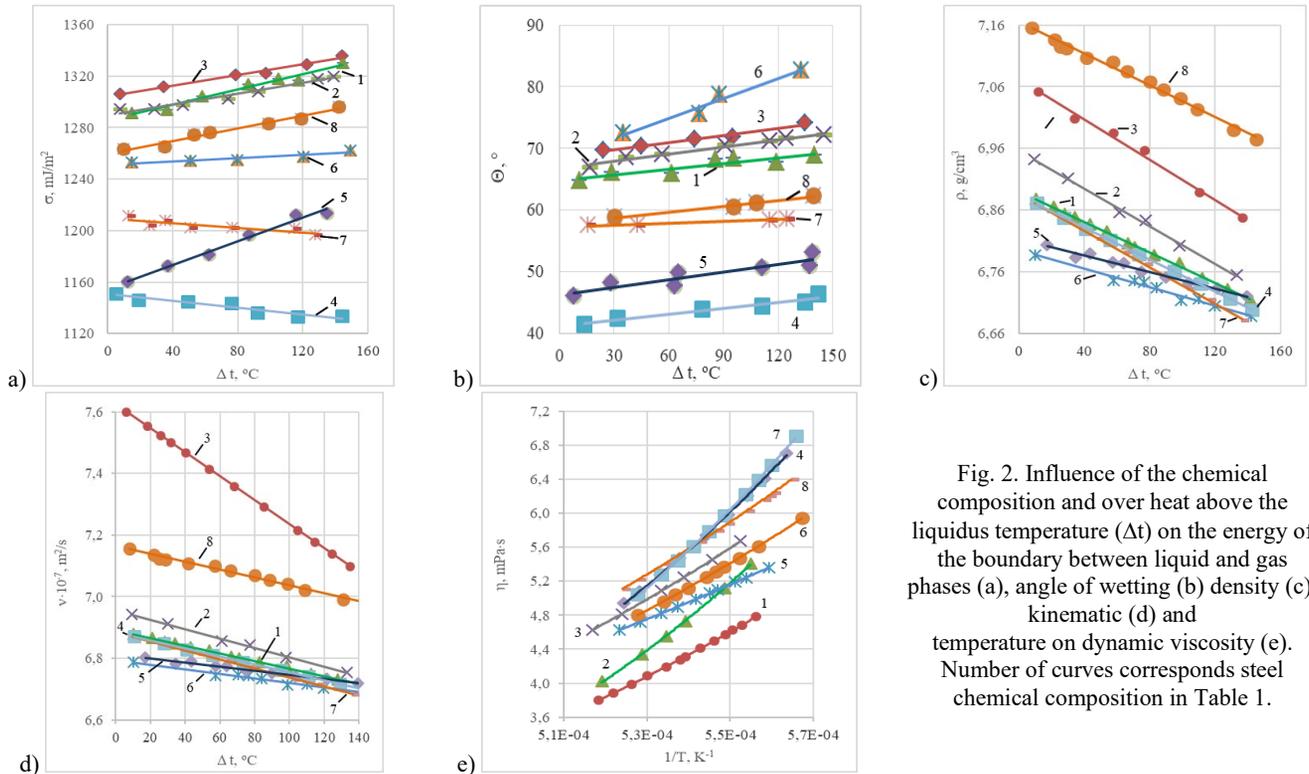


Fig. 2. Influence of the chemical composition and over heat above the liquidus temperature (Δt) on the energy of the boundary between liquid and gas phases (a), angle of wetting (b) density (c), kinematic (d) and temperature on dynamic viscosity (e). Number of curves corresponds steel chemical composition in Table 1.

The study of the element effect shows that V, Cr and Si naturally decrease, while O, C and Mn increase the contact angle (Fig. 2b, Table 3).

The analysis of the element influence (Fig. 2d, e) shows that O, Cr, C, P and Mn naturally decrease melt viscosity, while Si and V increase the melt viscosity of steels (Table 3). The similar effect is observed on the activation energy of the viscous flow, which characterizes the energy of interaction between different layers of the liquid.

Analyzing the results it can be assumed the following mechanism of the influence of alloying elements and impurities on steel properties. They change of the numbers of clusters and the energy of interaction of atoms and microgroups containing various elements between them and iron atoms and clusters (Table 4). As can be seen from Table. 4 the bond energy of the main components of the melt with Fe, excepting Mn, is higher than the Fe-Fe bond.

Consequently, when these elements /i/ are introduced into the melt, excepting Mn, the Fe-Fe bonds will be weakened due to the formation of new stronger Fe-i bonds. These bonds predetermine the possibility of both increasing and decreasing volume of the melt. In this case, the resulting effect will depend on the element distribution and the relative change of the specific volume, cluster density and the disordered melt zone.

Taking into account the established quantitative patterns of changes in the activation energy of a viscous flow (Table 3) it can be noted that Cr, C, P and Mn decrease, whereas Si and V increase the number of active clusters capable to growing.

The analysis of Table. 3 show that the ratio of the influence of elements on the forces of interatomic interaction and the number of active clusters is such that C and Cr naturally decrease, and O, Si, V, P, Mn increase the density of industrial melts.

Table 2.

Values of energy of the boundary (σ), angle of wetting (Θ), density (ρ), kinematic (ν) and dynamic (η) viscosity at liquidus temperature, viscous flow activation energy (E_n), coefficients (A_i) of the regression Equation 7 - 9 and correlation coefficients (r).

No	Energy of the boundary (Eq. 7)			Angle of wetting (Eq. 7)			Density (Eq. 7)		
	σ , mJ/m ²	A_σ	r	Θ , °	A_Θ	r	ρ , g/cm ³	A_ρ	r
1	1286	0.298	0.987	65	0.0303	0.910	6.890	-0.0012	0.999
2	1289	0.212	0.982	67	0.0394	0.986	6.956	-0.0015	0.998
3	1304	0.209	0.992	69	0.0396	0.989	7.071	-0.0016	0.996
4	1151	-0.132	0.948	41	0.0322	0.972	6.884	-0.0013	0.999
5	1155	0.462	0.992	46	0.0420	0.919	6.813	-0.0007	0.990
6	1251	0.066	0.927	68	0.1080	0.982	6.795	-0.0007	0.988
7	1210	-0.093	0.862	57	0.0093	0.982	6.885	-0.0015	0.999
8	1260	0.249	0.987	58	0.0311	0.984	7.164	-0.0013	0.995

Table 2. continued

No	Kinematic viscosity (Eq. 8)				Dynamic viscosity (Eq. 9)				
	A_0	A_t	r	$\nu \cdot 10^{-7}$, m ² /s	A , mPa·s	E_n/R	E_n , J/g at.	r	η , mPa·s
1	0.141	$2.5 \cdot 10^{-4}$	0.996	7.08	0.164	6065	729	0.999	4.87
2	0.125	$3.2 \cdot 10^{-4}$	0.999	7.97	0.053	8317	1000	0.999	5.52
3	0.122	$1.9 \cdot 10^{-4}$	0.999	8.19	0.241	5714	687	0.999	5.79
4	0.100	$2.5 \cdot 10^{-4}$	0.998	10.01	0.083	7785	936	0.999	6.86
5	0.124	$1.5 \cdot 10^{-4}$	0.998	8.04	0.538	4112	495	0.999	5.48
6	0.112	$1.9 \cdot 10^{-4}$	0.998	8.90	0.279	5390	648	0.999	6.04
7	0.097	$2.6 \cdot 10^{-4}$	0.999	10.31	0.064	8281	996	0.999	7.07
8	0.110	$1.8 \cdot 10^{-4}$	0.999	9.06	0.282	5528	665	0.999	6.49

Table 3.

Coefficients (A_i) of the regression Equation 10, multiple correlation (R), relative approximation error (δ) and Student criteria (t_{st}) for determining the chemical composition influence on the selected parameters of steel melts.

Property	Parameter	Independence factors (Critical of the $t_{st(cr)} = 2$)											R	δ , %
		A_0	C	Si	Mn	Cr	S	P	V	N	O	Δt		
Energy of the boundary, J/m ²	A	1071.8	*	-	1066.2	-	*	4540.7	-92.5	*	5528.8	0.1515	0.991	0.54
	t_{st}	48.2		625.4	14.6	420.7	-8.3	5.7	-2.4	7.3	5.3			
Angle of wetting, °	A	25.0	502	-	101.5	-26.9	*	*	-20.5	*	514.0	0.0377	0.996	1.15
	t_{st}	12.6	19.8	143.5	35.4	-5.7			-4.3	6.1	9.7			
Density, g/cm ³	A	6.76	-7.0	0.718	2.45	-2.37	*	21.6	0.961	*	11.3	-0.001	0.995	0.13
	t_{st}	228.6	-27.3	11.1	26.9	-35.0		20.1	18.1	9.08	-32.31			

Kinematic viscosity, m ² /s	A	11.0	-10.8	15.0	-14.3			-100.1	6.21		-40.4	-0.013	0.987	1.54
	t _{st}	37.0	-4.29	19.6	-19.9	*	*	-12.9	11.9	*	-3.79	-32.2		
Dynamic viscosity, mPa·s	A	7.0	-14.9	10.7	-6.89	-2.23		-38.1	4.46			-0.01	0.986	1.67
	t _{st}	51.5	-7.69	18.1	-10.2	-3.67	*	-5.40	16.9	*	*	-28.3		
Viscous flow activation energy, J/gr. at.	A	1965	-11625	4887	-3427	-47.8	*	-30174	23.3	*	*	-	0.740	10.9

* the influence of factors is not significant

The dendritic structures of the investigated steels are shown on Figure 3. The results of numerous measurements of the images above and influence of all parameters derived are summarized in Table. 5 and Table 6.

The analysis of the experimental data given in Table 6 shows that there is no significant effect of energy of the boundary and contact angle on the dendritic structure of steels. This confirms well-known fact that the dispersion of the dendritic structure of industrial steels is mainly determined by the grain nucleation patterns growth.

Table 4.
Energy of chemical bonds of the elements

Element, i	Compound	E _{Fe-i}	E _{i-i}	State
		kJ/mol		
Fe	-	83	83	Solid
Mn	FeMn	76*	57	
Cr	FeCr	87*	79	
V	FeV	105*	103	
Fe	-	75	75	Liquid
O	FeO	139	131	
S	FeS	120	139	
N	Fe ₄ N	106	84	
C	Fe ₃ C	165	245	
P	FeP	110	71	
Si	FeSi	125	139	

* Due to the absence of E_{Fe-i} values in the melt for Mn, V and Cr, their values were calculated in the solid state according to the method given in [27].

The effectiveness of the influence of selected parameters on the dendritic structure is shown in Figure 4.

The data show that with an increase of the density and viscosity of the melts, the dispersion of the dendritic structure increases. In this case, there is a different efficiency of the influence of density and viscosity.

Calculations show that an increase of density at a constant kinematic viscosity leads to a decrease in the length of dendrites and branches of the second order dendrites by 48 and 93%, respectively, and practically does not effect on the SDAS (Fig. 4a).

A change of the melt viscosity at a constant density has a more significant effect on the dendritic structure of steels. With an increase in both dynamic and kinematic viscosity within the studied limits there is a decrease in the length of dendrites and branches of the second order of dendrites in 3.1-3.2 and 2.1-2.2 times, respectively, and the distances between the branches of the second order of dendrites in 2.1-2.2 times (Fig. 4b, c).

Analysis of undercooling in front of a growing crystal (Eq. 3) and the growth rate of the solid phase shows that significant factors (density and viscosity of melts) have an ambiguous effect on the dendritic structure.

For example, density increasing leads to a decrease of undercooling in front of a growing crystal (Eq.3), which, in the case of dendritic growth with the formation of two-dimensional nuclei on its surface, should be accompanied by a decreasing of the growth rate. In the case of the presence of dislocations in the crystal or with continuous growth (Eq.4) the rate increases.

In addition, the density effects the dynamic viscosity, which determine the diffusion mobility of the elements in the melt (Eq.2).

The dynamic viscosity increasing is accompanied by a decrease of the element diffusion mobility in the melt (Eq. 2) and, as a result, creates prerequisites for a decreasing of the growth rate of dendrites, both in the case of the presence of dislocations in the crystal and during continuous growth (Eq. 4).

The effect of viscosity increases with a decrease of the dendrite sizes mainly due to reduction of the diffusion mobility of elements in the melt, directly proportional to the growth rate of crystals, both by the dislocation mechanism and by the mechanism of continuous growth.

A decreasing of the element diffusion mobility in a melt with an increasing of viscosity is, apparently, one of the factors that leads to a decreasing of the SDAS. In this case the process of transition of atoms from a liquid to a solid state slows down and the growth rate of dendrites decreases.

Difficulty in the formation of new layers, a changing of viscosity or diffusion leads to a change in the shape of the growing crystal and the space in which the movement of atoms is possible. This is accompanied by the growth of branches in the perpendicular direction [28]. It was shown in [19] that the SDAS is directly proportional to the diffusion mobility of elements between the branches.

In the results of the performed experiments, it is believed that the effect of the properties of liquid industrial steels on the characteristics of the dendritic structure of castings is mainly associated with a change of the dynamic viscosity of the melts.

The high values of average relative approximation error (δ) are due to the fact that the article does not consider the influence of the chemical composition on the concentration undercooling, the heat of crystallization and the thermal conductivity of the solidified metal, which also has a significant effect on the formation of the dendritic structure of steel castings and requires a separate study.

4. Conclusions

Considering that the equations describing such determining parameters of crystallization as the rate of nucleation of centers and the linear rate of crystallization include the characteristics of energy of boundary, contact angle, density and viscosity of the melt, it was studied the influence of the chemical composition of cast low- and medium-alloyed structural steels on these selected parameters.

The analytical patterns of their changes for the typical content of alloying elements and impurities in steels were established. The relative error of calculations is of 0.13-10.9%.

According to the degree of increasing influence, the elements are arranged in the following sequence:

- energy of the boundary is increased by P, O, Mn and decreased by V, Cr and Si;
- the contact angle is increased by O, C, Mn and decreased by V, Cr and Si;
- the density is increased by O, Si, V, P, Mn and decreased by C and Cr;
- kinematic and dynamic viscosity increase Si and V, and O, Cr, C, P and Mn decrease;
- the activation energy of the viscous flow is increased by Si and V, and decreased by Cr, C, P and Mn.

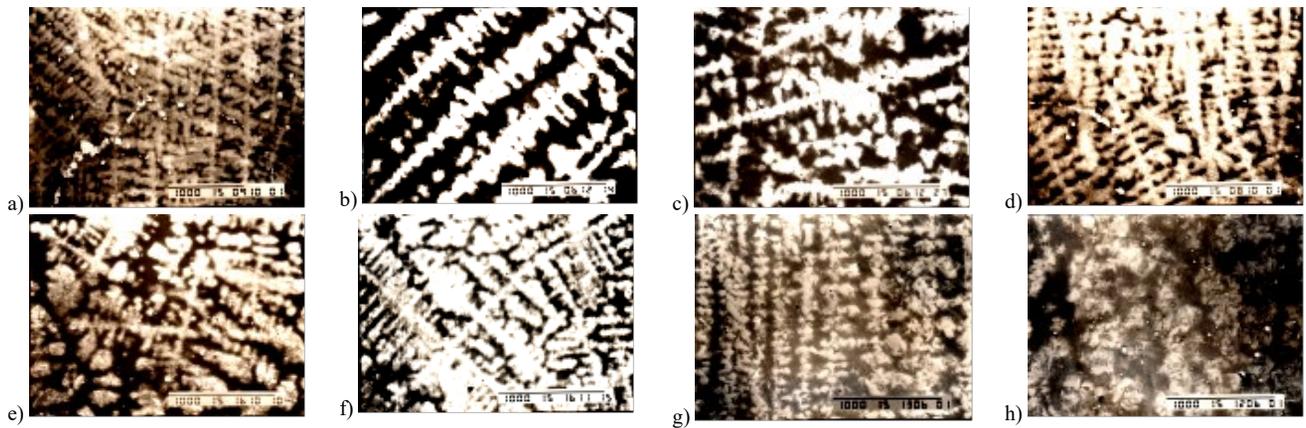


Fig. 3. Dendritic structure of the investigated steels:

a - 1; b - 2; c - 3; d - 4; e - 5; f - 6; g - 7; h - 8. Numbers correspond the chemical composition according Table 1.

Table 5. Maximum, minimum and average values of primary arm length (l_1), length of secondary order branch (l_2) and SDAS (Δ_2)

No.	Kind of value	μm		
		l_1	l_2	Δ_2
1	Minimum	1181	85	46
	Maximum	2564	608	253
	Average	1813	257	114
2	Minimum	841	85	48
	Maximum	2782	750	289
	Average	1712	282	126
3	Minimum	856	67	67
	Maximum	2592	543	251
	Average	1608	217	145
4	Minimum	842	132	61
	Maximum	1777	558	240
	Average	1283	256	116
5	Minimum	721	64	31
	Maximum	1238	486	214
	Average	1023	209	89
6	Minimum	683	73	43
	Maximum	2081	735	140
	Average	1257	278	83
7	Minimum	1125	55	43
	Maximum	1821	420	196
	Average	1435	164	96
8	Minimum	152	29	24
	Maximum	474	177	108
	Average	292	80	49

By analyzing the dependence of the main characteristics of the dendritic structure of castings from the physical properties of the melt, analytical dependences have been established, according which the increasing of density and viscosity contributes to the dispersion of the dendritic structure. In this case, the influence of melt viscosity is most significant. The relative error of calculations is 9.2 - 13.3%.

The established quantitative patterns make it possible to comprehensively evaluate and purposefully control the process of formation of the dendritic structure of cast structural low- and medium-alloy steels. This is of great importance for the developing new class of steels attractive to wide application in machinery.

Table 6.

Parameter and t_{st}	Factors						R	δ , %
	A_0	σ_1	Θ_1	ρ_1	ν_1	η_1		
l_d , micron	366262	*	*	53496	$4.32 \cdot 10^{11}$	-62845	0.911	13.3
t_{st}	-3.74			3.49	3.59	-3.6		
l_2 , micron	-35981	*	*	5278	$4.41 \cdot 10^{10}$	-6426	0.906	10.9
t_{st}	-2.37			2.37	2.52	-2.53		
Δ_2 , micron	-26504	*	*	3868	$3.06 \cdot 10^{10}$	-4443	0.909	9.2
t_{st}	-4.04			4.06	4.08	-4.09		

*- the influence of factors is not significant (Critical $t_{st(cr)} = 2.36$)

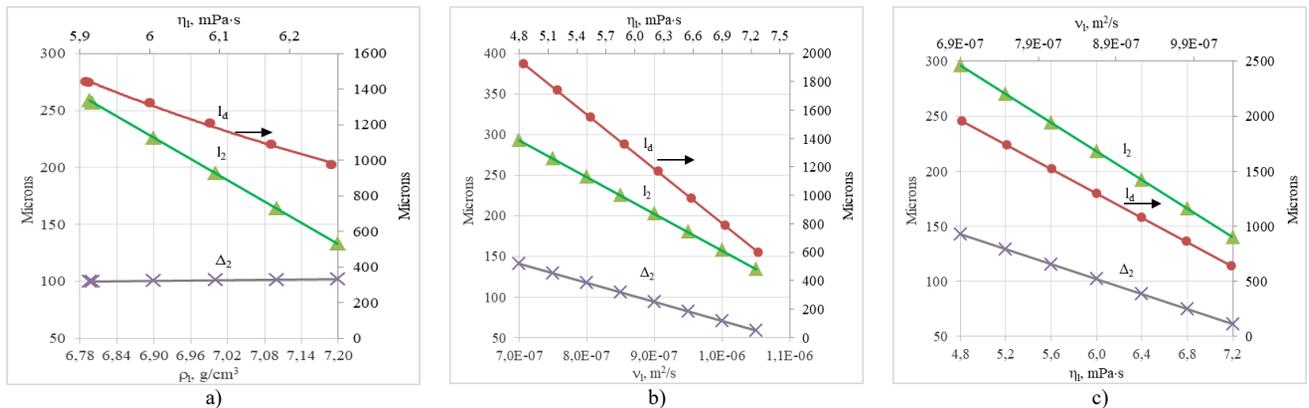


Fig. 4. Influence of the of density (ρ), kinematic (ν) and dynamic (η) viscosity at liquidus temperature on the primary arm length (l_d), length of secondary order branch (l_2) and SDAS (Δ_2) of the investigated steels, according with equation 10.

Coefficients (A_i) of the regression equation 10 are shown in Table 6.

a - kinematic viscosity (ν) is constant and equal to $8.695 \cdot 10^{-07} \text{ m}^2/\text{s}$; b, c - density (ρ) is constant and equal to $6.93 \text{ g}/\text{cm}^3$

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