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ELABORATION OF HIGH QUALITY STRUCTURAL STEELS

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Abstract. On the basis of complex analytic and experimental studies of processes of crystallization from liquid state and recrystallization basic physical-chemical and phase parameters of structural steels, containing up to 0,4 wt.% C; 3% Si, Mn and Cr; 0,035% N; 0,3% V, were defined and qualitative regularities of their influence were established. These regularities give possibility to forecast analytically chemical compositions and conditions of heat treatment of castings and forgings of structural steels with required combination of casting and mechanical properties, hardenability, fatigue strength, cold resistance, toughness of destruction, abrasive wear resistance, heat stability and stability to reverse temper brittleness. The results of investigations implemented have shown, that low- and medium-alloy by manganese, silicon, and chromium structural steels in combination with nitride-vanadium hardening possess essential potential of physical-mechanical properties, which is realized at complex optimization of their chemical composition, deoxidization, types and conditions of heat treatment. The influence of these factors is so extreme and ambiguous that can be effectively optimized only by machine experiment of determined dependencies, presenting themselves as theoretical basis of computer metallography of structural steels. Study of many structural steels shows, that computer elaboration of their chemical composition, conditions of deoxidization and heat treatment ensure the creation new class of cost - efficient alloy steels with unique combination of strength, plastic and exploitation properties. Some examples of optimum heat treatment regimes of castings and forgings for a achieving such properties are presented.

Key words: structural steel, chemical composition, heat treatment, mechanical properties, hardenability, fatigue strength, cold resistance, toughness of destruction, abrasive wear resistance.

Introduction

The accumulated practical experience shows, that it's possible to improve quite effectively the properties of cast steels by complex optimization of alloying, modifying and heat treatment . However it requires the significant volume of experimental work. Herewith the most rational combination of the expenditure of alloying and modifying elements and the level of property improvement is not always achieved.

Formulation of problem

In the considerable number of studies separate aspects of the value of alloying and modification parameters, and heat treatment in the forming of structure and properties of parameters, and heat treatment in the forming of structure and properties of structural steels are viewed, but the publications on complex mathematical model of their optimizations are absent.

Analysis of recent research results

The known results of mathematical modeling present, as a rule, statistical processing of experimental data and characterize basically the influence of chemical composition and conditions of production on some parameters of phase transformations, structure and properties. These dependencies are not sufficient for the optimization of cast steel properties, because they give information just on quantitative influence of one or another factor on the function of response and do not explain the substance of such an influence. Such algorithms reflect the achieved level of foundry production, but do not provide the effective search of new optimum solutions for many-sided industry environment.

The next step in managing the process of the forming of structural steel properties should be the transition from formal regressive dependencies chemical composition - steel properties to the equations, which include structure parameters in initial factors .These parameters depend on chemical composition, conditions of solidification and regimes of heat treatment. Therefore the purpose of present work is to establish quantitative regularities of the influence of structural parameters on such basic properties of cast structural steels, as fluidity (castability), shrinkage (contraction), crack stability, tensile and yield strength, relative elongation and narrowing, hardenability, cold-resistance, fatigue strength and abrasive wear-resistance.

Results of research

As the object of studies the most widely used in industry carbon, low - and medium-alloy steels, containing up to 0,4 % of carbon, up to 3 % Si, Mn, Cr, up to 0,3 % V and 0,03 % N were chosen.

Quantitative laws, at probability more than 95 %, we approximated by polynomes of the first and higher degrees.

Coming from the fact, that casting properties of steel are defined basically by physical properties of a melt, heat-power conditions of solidification and dispersity of forming dendrite structure , we have established, that:

- castability with correlation factor 0,637 and error 13,8% is determined by properties of liquid metal, heat conduction of steel at temperature of solidus, crystallization heat, dispersity of dendrite structure and value of superheat of melt over temperature of liquidus; - density with correlation factor 0,709 and error 1,2% with an exception of crystallization heat and in addition to parameters, indicated for castability is defined by interval of crystallization;

- foundry contraction and its components with correlation factor from 0,828 to 0,993 and error from 0,18% to 9,6% are defined by value of superheat over temperature of liquidus, crystallization heat, heat conduction of steel at temperature of solidus, dispersity of dendrite structure and alloying degree of austenite;

- characteristics of crack stability, determined on a specially developed unit (Fig. 1), including temperature boundaries of interval of heat-brittle and deformation in it, pressure and relative elongation of crack formation, with correlation factor from 0,72 to 0,989 and error from 0,7 to 26% are defined by parameters of foundry contraction, dispersity of dendrite austenitic structures.

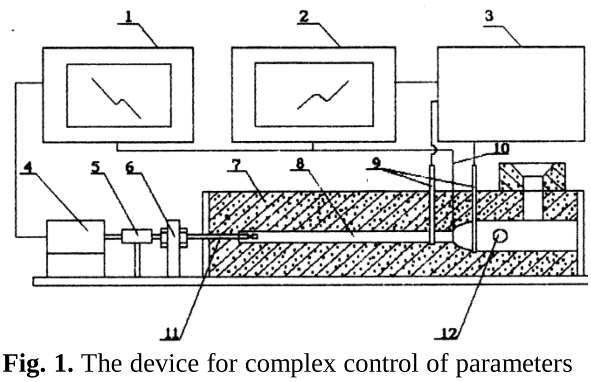

Fig. 1. The device for complex control of parameters of cracks formation in cast steels.

1,2 - potentiometers; 3 - measuring bridge; 4 - transformer of linear deformation in electric potential; 5 - indicator of linear deformation; 6 - elastic plate ; 7 - damp - sand-clay mould; 8 - casting; 9 - electrodes; 10 – thermo-couple; 11 - tie rod; 12 - bolts for one- side braking of casting contraction.

The analysis of influence of C, Si, Mn, Cr, N and V shows, that the most essential influence renders N and V (Fig. 2, 3).

As a result of investigation of physico-mechanical properties of steels the following dependencies were determined:

- hardenability with correlation factor 0,981 to 0,934 and error 12.8% - on the size of austenite's grain and alloying degree of austenite;

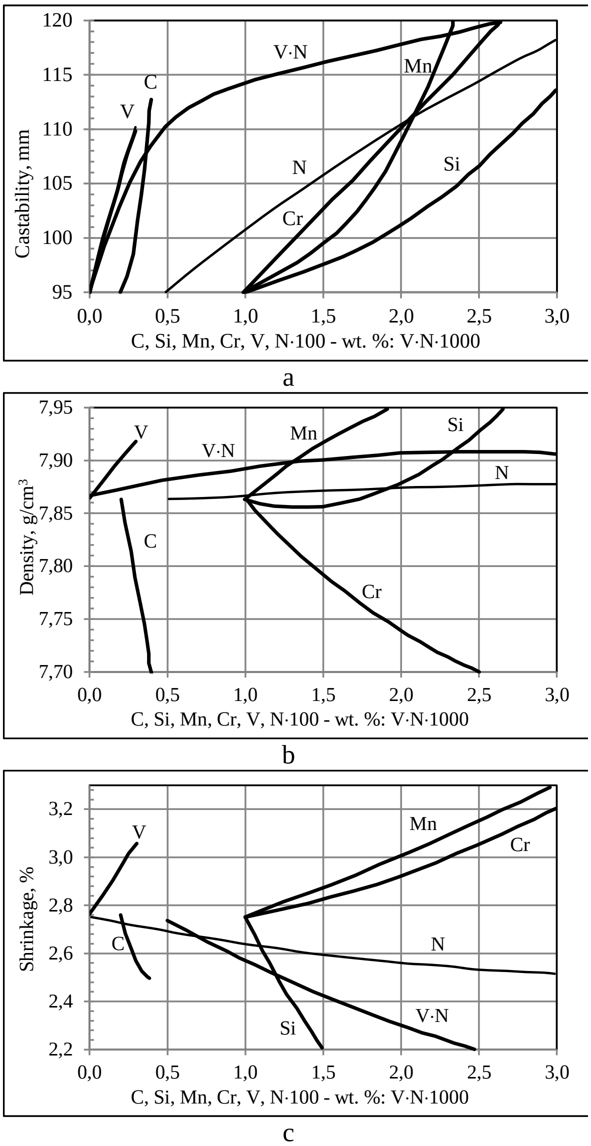

Fig. 2. The influence of contents of elements on the castability (a), density (b) and casting shrinkage (c) of steels.

The pouring at 1550ºC. The base is - steel containing 0.2%C, 1Si, 1 Mn, lCr.

-strength, plastic properties and impact toughness high temperature tempering of steels with correlation factor from 0,824 to 0,934 and error from 5,32% to 12,3% - on the size of austenite's grain and content of nitride-vanadium phase in it, alloying degree of ferrite, solubility and diffusion mobility of carbon and nitrogen in it, quantity of precipitated carbide and nitride phases;

-characteristics of cold-resistance at temperatures to - 60 °C, including ultimate tensile strength and fluidity, relative elongation and narrowing, micro destruction resistance and coefficient of pressure intensity in crack's orifice, with correlation factor from 0,779 to 0,981 and error from 5,02 to 18% - on diffusion mobility of carbon and nitrogen; temperature of brittleness with correlation factor 0,934 and error 12,5% in addition to above parameters - on the size of austenite's grain, content of nitride-vanadium phase in it and of carbon and nitrogen - in ferrite, value of energy of binding of dislocations with interstitial atoms and atoms of formation of new surfaces in ferrite and on grain's boundaries, as for work on crack formation, in addition, - on the size of austenite's grain and alloying degree of ferrite by elements of substitution; work on crack spreading - on content of nitride - vanadium phase in austenite;

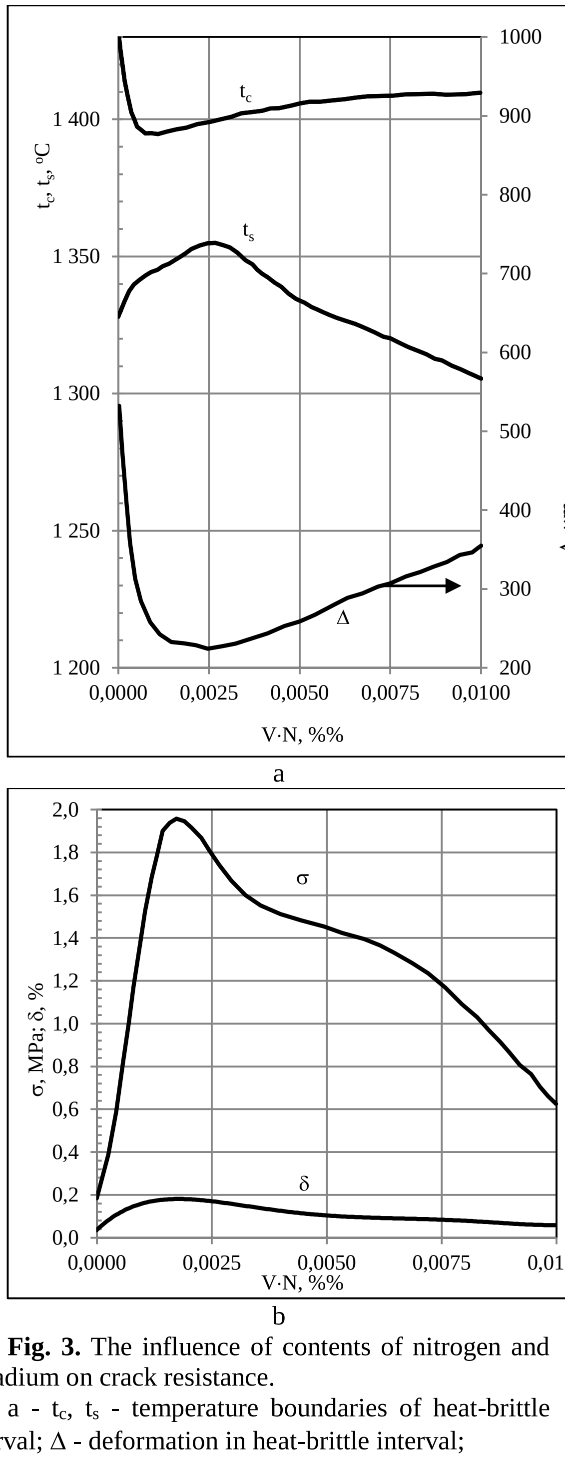

Fig. 3. The influence of contents of nitrogen and vanadium on crack resistance.

a - t_c, t_s - temperature boundaries of heat-brittle interval; Δ - deformation in heat-brittle interval;

b - σ, δ - stress and relative elongation of crack formation, accordingly.

The pouring at 1550 ºC. The base is - steel containing 0.2%C, 1Si, 1 Mn, lCr.

-the number of cycles of fatigued crack formation in normalized steels with correlation factor 0,707 and error 2,31% - on the content of carbides in ferrite at temperature of ending of diffusion disintegration of austenite, the number of cycles of spreading, with correlation factor 0,704, error 7,2% - on the content of vanadium nitrides in ferrite, alloying degree and energy of binding of dislocations with interstitial impurities, formation of new surface in ferrite and on its boundaries. In case of high temperature tempering the process of formation of fatigued cracks is determined by such characteristics of secondary structure, as alloying degree of ferrite, solubility of carbon and nitrogen in it and their diffusion mobility. As for spreading, in addition, - by the size of austenite's grain and content of nitride-vanadium phase in it with correlation factor from 0,887 to 0,888 and error from 3,72 to 9,6%;

-abrasive wear-resistance of hardened and low-tempered steels with structure of martensite with correlation factor 0,854 and error 10,6% - on alloying degree of solid solution, length of martensite's needles and content of nitride- vanadium phase. In case of high temperature tempering steels with correlation factor 0,754 and error 18,3% - on homogeneity of distribution and dispersity of carbide and nitride-vanadium phases;

- the characteristics of heat resistance, including mechanical properties, characteristic of destruction at increased temperatures, parameters of creep and long-term strength with factors of correlation from 0,734 to 0,962 and error from 11,6 to 18,6 % - on influence of alloying elements on solubility and diffusion mobility of carbon and nitrogen at temperatures of high temper and exploitation, determining dispersity and uniformity of precipitation carbide and nitride phases at heat treatment and their stability to coagulation in conditions of creep;

- the resistance to development of convertible tempered brittleness with factor of correlation 0,729 and error of 13,5 % - on the contents of phosphorus on borders of ferrite grain and intergrain energy of formation of new surface.

The analysis of influence of elements on physical-mechanical properties of structural steels shows, that the most essential action renders the microalloying of steel by nitrogen and vanadium (Fig. 4-8), which is connected with their effective influence on thermo - kinetic parameters of phase transformations during formation of secondary structures, stabilization of austenite's of grain at austeniting heating and development of chemical heterogeneity.

The nitride - matrix interfaces and zones of a stressed state near nitride particles are so effective drains of the interstitial elements and vacancies with sudstitutional elements, interacting with them, as well as with places of segregation of a carbide phase that in the event of rational microalloying by nitrogen and vanadium we practically attain the considerable dispersity of microstructure elements, reduction of the chemical and structural nonhomogeneity, including the grain boundary one.

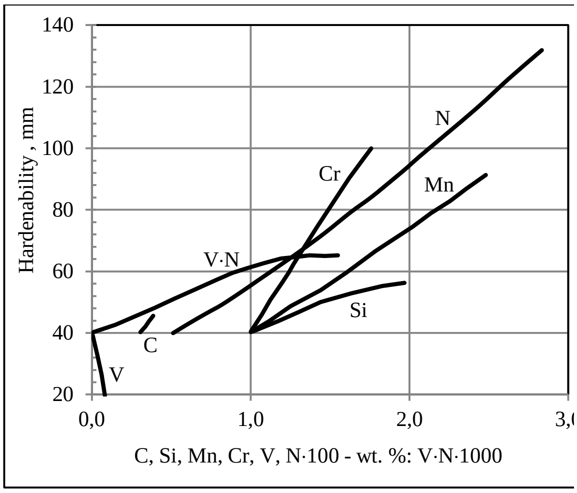

Fig. 4. The influence of contents of elements on the hardenability of steels The face hardening from 950 ºC;

The base is - steel containing (wt.%):

0.3C, 1Si, 1Mn, 1Cr.

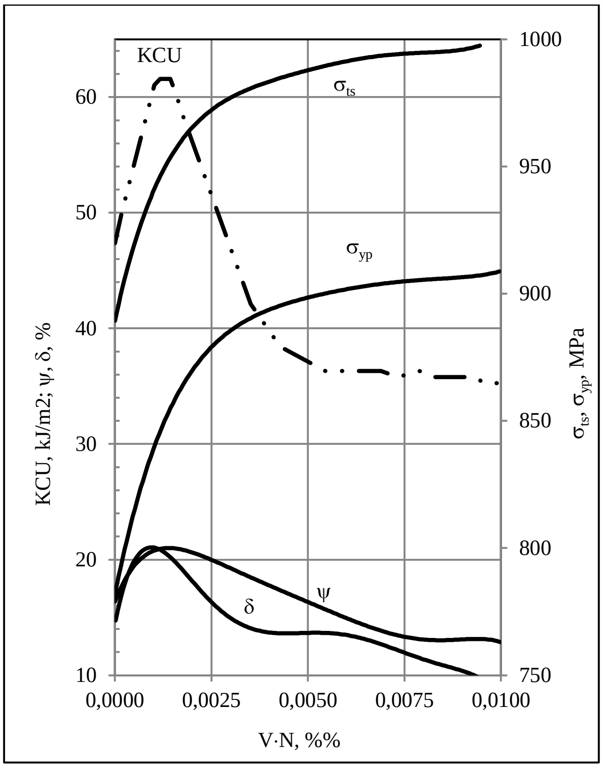

Fig. 5. The influence of nitrogen and vanadium contents on mechanical properties of steels after hardening from 950 ºC and tempering at 650 ºC during 2 hour.

The base is - steel containing 0.2% C, 1 Si, 1 Mn, l Cr.

Taking into consideration the predominant precipitation of vanadium nitride in solid solution , in comparison with other phases, new principles of optimization of alloying, deoxydation and heat treatment of cast structural steels have been elaborated. On the basis of these principles the cast carbon- and low-alloy steels, containing nitrogen and vanadium, with yield strength increased by 80-120 MPa in normalized and by 200 - 300 MPa in quenched and tempered states, without decrease of plastic properties, with fatigue limit increased by 100 - 120 MPa, have been developed (Table 1).

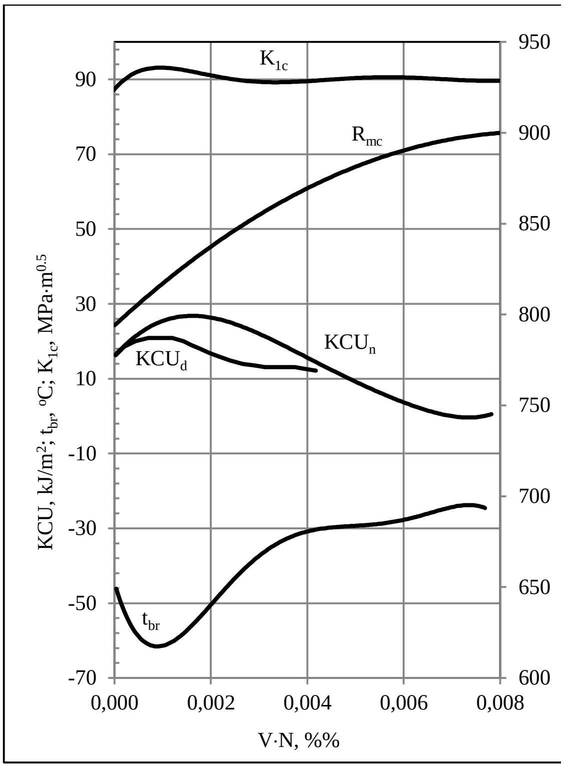

Fig. 6. The influence of nitrogen and vanadium on the cold - resistance of steels at minus 60 °C.

The base is - steel containing 0.2% C, 1 Si, 1 Mn, l Cr.

Table 1. Mechanical Properties of Carbon and Low-Alloy Structural Steels[1]

C	Si	Mn	Cr	σ_{ts}	σ_{ys}	δ	ψ	KCU
Wt., %				MPa		%		MJ/m^2
0.26	0.36	0.62	0.10	573[2] 632 595[3] 800	299 392 350 629	28 28 19 18	49 59 52 48	0.69 0.75 0.76 0.50
0.40	0.37	0.65	0.30	1300[4] 1765 1220[5]/ 1600 760[3] 870	- - - 560 795	0.6 0.8 2.0 3.0 12 14.0	0.5 0.9 4.0 5.0 43 44	0.15 0.23 0.17 0.25 0.70 0.90
0.30	0.30	0.60	0.90	560[2] 724 636[3] 985	390 475 540 865	17 17 12 14	34 36 34 43	0.4 1.4 0.46 0.70
0.23	0.35	1.05	0.22	567[2] 665 675[3] 840	375 445 496 725	22.5 23.0 18.0 18.5	- 36.0 43.5	0.70 0.80 0.65 0.72

1 - the numerator shows the properties of steels without additions and the denominator shows the properties of steels after modifying by nitrogen and vanadium; 2 - normalizing; 3 - hardening + high - temperature tempering; 4 - hardening; 5 - hardening + low - temperature tempering.

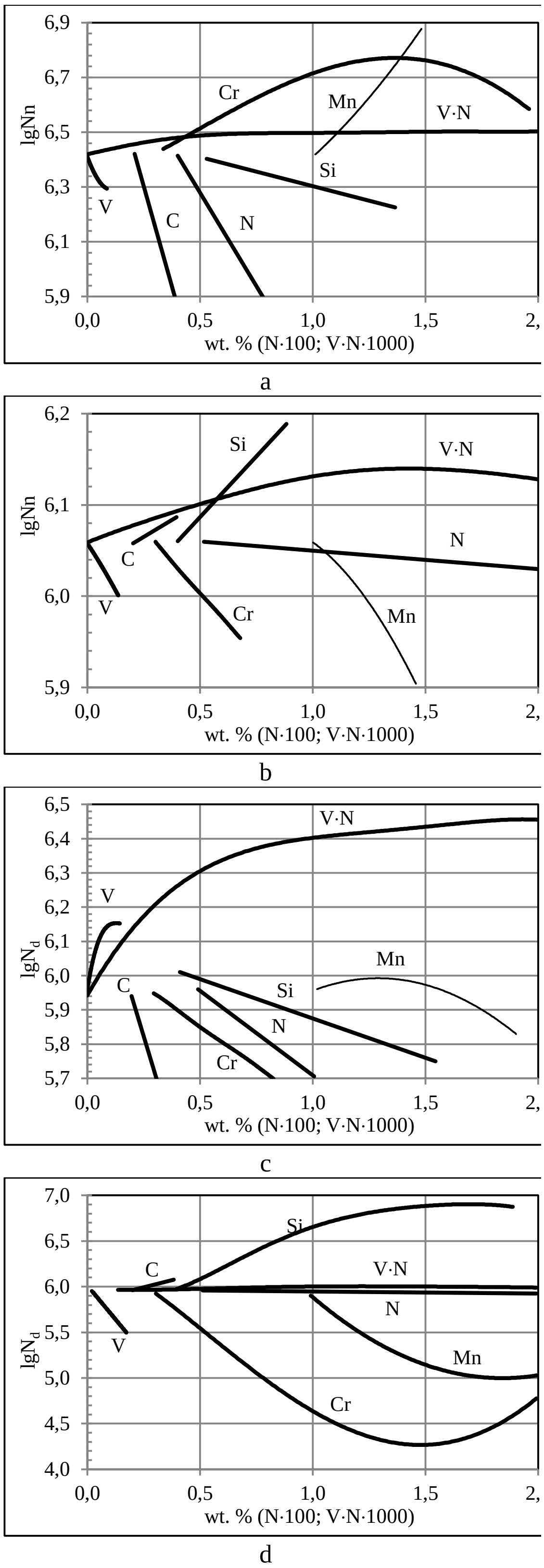

Fig. 7. The influence of element contents on the process of nucleation (a, b) and distribution (c, d) of fatigue cracks in normalized above-spring beams at load force 0.2MN (a, c) and high temperature tempering automatic coupling bodies at load force 0.15MN (b, d) of freight cars.

The base is - steel containing (wt.%):

0.2C, 0.4Si, 1Mn, 0.3Cr.

Normalization and hardening at 950 ºC;

Tempering at 650 ºC.

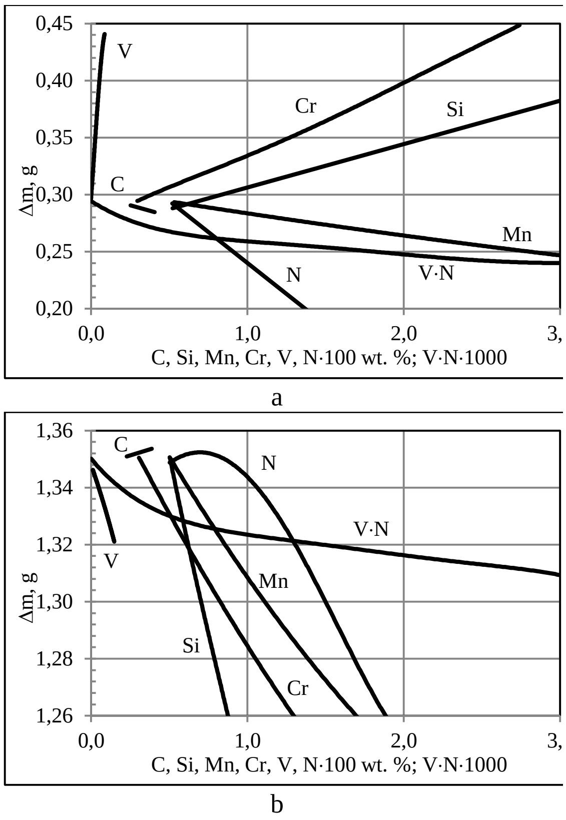

Fig. 8. The influence of contents of elements on the abrasive wear-resistant of steels in unfastened sand

a – Hardening at 950 ºC; Tempering at 350 ºC.

b – Hardening at 950 ºC; Tempering at 650 ºC.

The base is - steel containing (wt.%):0.2C, 0.5Si, 0.5Mn, 0.3Cr.

Speed movement of a sample – 0.385 metre/second. Pressure – 0.2 MPa. Time of friction – 1 hour.

For example, low - alloy Cr, Mn, Si steel, containing N and V, destined for the manufacture of automatic coupling bodies, above-spring beams and lateral frames of freight cars, guarantees the following level of properties: σ_{ts} >840 MPa; σ_{ys} >700 MPa; δ>10 %; ψ>25 %; KCU^{-60}>0.25 MJ/m^2; K_{Ic}^{-60}>100 MPa·m$^{0\ 5}$. The stability of reproduction of mechanical properties of steels, containing V and N is increased in 2-3 times as much.

The optimization of the process of the production of structural steels with nitrogen and vanadium gives possibility to reduce the content of alloying elements for achievement of required operational properties of castings. For example, low - alloy chromium steels, containing N and V, are successfully applied for the production of fittings for oil and gas wells instead of steel,

alloyed by 1-5% Cr and .2-.5% Mo and have, after heating during 100000 hours at 500 - 550 °C long-term rupture-strength of 150 and 70 MPa accordingly, and wear resistance higher than the Hadfield steel. Manufacturing of caterpillar links and tractor rolls of such steels instead of the Hadfield steels and carbon steel, containing 0.12% V, ensure the increase of wear resistance accordingly 1.9 and 2.4 times as much (Table 2).

Table 2. Exploitation test of agricultural tractors

Type of roll strengthening	Accrued operating time, motohours	Wear, mm	Average rate of wear, 10^{-3} mm/ motohour
Serial rolls of carbon steel containing 0.45-0.50% C and 0.07-0.15% V	5000	14.0	2.80
Surface borading of rolls by boron carbide	6500	12.1	1.85
Bimetallic rolls with surface layer of wear-resistant cast iron, containing 16% Cr and 2% Mo	3000	4.2	1.40
The rolls of steel (30ХАФЛ) containing 0.30-0.35% C, l% Cr, V+N	6500	7.7	1.18

Conclusions

1. On the basis of complex analytic and experimental studies of the influence of chemical composition on processes of crystallization and recrystalization basic physico-chemical and phase parameters, determining formation of structure and properties of cast structural steels, containing in general up to 0,4 wt.% carbon, up to 3% of manganese, silicon and chromium, up to 0,035% of nitrogen, up to 0,3% of vanadium were defined, as well as qualitative regularities of their influence. Obtained qualitative regularities ensure the possibility of analytic forecasting of chemical compositions and conditions of heat treatment of cast structural steels with the required combination of casting and mechanical properties, hardenability, fatigue strength, cold-resistance, toughness of destruction, abrasive wear-resistance, heat-resistance, and stability to reverse temper brittleness.

2. The results of the implemented investigations have shown, that low- and medium-alloy cast structural steels containing manganese, silicon, and chromium in combination with nitride-vanadium hardening posses essential potential of physico-mechanical properties, which is realized by complex optimization of their chemical composition, deoxidization, types and conditions of heat treatment. The influence of these factors is so highly extreme and ambiguous, that can be effectively optimized only by machine experiment of determined dependencies, presenting them as theoretical basis of computer metallography of cast structural steels.

3. An example of study of many structural steels shows, that computer elaboration of their chemical composition, conditions of deoxidization and heat treatment ensures the creation of new class of efficiently alloyed steels with unique combination of strength, plastic and exploitation properties.

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РОЗРОБКА ВИСОКОЯКІНИХ КОНСТРУКЦІЙНИХ СТАЛЕЙ

Є. Г. Афтанділянц

Анотація. На підставі комплексних аналітичних і експериментальних досліджень процесів кристалізації з рідкого стану і перекристалізації в твердому визначені основні фізико-хімічні і фазові параметри конструкційних сталей, що містять до 0,4 мас.% C; 3% Si, Mn і Cr; 0,035% N; 0,3% V і встановлені якісні закономірності їх впливу. Ці закономірності дають можливість аналітично прогнозувати хімічні склади і умови термічної обробки виливків і поковок з конструкційних сталей з необхідною комбінацією ливарних і механічних властивостей, прогартованості, втомної міцності, холодостійкості, ударної в'язкості, абразивної зносостійкості, термостійкості і стійкості до розвитку зворотної відпускної крихкості. Результати проведених досліджень показали, що низько- і середньолеговані марганцем, кремнієм і хромом конструкційні стали в поєднанні з нітрид-ванадієвим зміцненням мають значний потенціал фізико-механічних властивостей, який реалізується при комплексній оптимізації їх хімічного складу, розкислення, виду і умов термічної обробки. Вплив цих факторів екстремальний і настільки неоднозначний, що може бути ефективно оптимізований тільки комп'ютерним експериментом за встановленими залежностями, які є теоретичною основою комп'ютерного металознавства конструкційних сталей. Дослідження численних конструкційних сталей показує, що комп'ютерна розробка їх хімічного складу, умов розкислення і термічної обробки забезпечує створення нового класу економнолегованих сталей з унікальним поєднанням міцності, пластичності та експлуатаційних властивостей. Наведені приклади оптимальних режимів термічної обробки виливків і поковок для досягнення таких властивостей.

Ключові слова: конструкційна сталь, хімічний склад, термічна обробка, механічні властивості, прогартованість, втомна міцність, холодостійкість, в’язкість руйнування, зносостійкість.

РАЗРАБОТКА ВЫСОКОКАЧЕСТВЕННЫХ КОНСТРУКЦИОННЫХ СТАЛЕЙ

Е. Г. Афтандилянц

Аннотация. На основании комплексных аналитических и экспериментальных исследований процессов кристаллизации из жидкого состояния и перекристаллизации в твердом определены основные физико-химические и фазовые параметры конструкционных сталей, содержащих до 0,4 мас.% C; 3% Si, Mn и Cr; 0,035% N; 0,3% V и установлены качественные закономерности их влияния. Эти закономерности дают возможность аналитически прогнозировать химические составы и условия термической обработки отливок и поковок из конструкционных сталей с необходимой комбинацией литейных и механических свойств, прокаливаемости, усталостной прочности, хладостойкости, ударной вязкости, абразивной износостойкости, термостойкости и стойкости к развитию обратимой отпускной хрупкости. Результаты проведенных исследований показали, что низко- и среднелегированные марганцем, кремнием и хромом конструкционные стали в сочетании с нитрид-ванадиевым упрочнением обладают значительным потенциалом физико-механических свойств, который реализуется при комплексной оптимизации их химического состава, раскисления, вида и условий термической обработки. Влияние этих факторов экстремально и настолько неоднозначно, что может быть эффективно оптимизировано только компьютерным экспериментом по установленным зависимостям, которые являются теоретической основой компьютерного металловедения конструкционных сталей. Исследование многочисленных конструкционных сталей показывает, что компьютерная разработка их химического состава, условий раскисления и термической обработки обеспечивает создание нового класса эконолегированных сталей с уникальным сочетанием прочностных, пластических и эксплуатационных свойств. Приведены примеры оптимальных режимов термической обработки отливок и поковок для достижения таких свойств.

Ключевые слова: конструкционная сталь, химический состав, термическая обработка, механические свойства, прокаливаемость, усталостная прочность, хладостойкость, ударная вязкость, абразивная износостойкость.

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