Journal of Chemical Technology and Metallurgy, 58, 4, 2023, 798-805

DEVELOPMENT OF RATIONAL CHEMICAL COMPOSITION OF SPECIAL STEEL WITH INCREASED MECHANICAL AND PERFORMANCE CHARACTERISTICS

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Received 30 May 2022
Accepted 28 November 2022

ABSTRACT

To optimize the composition of steel in the work aims to identify the minimum required number of chemical elements and their content to avoid overheating and unnecessary economic costs. The solution is proposed in the form of microalloying, which leads to grinding of austenitic grains, and after phase transformation and ferritic grains, which improves the properties of steel. The established regularities allowed to quantitatively substantiate the chosen optimal chemical composition of steel, namely to establish the limit of variation of microalloying elements - chromium, vanadium and titanium. It was found that the obtained steel in comparison with the prototype has higher values of impact strength, while maintaining high strength and fluidity. Thus, the combination of improved service and mechanical properties of steel helps to increase the service life of its products.

Keywords: microalloying elements, chemical composition optimization, regression equations, response surfaces.

INTRODUCTION

Vehicles for various purposes are products with high consumer properties. The production of cars is constantly growing in the world, so their quality and performance characteristics should improve. One of the main problems in the production of trucks is the production of high-strength wheels [1]. The solution of this problem will allow not only to increase the weight of the load, but also to reduce the mass of the wheel, to reduce the fuel consumption of the car, as well as tire and road surface wear. This problem is relevant for Ukraine, since PJSC Kremenchug Wheel Plant is successfully operating in it - one of the largest enterprises in Europe, whose products are in demand not only in the domestic market, but also abroad. According to the operating conditions, the wheel must meet a number of requirements that ensure traffic safety and the economic performance of the vehicle. First of all, this is the strength of all its parts, the rigidity and quality of wheel rims, fasteners, minimal runout and imbalance of wheels [2]. In the automotive industry, steels are widely used, which have high ductility and strength, which are easily deformed in industrial conditions. New low-alloy steels will improve the quality of the wheels. They will be able to ensure the preservation of the strength characteristics of the wheel while reducing the metal consumption of the product [3].

Thin-sheet low-carbon steel is used for car wheel rims. Analysis of the chemical composition and mechanical properties of these steels shows that they have the highest relative elongation compared to steels with a high carbon content, which leads to their use for stamping, since large, in some places, different, tension, at which cracks and folds should not occur. In addition, these steels do not need additional heat treatment and have good weld ability [4].

The basics of alloying and technology for the metallurgical processing of low-carbon steels are quite fully formulated in works [4, 6, 7]. However, due to the lack of justified alloying complexes, they assessed the impact of the selected components on the properties of steel, mainly, only by changing the phase composition. Therefore, the steels were often over-alloyed with the Mn - Si - Cr - Mo system. Even a decrease in the carbon content did not provide the required mechanical properties. The main reason for the reduced ductility of open-cast low-carbon steels is the presence of a two-phase ferrite-martensite structure. At the same time, dispersed particles of chromium, vanadium, and titanium carbonitrides, inhibiting the growth of ferrite and austenite grains during heat treatment, can significantly increase strength by means of dispersion strengthening.

The attempts of many scientists [5, 6] on hot-rolled strips, from less alloyed Mn - Si - Cr steel, by winding at lower temperatures (500°C - 550°C), to obtain high mechanical properties were not successful due to the instability of their performance. This forced the researchers to complicate the technological process, to carry it out in three stages, which affected the increase in the cost of steel. This forced the researchers to complicate the technological process, to carry it out in three stages, which affected the increase in the cost of steel [9]. Recent studies carried out in Ukraine, and abroad [5, 8, 10] have shown that a simultaneous increase in strength and resistance to brittle fracture of low-alloy and ordinary low-carbon steels is possible by microalloying: the introduction of microadditives (up to 0.15 %) of elements predominantly IV and V groups of the periodic system. The most common microalloying elements are niobium, vanadium, and titanium [10]. These elements have a high affinity for nitrogen and carbon and easily form nitrides and carbides (or carbon-nitrides). When heated, carbo-nitrides dissolve in a solid solution, and when cooled, they precipitate as an independent dispersed phase. These processes constitute one of the main mechanisms of steel hardening. In the traditional rolling process, microalloying additives increase the strength of steel mainly due to precipitation hardening, and in controlled rolling or normalization (austenization with air cooling) - mainly through grain refinement [11 - 13].

The aim of this work is to optimize the chemical composition of steel using the planned active mathematical experiment, which provides the desired physical and mechanical properties of 10HFTBch steel.

EXPERIMENTAL

The complex effect of alloying elements, including rare earth metals, on the mechanical and service properties was determined using mathematical processing of test results. To select alloying complexes, as well as factors and ranges of their variation, the following were used:

- literature data on the quantitative and qualitative influence of alloying elements on the phase composition and properties of low-alloyed ferritic-pearlitic steels [7, 15, 16];
- experimental and literature data on thermal and thermos-mechanical treatment of low-alloyed steels [14 - 17].

Using the method of mathematical planning [18], an experiment was carried out and the dependence of a number of mechanical characteristics of the proposed steel depending on its chemical composition was determined: tensile strength σ_b, MPa, yield strength σ_y, MPa, impact strength KCU, MJ m^{-2}, relative elongation δ_5, %.

At the first stage, a screening experiment was carried out using steels containing components that go beyond the boundaries of the expected chemical composition of the steel. In the process of finding the optimal composition of the alloy, laboratory steels were made in an induction furnace with a main lining with a capacity of 50 kg. The resulting castings were forged into blanks 10 x 80 x 120 mm in size, followed by hot rolling. Table 1 presents the results of a study of the mechanical properties of the obtained samples. The experiment made it possible to determine the research factors, their levels and intervals of variation.

At the second stage of the study, the following variables were chosen as independent variables: chromium content in steel (X_1), vanadium content in steel (X_2), titanium content in steel (X_3). Intervals and levels of change of factors are given in Table 2. To reduce the number of experiments and assuming the non-linear nature of the response functions, we used a second-order symmetrical composition plan [18].

RESULTS AND DISCUSSION

The series of influence of the chemical composition on the tensile strength, yield strength, relative elongation and impact strength are established:
- series of influence on σ_b: Ti → V → Cr;
- series of influence on σ_y: Ti → V → Cr;
- series of influence on δ_5: Cr → V → Ti;
- series of influence on KCU: Cr → Ti → V.

The influence of carbon, manganese and silicon

Table 1. Experimental mechanical characteristics of steel.

Steel No.	Mechanical characteristics, not less than			
	σ_b, MPa	σ_y, MPa	δ_5, %	KCU, MJ m^{-2}
1	427	321	33	0,85
2	525	473	25	0,65
3	502	345	30,5	0,95
4	499	443	29,5	0,80
5	503	451	28	0,90
6	413	309	29,5	0,50
7	575	496	18	0,45
Prototype	360	265	34	0,80

Table 2. Research factors.

Characteristic	Factors		
	Cr, % wt.	V, % wt.	Ti, % wt.
Code	X_1	X_2	X_3
Basic level	0,15	0,15	0,15
Variation interval	0,05	0,05	0,05
Lower level	0,10	0,10	0,10
Upper level	0,20	0,20	0,20

Table 3. Results of the regression analysis of the alloying complex.

Alloying complex	Regression equations	Δb	t-criterion	F-criterion
Cr - V - Ti	$\sigma_b = 824 - 7385Cr - 991V + 1627Ti + 23222Cr^2 - 9417Ti^2 + 4800CrV + 4200CrTi + 3600VTi$	2.55	2.78	6.09 > 4.39
Cr - V - Ti	$\sigma_y = 716 - 9636Cr + 162V + 2586Ti + 32983Cr^2 + 2153V^2 - 11033Ti^2 + 3500CrV + 2900CrTi + 2300VTi$	2.55	2.78	6.26 > 5.61
Cr - V - Ti	$KCU = 0.52 + 9.52Cr - 1.63V - 2.67Ti - 31{,}78Cr^2 + 12{,}22Ti^2 + 7.0CrV - 10{,}0CrTi$	0.015	2.78	6.16 > 4.88
Cr - V - Ti	$\delta_5 = 32 + 280Cr - 161V - 115Ti - 1206Cr^2 + 353Ti^2 + 735CrV - 215CrTi + 65VTi$	0.025	2.78	6.26 > 4.79

were excluded from the analysis because it is known that these elements are the main hardeners of steel, while an increase in the content of elements of hardeners caused a decrease in the relative elongation. The numerical values of the regression coefficients and their significance, determined taking into account the difference in variances for each response function, as well as the significance test by the Student's criterion and the evaluation of the adequacy of the model by the Fisher criterion are presented in Table 3.

Using the MatLab software package, three-dimensional models are built that simplify the study of the relationship between a group of factors and the mechanical properties obtained in this work (Fig. 1 - Fig. 4). In Fig. 1 and Fig. 2 it is shown that with a change in the chemical composition, the mechanical characteristics

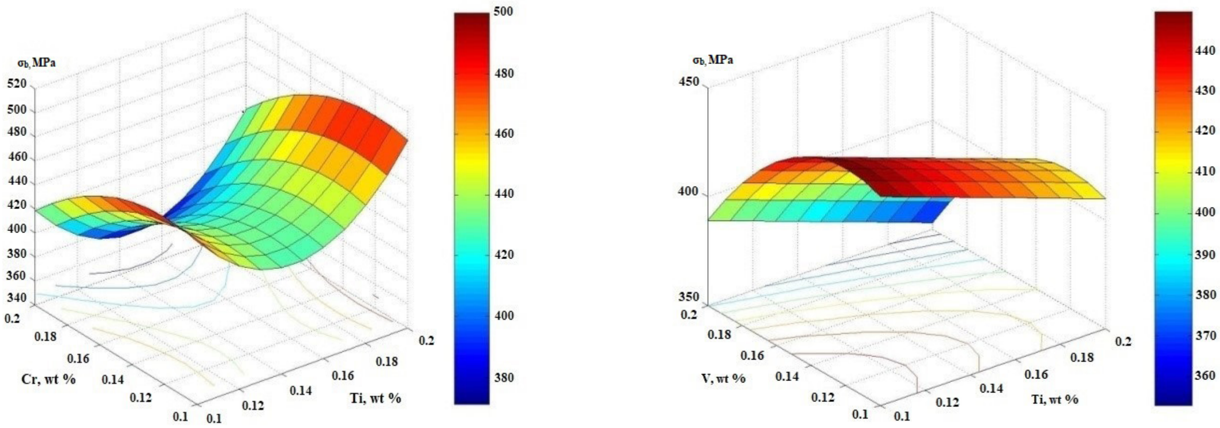

Fig. 1. Optimization of the chemical composition of steel in terms of ultimate strength σ_b.

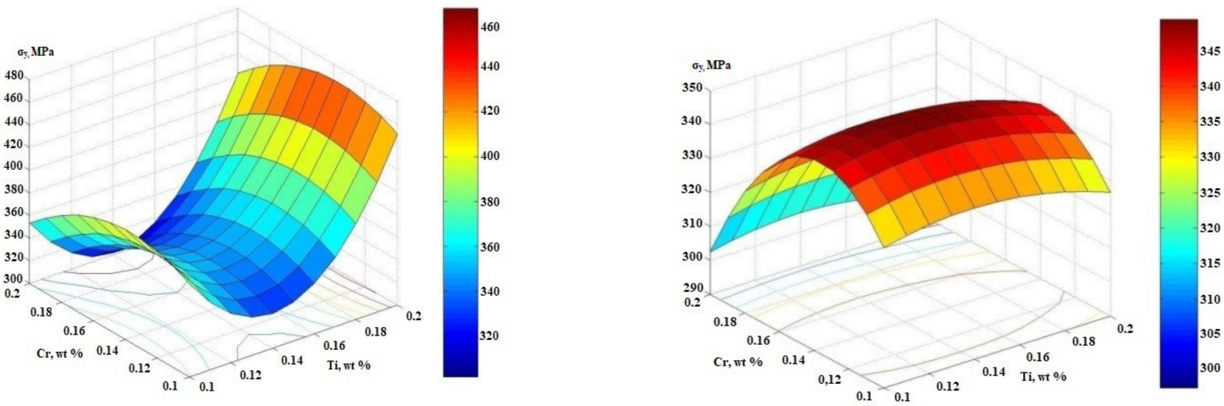

Fig. 2. Optimization of the chemical composition of steel in terms of yield strength σ_y.

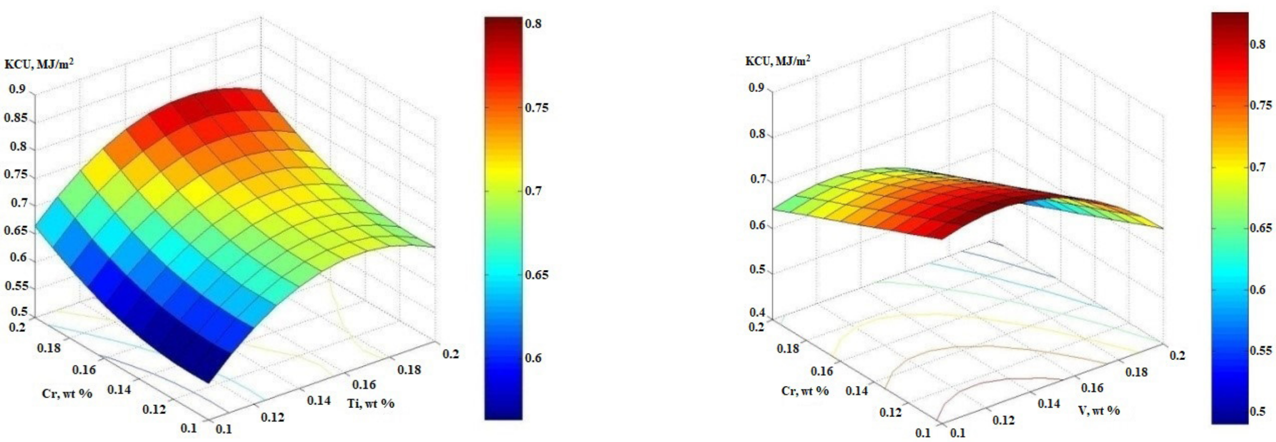

Fig. 3. Optimization of the chemical composition of steel in terms of impact strength.

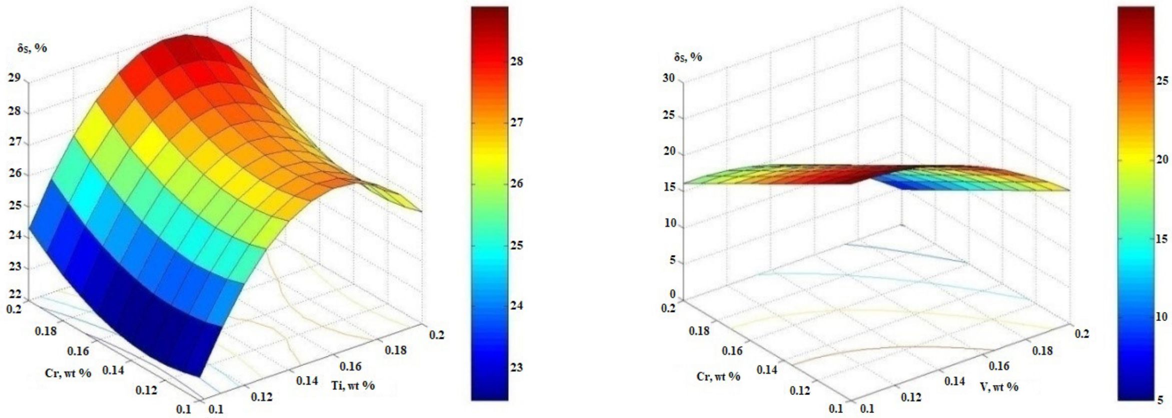

Fig. 4. Optimization of the chemical composition of steel by relative elongation.

Table 4. Composition of alloying elements of steel, providing optimal properties.

Cr,% wt.	V,% wt.	Ti,% wt.
0.14 - 0.16	0.10 - 0.15	0.12 - 0.15

of the steel change. Tendencies of increase in tensile strength and yield strength are visible. For example, when the content of Ti is 0.2 % and Cr is 0.14 %, the maximum value $\sigma_b = 500$ MPa, $\sigma_y = 450$ MPa takes place.

Fig. 3 and Fig. 4 show the change in impact strength and relative elongation from the same chemical elements. With Ti - 0.16 % and Cr - 0.2 %, KCU = 0.8 MJ m^{-2}, $\delta_5 = 30$ %.

Thus, the optimal content of the main chemical elements in steel is presented in Table 4.

According to the results in Fig. 1 - Fig. 4, it can be seen that the mechanical properties of steel depend most of all on the content of chromium and titanium in the steel. Their ratio has a significant effect. Representing the results of the experiment by a polynomial of the second degree turned out to be justified - a significant part of the nonlinear terms here significantly differs from zero.

The established regularities make it possible to formulate the rationale for the chosen chemical composition of steel.

The carbon content should be in the range of 0.08 - 0.12 wt. %. This is due to: the lower limit - a sharp decrease in strength properties; the upper limit is the limit beyond which the mass precipitation of embrittlement secondary phases begins, which helps to reduce the ductility of the steel. The chromium content should be in the range of 0.14 - 0.16 wt. %. This is due to the need to ensure the formation of carbides in a wide temperature range, which is important in the welding process. The content of vanadium should be in the range of 0.10 - 0.15 wt. %. This is due to: the lower limit is limited by its sufficient concentration to affect the structure and properties of the alloy; the upper limit is the efficiency of its useful action in inhibiting the formation of iron carbides and nitrides. The titanium content should be in the range of 0.12 - 0.15 wt. %. This is due to a decrease in ductility and impact strength, due to the prevention of the formation of aluminum nitrides, when going beyond the specified limit. The content of niobium should be in the range of 0.07 - 0.15 wt. %. This is due to: the lower limit is when the sufficiency of its concentration to start influencing the structure and properties of the alloy; the upper limit is the effectiveness of its beneficial action in inhibiting the formation of high-chromium carbides, being a competitor of titanium in liquid metal, active binding of carbon into carbides of the NbC and Nb_2C type, when the upper limit of the niobium content is exceeded, the impact strength and ductility of steel decrease.

The introduction of barium into steel, along with the globularization of non-metallic inclusions, is due to the cleaning of grain boundaries from harmful impurities in steel, affects the dislocation structure, ensures its uniformity and the minimum level of local micro distortions, and contributes to a more uniform distribution of alloying elements. The introduction of chromium, vanadium, titanium and niobium within the specified limits ensures the formation of a carbide skeleton that prevents the migration of grain boundaries, while maintaining fine grain and, accordingly, high impact strength of both welds and the heat-affected zone. The introduction of rare earth metals from the group of cerium, lanthanum, praseodymium, neodymium provides a decrease in the diffusion mobility of carbon atoms, promotes the grinding of carbides and nitrides, and their uniform distribution in the steel structure, thereby reducing its brittleness.

Based on the data obtained as a result of the studies, it was possible to derive an empirical formula for the ratio between the content of carbon and nitrogen present in the alloy, and also the content of the carbide-forming elements of chromium, vanadium, titanium and niobium, which is also necessary. The ratio takes into account the need to bind carbon and nitrogen into carbides and nitrides. With this ratio, it is possible to achieve the highest technological and operational characteristics of low-alloy steels:

$$0.6 > (Nb + Ti + V + Cr) = [10\,(C + N)^2 + 0.375] \quad (1)$$

where Nb - is the content of niobium in the alloy, in mass. %;
Ti - is the content of titanium in the alloy, wt. %;
V - is the content of vanadium in the alloy, wt. %;
Cr - is the content of chromium in the alloy, wt. %;
C - is the content of carbon in the alloy, in mass. %;
N - is thecontent of nitrogen in the alloy, in mass. %.

The content of sulfur, as a permanent harmful impurity, and phosphorus must be less than 0.035 wt. %. This is due to a sharp deterioration in the plastic properties of steel.

The introduction of barium into the proposed steel, in the range of 0.0005 - 0.0015 wt. % is due to: the lower limit is the required concentration for the active binding of metal oxides and gases that pollute the alloy, and their removal into slag, as well as promoting the deoxidation and desulfurization of the alloy; the upper limit is the efficiency of the refining action for binding, and the removal of oxides and gases that pollute the alloy, provides a decrease in the alloy contamination index, and an increase in steel ductility.

The introduction of one or more rare earth metals from the group of cerium, lanthanum, praseodymium, neodymium in the proposed steel in the range of 0.001 wt. % - 0.010 wt. %, due to their useful action to reduce the diffusion mobility of carbon atoms, which prevents the appearance of coarse carbide and nitride precipitates at the grain boundaries, and also contributes to grinding and uniform distribution of secondary phases in the structure of the alloy, due to which it is possible to reduce its brittleness.

Compared with analogues containing aluminum, boron, calcium, nickel, the rejection of these alloying elements in the proposed solution and the introduction of such components as barium and rare earth elements makes it possible to obtain low-alloy steel with high impact strength, which provides an increase in its welding ability [19]. Thus, the chemical composition determines the fine-grained structure of the proposed steel and the increase in its mechanical and operational properties.

Thus, the goal of optimizing the chemical composition of the new steel grade was achieved by the fact that iron-based steel, in addition to the base, contained carbon, silicon, manganese, chromium, vanadium, titanium, niobium, sulfur, phosphorus, and additionally contained barium and one or several rare earth metals from the group of cerium, lanthanum, praseodymium, neodymium with such a ratio of elements, in mass. %: carbon - 0.08-0.12; silicon - 0.10 - 0.50; manganese - 0.15 - 0.50; chromium - 0.14 - 0.16; vanadium - 0.10 - 0.15; titanium - 0.12 - 0.15; niobium - 0.07 - 0.15; barium - 0.0005 - 0.0015; rare earth metals (REM) - 0.001 - 0.010; iron – the rest, while the content of sulfur and phosphorus in steel does not exceed 0.035 %.

It has been established that the proposed steel, in comparison with the prototype [17], has higher impact strength values, while maintaining high strength and fluidity. Thus, the combination of increased service and mechanical properties of steel contributes to an increase in the service life of products made from it. The patent of Ukraine No. 105341 dated April 25, 2014 was obtained for the developed chemical composition of the new steel grade [19]. Analogue steels according to European standards: 1.0045/S355JR, 1.0570/St52-3.

CONCLUSIONS

Optimization of the chemical composition of 10HFTBch steel showed that many factors can affect the final properties of hot-rolled metal. Based on a priori information and preliminary studies, with the choice of alloying complexes (Cr, V, Ti), the levels of micro-alloying of ferrite-pearlitic 10HFTBch steel were established to optimize its chemical composition. Based on the results of the regression analysis of the alloying complex, using the MatLab software package, three-dimensional models of the dependencies of a group of factors on the mechanical properties of steels were built. Thanks to this, the optimal chemical and structural composition of 10HFTBch steel was established. As a result, the mechanism of influence of individual elements of the chemical composition and their joint influence on the mechanical properties of low-alloy steels was established. This made it possible to optimize the composition of steel, wt. %: Cr - 0.14 - 0.16; V - 0.1 - 0.15; Ti - 0.1 - 0.15, which provides a high level of mechanical properties: σ_b - 490 - 502 MPa, σ_y - 320 - 345 MPa, δ_5 - 27 % - 29 %.

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