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Forecast and Control of Structure and Properties of Ultra-Low-Carbon Steels

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Concentration ranges of elements' containing to optimize the composition of 01YuTA, 01YuT steels and to ensure the required set of rolled products properties are obtained using the method of physico-chemical modelling. The effect of rolling deformation modes in the ferritic temperature range on the formation of the structure and on the properties of ultra-low-carbon steel is investigated. The obtained data can be used to control the processes of structure formation and to establish rational technological regimes for the processing of rolled sheet material for automobile and machine-building enterprises.

Key words: structure of ultra-low-carbon steels, hot rolling, deep drawing, physico-chemical modelling, mechanical properties.

За допомогою методу фізико-хемічного моделювання отримано концентраційні інтервали вмісту елементів для оптимізації складу сталей 01ЮТА, 01ЮТ і забезпечення необхідного комплексу властивостей вальцівки. Досліджено вплив деформаційних режимів вальцювання у феритному інтервалі температур на формування структури і властивості ультранизьковуглецевої сталі. Отримані дані можуть бути використані для керування процесами структуроутворення та встановлення раціональних технологічних режимів обробки тонколистової вальцівки для підпри-

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ємств автомобіле- та машинобудівної промисловості.

Ключові слова: структура ультранизьковуглецевих сталей, гаряче вальцювання, глибока витяжка, фізико-хемічне моделювання, механічні властивості.

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1. INTRODUCTION

At the present day, most metal parts in the automobile construction and machine construction, as well as in the production of household appliances, are produced from light cold-rolled sheet by stamping and deep drawing methods. Die stamping is used in many industries to process rolled metal products. The basic requirements to sheet steels for deep drawing are increased deformability, high strength and products surface quality.

IF (interstitial free)-steels meet these requirements, the achievement of properties in such steels is determined by the requirements for chemical composition—ultra-low content of carbon, nitrogen, low content of non-ferrous metals impurities (Cr $< 0.03\%$, Cu $< 0.03\%$), silicon (Si $< 0.2\%$), sulphur (S $< 0.01\%$), requirements to mechanical properties and sheet surface quality. The IF-steels main feature is the introduction of titanium and/or niobium into their composition, which bind carbon and nitrogen and are interstitial elements. As a result, cold-rolled steel sheet takes on stretching properties that allow stamping complex shape products.

Renowned automobile construction steelmakers in Japan, Germany, Sweden and the United States are addressing the issues of lower production costs and increasing demands for fuel efficiency, safety and longer vehicle life by increasing the structural strength of the vehicle body while reducing its weight [1, 2].

The use of technically pure oxygen and methods of converting electrical energy into thermal energy affect the method of making sheet steel, its cost and quality [3, 4].

In the oxygen converter production, Bensisk Metallurgical Group LLC (PRC) has mastered the production of automotive IF-steels with a carbon content of no more than 0.0025% and a nitrogen content of no more than 0.0025% for the manufacture of internal and front parts of cars. However, the issue of the hot-rolled sheet surface quality remains unsolved [5].

In order to improve the quality of rolled products, stringent market requirements for the content of carbon, nitrogen and sulphur in steel at a number of metallurgical enterprises are being strengthened: no more than $0.003–0.004\%$ C, 0.004% N, and 0.007% S. Foreign manufacturers receive ultra-low concentrations of carbon less than 0.002% and nitrogen less than 0.002% in IF-steels, which provides increased plastic properties and good stamping. One of the important criteria for the quality of steel is purity for non-metallic inclusions.

The chemical elements content that determine the composition of IF-steel is presented in Table 1. The relative volume of micro-regulating elements (titanium and niobium), which are introduced into steel, depending on the actual content of carbon, nitrogen and sulphur in the liquid-alloy, is determined by means of a calculation:
a) for steel microalloyed with titanium: $\mathrm{Ti} = (4\mathrm{C} + 1.5\mathrm{S} + 3.43\mathrm{N})$, %;
b) for steel microalloyed with titanium and niobium: $\mathrm{Ti} = (2.4\mathrm{S} + 3.43\mathrm{N})$, %; $\mathrm{Nb} = 7.75\mathrm{C}$, %. Allowance is of content in steel for titanium + 0.03%, for niobium + 0.02%.

One of the main limitations of the chemical composition of low-silicon automotive sheet steels is the regulated silicon content (at the trace level), since silicon increases the flow limit and tensile strength, but reduces the steel elongation [4, 6].

Currently, the technologies used at domestic metallurgical enterprises do not allow obtaining ultra-low carbon and nitrogen content in the final product.

The methods of influencing the processes of structure formation of alloys are being improved; their role in the complex structural-chemical approach to the issue of controlling the properties of materials is growing. Nevertheless, determination of the optimal chemical composition and potential capabilities of steels and alloys as structural materials is a critical task. Nowadays, this problem is of particular importance in connection with the desire to ensure high quality metal products and their competitiveness in the domestic and world markets to improve resource saving in the context of energy and environmental complications [7].

Determination of the quantitative ratio of ordinary and special boundaries in the ferritic component of structural steels is of scientific interest; this will allow purposefully influencing the grain-boundary structure and improving the performance characteristics of metals and alloys with a body-centred cubic lattice [8].

The works consider the development of technology for smelting ultra- and low-carbon steels and rolled sheet material manufacture [9,

TABLE 1. IF-steel chemical composition, % mass [2].

Element content, %									
C	S	P	Si	Cr	Ni	Cu	Mn	Al	N_2
Not more							0.20	0.030	0.005
0.005	0.005	0.005	0.005	0.005	0.005	0.005			

10]. Special attention is given to the study of the structure effect on the metal mechanical properties.

As can be seen from the above, today it is relevant to determine the optimal composition and modes of deformation processing to ensure the formation of a favourable structure and a high complex of properties of rolled products from ultra-low-carbon steels.

Paper object: optimization of 01YuT, 01YuTA steels composition by the method of physical and chemical modelling to obtain the required set of rolled products properties, which is used for the manufacture of parts by cold stamping in the automobile construction and machine construction.

2. MATERIAL AND METHODS OF RESEARCH

After hot rolling on a wide-strip mill (NWSP 2000) and pickling treatment on a continuous pickling unit (CPU), steel 01YuTA, 01YuT cards with a thickness of 3.5 mm are selected. The chemical composition of the studied steel grades is shown in Table 2.

The deformation modes of rolling of the investigated steels are presented in Table 3. Heating of the metal before rolling is carried out in an electric furnace CH 1,62,51/11-И2 at a speed of 3°C/s, holding time 2–4 s. Rolling is carried out on a laboratory single-stand mill DUO 280 in two passes in the austenitic and ferritic temperature ranges (the rolling speed is 1.4 m/s, the pause duration between passes is 13–15 seconds). After rolling, in order to simulate the balling-up process, the cards are loaded into 25414/11-И1 electric furnace, the temperature of which corresponds to the temperature of balling-up into a coil, and cooled with the furnace to ambient temperature ($V_{\text{cooled}} \sim 0.05$°C/s).

3. RESEARCH RESULTS

It has been established that the final mechanical characteristics of finished rolled products are determined by the relationship between the

TABLE 2. Rated composition of 01YuTA, 01YuT steels for modelling atomic interaction and integral parameters.

Steel grade	Content of chemical elements, % mass											
	C	Mn	Si	P	S	Cr	Ni	Cu	Al	Ti	N_2	Ca
01YuTA	0.002	0.12	0.01	0.006	0.011	0.01	0.01	0.02	0.050	0.062	0.005	0.0002
01YuT	0.003	0.13	0.02	0.008	0.012	0.01	0.01	0.02	0.041	0.056	0.004	–
01YuT[*]	0.003	0.12	0.01	0.005	0.011	0.01	0.01	0.02	0.041	0.070	0.004	0.0003

[*] Additionally contains calcium.

TABLE 3. Deformation modes of ultra-low-carbon steels rolling.

Steel grade	T_{heat}	$T_{1\text{roll}}$	h_0	h_1	Δh_1	ε_1	$T_{2\text{roll}}$	h_2	Δh_2	ε_2	$\Sigma\Delta h$	$\Sigma\varepsilon$	T_{reel}
	°C		mm			%	°C	mm		%	mm	%	°C
01YuTA	1000	970–980	3.5	1.80	1.70	48.6	730–740	1.3	0.5	27.8	2.2	62.9	660–680
01YuT	1000	970–980	3.5	1.80	1.70	48.6	730–740	1.35	0.45	25.0	2.15	61.4	660–680
01YuT*	1000	970–980	3.5	1.80	1.70	48.6	730–740	1.4	0.4	22.2	2.1	60.0	660–680

Note: T_{heat}—steel sheet heating temperature; $T_{1\text{roll}}$—rolling temperature of sheet steel in the first pass; $T_{2\text{roll}}$—rolling temperature of sheet steel in the second pass; h_0—initial sample thickness; h_1—sample thickness after the first pass; h_2—sample thickness after the second pass; Δh_1—absolute metal reduction in the first pass; Δh_2—absolute metal reduction in the second pass; Σh—total metal reduction in two passes; ε_1—relative degree of metal deformation in the first pass; ε_2—relative degree of metal deformation in the second pass; $\Sigma\varepsilon$—total degree of metal deformation in two passes; T_{rell}—reel temperature.

chemical composition and the structural state of the material.

Application of physical-chemical modelling method allows predicting and controlling the properties of alloys.

The author of works [7, 11] E. V. Prykhodko developed a physical-chemical model of the alloys structure, which is based on the use of the system of unpolarized ionic radii (SUIR) equations to calculate the parameters. By combining these parameters, it is possible to characterize the properties of the liquid-alloy as a chemically unified whole for any number of components in the system and various ratios between their concentrations.

SUIR basic parameters:

– Zy—the number of electrons involved in the formation of the average acceptor bond; this value is an integral characteristic of atomic interaction in a multicomponent system and can be interpreted as a chemical equivalent of a given composition;

– ρl—directional charge density at the ion surface;

– d—internuclear distance corresponding to zy;

– tgα—slope ratio of straight lines in Ru-n coordinates, where Ru—unpolarized ionic radii, n—number of electrons in atom orbitals.

Depending on the components chemical characteristics, first of all, their position in the Periodic Table and the electronic configuration corresponding to this position, the role of the basic parameter that controls changes in one or another property can be played by Zy, or d, or tgα.

The calculated composition of 01YuTA, 01YuT steels for modelling atomic interaction are presented in Table 2. The concentration range of elements is determined based on literature data.

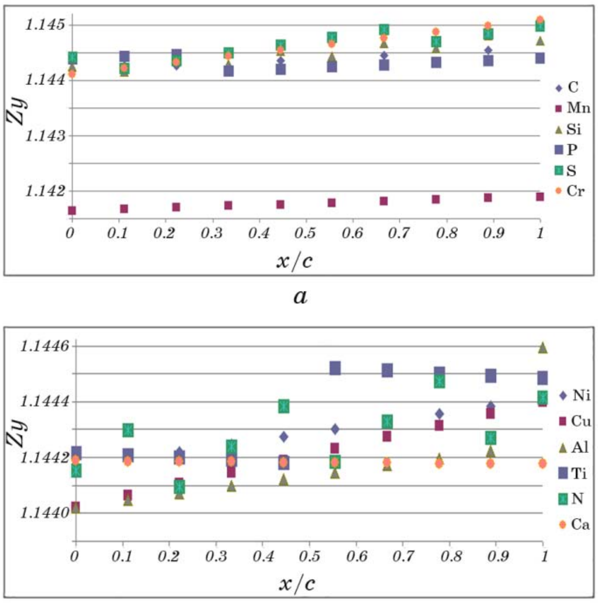
We analyzed 150 compositions of 01YuTA, 01YuT steels. *Zy* and *d* parameters are calculated to study the effect of elements. The above parameters for fifteen alloys within the framework of variation of an individual element are calculated to assess the effect of the concentration of elements.

Figure 1 and Table 4 show the dependence of the *Zy* parameter on the composition of 01YuTA steel.

Analysis of the data in Fig. 1 and Table 4 shows that with a manganese content of 0.009–0.024%, the *Zy* parameter does not change, with an increase in the chromium content, the *Zy* parameter increases. With a calcium content of 0.0001–0.0004%, the *Zy* parameter does not change, with an increase in the nickel content, the *Zy* parameter increases (Fig. 1, *b*).

The *Zy* parameter determines the number of electrons involved in the formation of the average acceptor bond.

An important parameter for a liquid-alloy is the average distance between atoms 0.1*d* nm, which characterizes the interaction of elements with each other.



a

b

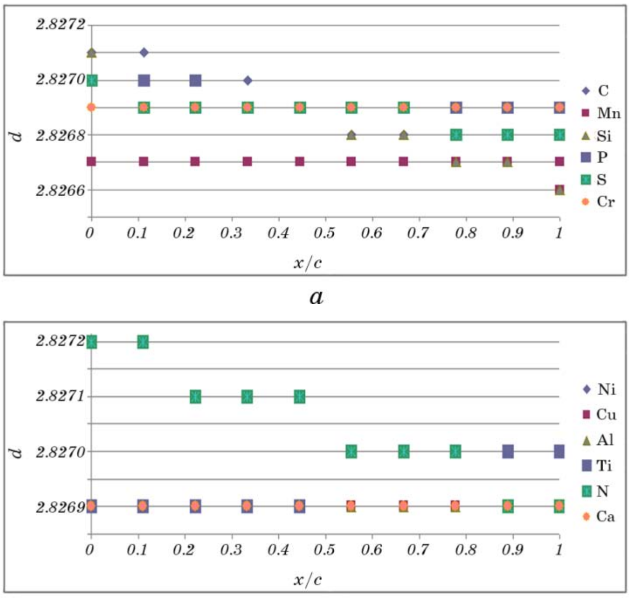
Fig. 1. Change in the *Zy* parameter depending on the content of carbon, manganese, silicon, phosphorus, sulfur, chromium (*a*) and nickel, copper, aluminium, titanium, nitrogen, calcium (*b*) in 01YuTA steel.

TABLE 4. Quantitative data on the change in the Zy parameter depending on the content (%) of alloying elements in 01YuTA steel.

	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
C	0.0010	0.0013	0.0016	0.0019	0.0022	0.0026	0.0029	0.0032	0.0035	0.0038
Mn	0.0090	0.0107	0.0123	0.0140	0.0157	0.0173	0.0190	0.0207	0.0223	0.0240
Si	0.0060	0.0076	0.0091	0.0107	0.0122	0.0138	0.0153	0.0169	0.0184	0.0200
P	0.0046	0.0050	0.0054	0.0058	0.0062	0.0066	0.0070	0.0074	0.0078	0.0082
S	0.0092	0.0115	0.0138	0.0161	0.0184	0.0208	0.0231	0.0254	0.0277	0.0300
Cr	0.0080	0.0111	0.0142	0.0173	0.0204	0.0236	0.0267	0.0298	0.0329	0.0360
Ni	0.0090	0.0106	0.0121	0.0137	0.0152	0.0168	0.0183	0.0199	0.0214	0.0230
Cu	0.0080	0.0111	0.0142	0.0173	0.0204	0.0236	0.0267	0.0298	0.0329	0.0360
Al	0.0400	0.0416	0.0431	0.0447	0.0462	0.0478	0.0493	0.0509	0.0524	0.0540
Ti	0.0560	0.0576	0.0591	0.0607	0.0622	0.0638	0.0653	0.0669	0.0684	0.0700
N	0.0027	0.0030	0.0033	0.0036	0.0039	0.0043	0.0046	0.0049	0.0052	0.0055
Ca	0.0001	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004

Figure 2 and Table 5 show the data on the change in parameter d from the composition of 01YuTA steel.

Data on the change in parameter d on the composition of the alloy shows that chemical elements have different effects on the distance be-



a

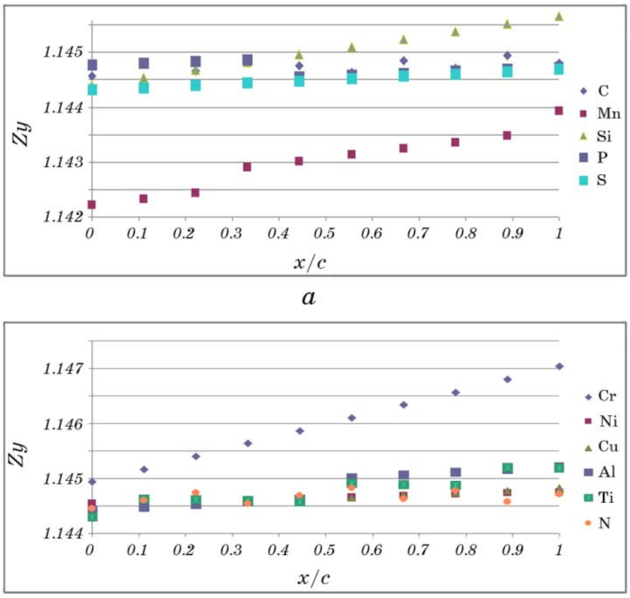
b

Fig. 2. Change in the d parameter depending on the content of carbon, manganese, silicon, phosphorus, sulphur, chromium (*a*) and nickel, copper, aluminium, titanium, nitrogen, calcium (*b*) in 01YuTA steel.

TABLE 5. Quantitative data on the change in the *d* parameter depending on the content (%) of alloying elements in 01YuTA steel.

	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
C	0.0010	0.0013	0.0016	0.0019	0.0022	0.0026	0.0029	0.0032	0.0035	0.0038
Mn	0.0090	0.0107	0.0123	0.0140	0.0157	0.0173	0.0190	0.0207	0.0223	0.0240
Si	0.0060	0.0076	0.0091	0.0107	0.0122	0.0138	0.0153	0.0169	0.0184	0.0200
P	0.0046	0.0050	0.0054	0.0058	0.0062	0.0066	0.0070	0.0074	0.0078	0.0082
S	0.0092	0.0115	0.0138	0.0161	0.0184	0.0208	0.0231	0.0254	0.0277	0.0300
Cr	0.0080	0.0111	0.0142	0.0173	0.0204	0.0236	0.0267	0.0298	0.0329	0.0360
Ni	0.0090	0.0106	0.0121	0.0137	0.0152	0.0168	0.0183	0.0199	0.0214	0.0230
Cu	0.0080	0.0111	0.0142	0.0173	0.0204	0.0236	0.0267	0.0298	0.0329	0.0360
Al	0.0400	0.0416	0.0431	0.0447	0.0462	0.0478	0.0493	0.0509	0.0524	0.0540
Ti	0.0560	0.0576	0.0591	0.0607	0.0622	0.0638	0.0653	0.0669	0.0684	0.0700
N	0.0027	0.0030	0.0033	0.0036	0.0039	0.0043	0.0046	0.0049	0.0052	0.0055
Ca	0.0001	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004

tween atoms in the liquid-alloy. The parameter d does not change with the content of manganese 0.009–0.024% and chromium 0.008–0.036% (Fig. 2, *a*) and does not change with the content of nickel 0.009–0.023%, copper 0.008–0.036%, calcium 0.0001–0.0004% (Fig. 2, *b*).



a

b

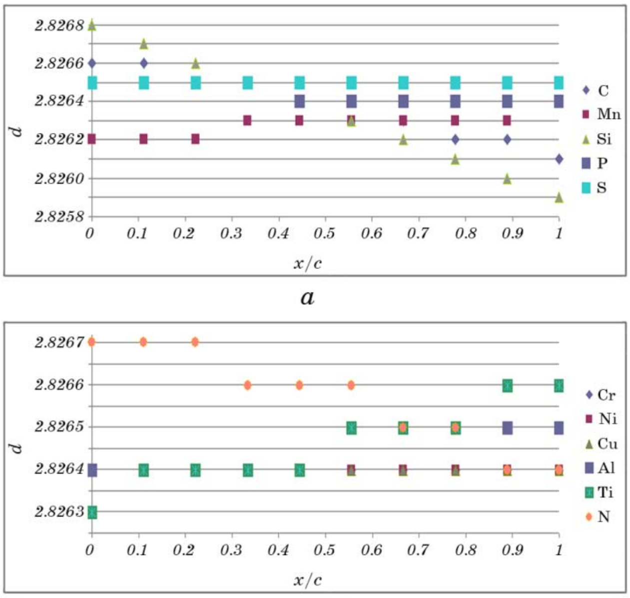
Fig. 3. Change in the *Zy* parameter depending on the content of carbon, manganese, silicon, phosphorus, sulphur (*a*) and chromium, nickel, copper, aluminium, titanium, nitrogen (*b*) in 01YuT steel.

TABLE 6. Quantitative data on the change in the *Zy* parameter depending on the content (%) of alloying elements in 01YuT steel.

	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
C	0.0020	0.0023	0.0026	0.0029	0.0032	0.0036	0.0039	0.0042	0.0045	0.0048
Mn	0.0290	0.0359	0.0428	0.0497	0.0566	0.0634	0.0703	0.0772	0.0841	0.0910
Si	0.0100	0.0131	0.0162	0.0193	0.0224	0.0256	0.0287	0.0318	0.0349	0.0380
P	0.0064	0.0067	0.0071	0.0074	0.0077	0.0081	0.0084	0.0087	0.0091	0.0094
S	0.0018	0.0025	0.0032	0.0039	0.0046	0.0052	0.0059	0.0066	0.0073	0.0080
Cr	0.0200	0.0267	0.0333	0.0400	0.0467	0.0533	0.0600	0.0667	0.0733	0.0800
Ni	0.0080	0.0093	0.0107	0.0120	0.0133	0.0147	0.0160	0.0173	0.0187	0.0200
Cu	0.0100	0.0131	0.0162	0.0193	0.0224	0.0256	0.0287	0.0318	0.0349	0.0380
Al	0.0310	0.0341	0.0372	0.0403	0.0434	0.0466	0.0497	0.0528	0.0559	0.0590
Ti	0.0440	0.0471	0.0502	0.0533	0.0564	0.0596	0.0627	0.0658	0.0689	0.0720
Ni	0.0030	0.0033	0.0036	0.0039	0.0042	0.0046	0.0049	0.0052	0.0055	0.0058

Figure 3 and Table 6 show the dependence of the *Zy* parameter on the composition of 01YuT steel. With an increase in the content of silicon and manganese (Fig. 3, *a*) and chromium (Fig. 3, *b*), the *Zy* parameter increases.

Figure 4 and Table 7 show the data on the change in parameter *d*



a

b

Fig. 4. Change in the *d* parameter depending on the content of carbon, manganese, silicon, phosphorus, sulfur (*a*) and chromium, nickel, copper, aluminium, titanium, nitrogen (*b*) in 01YuT steel.

TABLE 7. Quantitative data on the change in the *d* parameter depending on the content (%) of alloying elements in 01YuT steel.

	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
C	0.0020	0.002311	0.002622	0.002933	0.003244	0.003556	0.003867	0.004178	0.004489	0.0048
Mn	0.0290	0.035889	0.042778	0.049667	0.056556	0.063444	0.070333	0.077222	0.084111	0.0910
Si	0.0100	0.013111	0.016222	0.019333	0.022444	0.025556	0.028667	0.031778	0.034889	0.0380
P	0.0064	0.006733	0.007067	0.0074	0.007733	0.008067	0.0084	0.008733	0.009067	0.0094
S	0.0018	0.002489	0.003178	0.003867	0.004556	0.005244	0.005933	0.006622	0.007311	0.0080
Cr	0.0200	0.0267	0.0333	0.0400	0.0467	0.0533	0.0600	0.0667	0.0733	0.0800
Ni	0.0080	0.0093	0.0107	0.0120	0.0133	0.0147	0.0160	0,0173	0.0187	0.0200
Cu	0.0100	0.0131	0.0162	0.0193	0.0224	0.0256	0.0287	0.0318	0.0349	0.0380
Al	0.0310	0.0341	0,0372	0.0403	0.0434	0.0466	0.0497	0.0528	0.0559	0.0590
Ti	0.0440	0.0471	0.0502	0.0533	0.0564	0.0596	0.0627	0.0658	0.0689	0.0720
Ni	0.0030	0.0033	0.0036	0.0039	0.0042	0.0046	0.0049	0.0052	0.0055	0.0058

from the composition of 01YuTA steel.

With an increase in the silicon content (Fig. 4, *a*), the d parameter decreases. The *d* parameter does not change at a chromium content of 0.02–0.08%, nickel 0.008–0.02%, copper 0.01–0.038% (Fig. 4, *b*).

The considered integral parameters (*d*, *Zy*) characterize the state of the system and cause a change in the properties of steels. Calculations make it possible to select the concentration of elements for 01YuTA, 01YuT steels in the range: C (0.002–0.003%), Mn (0.12–0.13%), Si (0.01–0.02%), P (0.006–0.008%), S (0.011–0.012%), Al (0.04–0.05%), Ti (0.05–0.06%), N (0.004–0.005%), Ca (0.0002–00003%).

The concentration interval of elements, established according to the calculated data, should provide an optimal complex of steels properties.

The calculated concentration intervals of the elements have been confirmed by means of experiments and they will be used to determine the optimal composition of ultra-low carbon steels.

On a practical level, the rolling of a low-carbon steel sheet on a centerless grinding machine ends in the two-phase structure of austenite and ferrite due to high heat losses (Ar_3–Ar_1), which leads to an unsatisfactory final metal structure. A structure with a mixed grain size is formed, since the ferrite grain recrystallizes faster than the austenite grain, which deteriorates the properties of the sheet steel and its drawability [12, 13]. It is possible to control the structure of hot-rolled steel by changing the temperature conditions of the end of rolling and cooling modes of the metal.

At the same time, consumers' requirements for the quality of hot-rolled sheet products and, first of all, for characteristics that affect the technical and economic indicators of the use of metal in production and its service in finished products are constantly growing. The consumer wants to get a relatively inexpensive hot-rolled sheet for cold forming, which is characterized by a high level of service properties. Consequently, metallurgists develop and master new, more efficient technologies for the production of hot-rolled sheets. Many metallurgical plants have reached such a level of technology that allows the production of hot-rolled thin-sheet products with quality indicators that meet the requirements of standards for cold-rolled sheets. Consumers of rolled metal products will have the opportunity to use relatively inexpensive hot-rolled sheet products in their production facilities with a significant economic effect instead of expensive cold-rolled sheet products.

In the process of manufacturing and supplying hot-rolled sheet metal instead of cold-rolled one, in addition to an increase in labour productivity and a decrease in the metal consumption ratio, a manufacturer also receives energy and natural gas savings due to a decrease in the cost of additional operations—cold rolling and annealing. In addition, hot-rolled sheet can be a cost effective rolling stock for cold rolling mills. The surface layer of coarse grains negatively affects the quality of products obtained by cold forming, therefore, due to the unfavourable structure, hot-rolled metal cannot be used instead of cold-rolled metal [14, 15].

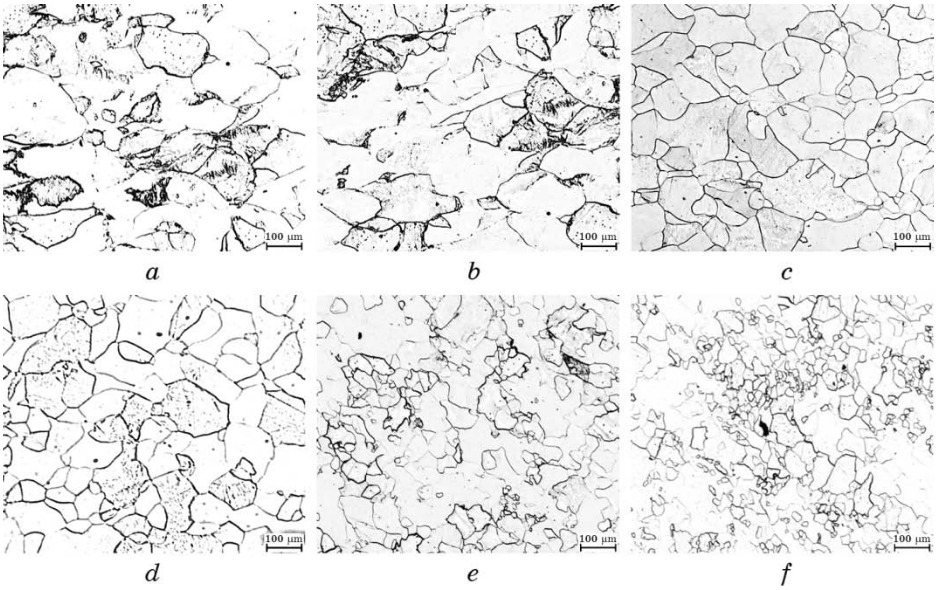
Rolling metal in a single-phase ferrite structure, that is, below the temperature Ar_1, prevents the unfavourable temperature conditions typical of traditional hot rolling technology on a centreless grinding machine. Favourable microstructure and better stamping are achieved by warm rolling in the finishing mill group of CGM steels with a carbon content of less than 0.02% (IF-steels) [16, 17]. The resulting microstructure will provide the metal with better stamping (ferrite grain size is not more than 62 microns, grain unevenness—within three adjacent grain numbers). Processing at low temperatures does not worsen the overall environmental situation and helps to solve the problem of energy saving.

Critical point Ar_3 for IF-steels with a carbon content of 0.002–0.003% is 30–40°C higher than for common low carbon steels. Two competing processes accompany plastic deformation in the austenitic state: a significant increase in the density of dislocations that cause strengthening (hot-cold work) and the rearrangement of these dislocations (steel softening). Hot-cold work occurs during hot deformation, softening—during deformation and after it [18]. Structural and substructural changes in steel are a complex set of processes that coincide with each other. During deformation, sliding within the grain, twinning and intergranular slip develop in austenite, which manifests itself in the wavy nature of grain boundaries. Because of the dislocations movement, their interaction upon meeting and blocking of slip by grain boundaries, the density of dislocations in grains and inside twins increases. The collar substructure is formed, which is characteristic of dynamic strengthening. Since the deformation temperature is high, along with strengthening, dynamic softening develops, which is a consequence of the processes of climb and ascent of dislocations and their annihilation [12, 19].

In the area of hot deformation, structural changes are associated with the formation of a subgrain structure. In the interval after reduction, the steel partially restores the structure. For these reasons, the structure of hot-worked steel is the result of several reductions at different temperatures and pauses between them, that is, there is an overlay of static and dynamic processes of structural changes [20].

During rolling and cooling, a number of processes take place one after one or simultaneously: phase matrix recrystallization, change in the size and shape of ferrite grains, orientation and degree of crystallites perfection. The nature of the development and the degree of completion of these processes depend on the temperatures at which rolling occurs and ends, on the degree of reduction, the rate of deformation and cooling of the metal.

The data of metallographic researches of samples of 01YuTA, 01YuT grades steels indicate that during processing in the austenitic and ferritic regions with cooling by a furnace, a structure is formed, which is characterized by island grain size, some grains are elongated. Ferrite grain size in the surface zone is 20–160 microns, in the central



a *b* *c*

d *e* *f*

Fig. 5. Microstructure of hot-rolled ultra-low carbon steels: *a*, *b*—01YuTA; *c*, *d*—01YuT; *e*, *f*—01YuT*; *a*, *c*, *e*—surface zone; *b*, *d*, *f*—central zone.

zone 25–170 microns (Fig. 5) [18].

Due to a decrease in the amount of the carbide component, which has barrier properties for grain growth, very large ferrite grains are formed in hot-rolled strip with a carbon content of 0.008%, which causes low properties of cold-rolled metal [21].

The authors [22] believe that titanium carbides and carbonitrides that precipitated from austenite block the migration of grain boundaries and the processes of accumulative and secondary recrystallization of ferrite in steel do not develop upon slow cooling.

At low temperatures of the rolling end, a structure with elongated ferrite grains is formed in the structure of the surface zones of a sheet of low-carbon steels (in the extreme parts of the coil, which are rapidly cooled). This structure arises due to the fact that the structural components of the impurity-rich sheet are difficult to recrystallize and stretch in the rolling direction.

To ensure a high deep drawing ability, the steel must have a low flow limit and high plastic properties [23].

Since the relationship between any one characteristic of mechanical properties and stamping of the sheet is difficult to establish, the assessment of the ability of steel to draw is carried out by the combination of properties.

Pulling test allows to determine the most important characteristics of the quality of the steel sheet—flow limit (σ_T), resistance to rupture σ_B, and calculate the flow number σ_T/σ_B. As is well known, the lower the flow limit, the less effort must be made to pull and the more the steel is strengthened at the initial moment of deformation (at constant resistance to rupture). It is very important that the flow limit is as low as possible (up to 200–250 MPa), and the resistance to rupture, on the contrary, should be high—at least 270–350 MPa. In this case, the flow number will be minimal, which will contribute to good stamping of sheet steel, although it does not give a full guarantee. In practice, the σ_T/σ_B ratio is reduced by lowering the flow limit due to the correct choice of technological parameters for steel smelting and rolling. The chemical composition and structure of steel especially affects the value of the flow limit; the lower the flow limit, the less force is needed for extraction, the larger the volume of metal can participate in plastic deformation, the less the likelihood of the formation of local thinning and rupture of the metal during deformation [24]. The flow limit is not only a criterion for assessing steel stamping, but also a criterion for assessing the tendency of steel to form shear lines during stamping: the lower the flow limit, the smaller the flow area on the tensile curve, the less likely the formation of shear lines during stamping [25].

Various mechanical characteristics of metals and alloys, which determine the complex of their strength and plastic properties, are interrelated, but their analysis is often difficult. Thus, it is important to establish the relationship between the strength and ductility of the metal depending on the processing in order to select the most optimal combination of these properties to ensure the quality of the material and to understand the nature of plastic deformation and the nature of fracture [18, 26]. σ_T/σ_B ratio characterizes the plasticity margin to provide the material with a given level of protection against transition to a brittle state.

The work authors [22] indicated the possibility of obtaining a combination of low strength properties and high ductility in microalloyed IF-steels for high stamping: $\sigma_T = 155$ MPa; $\sigma_B = 280$ MPa; $\delta_4 = 46\%$.

An increase in the size of ferrite grains reduces σ_B, σ_T/σ_B, and hardness, and increases the elongation [27].

As is known, the good ability of steel to deep drawing can be expected at $\sigma_T/\sigma_B \approx 0.6$, good—at $\sigma_T/\sigma_B = 0.65–0,75$ and poor—at $\sigma_T/\sigma_B >$ > 0.75. According to the works [12, 23], the value of $\sigma_T/\sigma_B \sim 0.65$ ratio can be practically achieved only in planished sheets with a thickness of more than 0.8 mm after cold rolling. The temper rolling is carried out with a total reduction rate of up to 2% in order to eliminate the flow area of the annealed material, improve the surface quality, reduce σ_T/σ_B ratio, *etc*.

Researches of ultra-low-carbon steels mechanical properties have shown that rolling in two passes and cooling by a furnace provides the metal with good deep drawing ability ($\sigma_B = 225–260$ MPa; $\sigma_T = 165–195$ MPa; $\sigma_T/\sigma_B \sim 0.72–0.73$; $\delta = 25–32\%$; *HRF* 73–75).

4. CONCLUSIONS

The composition of 01YuT, 01YuTA steels is optimized by the method of physical-chemical modelling.

The choice of the concentration of elements for 01YUTA, 01YUT steels implemented in the range: C (0.002–0.003%), Mn (0.12–0.13%), Si (0.01–0.02%), P (0.006–0.008%), S (0.011–0.012%), Al (0.04–0.05%), Ti (0.05–0.06%), N (0.004–0.005%), Ca (0.0002–0.0003%).

The concentration interval of the elements, established according to the calculated data, will provide a uniform structure and the necessary set of properties of steels capable of deep drawing. The structure and properties of 01YuTA, 01YuT deformed steels are investigated. It is found that as a result of processing, which includes rolling the studied steels in two passes and cooling with a furnace, an uneven structure and the following set of properties are formed: $\sigma_B = 225–260$ MPa; $\sigma_T = 165–195$ MPa; $\sigma_T/\sigma_B \sim 0.72–0.73$; $\delta = 25–32\%$; *HRF* 73–75.

The results of the work make it possible to determine the optimal composition of ultra-low-carbon steels, make the choice of rational technological modes of obtaining thin-sheet rolled products for the enterprises of the automobile construction and machine-building industries and predict an increase in metal deep drawing ability.

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