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DEVELOPMENT OF DUPLEX STAINLESS STEELS COMPOSITIONS

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ABSTRACT

Thermodynamic criteria have been developed for a reasonable prediction of compositions of advanced duplex stainless steels. The success of these criteria was studied under the influence of the primary and secondary alloying elements for duplex stainless steels, and the results of these studies have been generalized using multiple regression equations. It has been revealed that the chemical composition optimization of well-known commercial DSS grades, as well as the development of new grades with specified properties can significantly benefit from the use of these equations. Hot physical experiments have shown that thermodynamic modeling well describes the ferrite content found in experimental steels of different compositions at different quenching temperatures.

Introduction

Duplex stainless steels (DSS) with austenite and ferrite in nearly equal fractions [1], which ensures a favorable combination of mechanical properties along with high corrosion resistance of these steels [2–6], are currently widely used in the petrochemical industry.

To obtain the duplex structure of steel containing nearly equal fractions of austenite and ferrite, a balance of stabilizers of these phase components is necessary; therefore, with other things being equal, the content of nickel in DSS is lower than in conventional corrosion resistant austenitic stainless steels. Higher level of alloying of advanced DSS leads to the precipitations of undesirable secondary phases, in particular the σ-phase [7] and chromium nitrides [8]. Other secondary phases such as chromium carbides [9] and/or carbonitrides of microalloying elements [10] can also affect the properties of these steels, but the negative effect of the σ-phase and chromium nitrides is predominant [7–8].

Development of new advanced DSS compositions requires finding a compromise. An increase in chromium content in steel provides higher corrosion resistance, but to keep the "ferrite-austenite" phase balance the concentration of nickel increases [1], which causes the precipitations of an undesirable σ-phase [11–13]. To prevent or minimize the formation of σ-phase, nickel is replaced with nitrogen [14], which provokes the formation of unfavorable precipitation of chromium nitrides [15–17]. It means that there is an optimization task for a composition that would ensure an equal "ferrite-austenite" ratio at the temperature of hot plastic deformation, for example, hot rolling, but at the same time the temperature of the σ-phase and chromium nitrides precipitation should be minimal. It should be noted that the problem with chromium nitrides arises only in super duplex steels alloyed with more than 25% of Cr and more than 0.2% of nitrogen [18, 19]. Therefore, only for these steels we minimize the temperature at which Cr_2N begins to precipitate.

In accordance with the PREN (Pitting Resistance Equivalent Number), which rates the resistance of steel to pitting corrosion [20], duplex steels are classified into the following categories: economically alloyed, standard, super duplex and hyper duplex. The evolution of duplex stainless steel compositions has evolved in two directions [21]: the first one is the development of super duplex and hyper duplex grades with an increased degree of alloying, and the second one is the development of low alloyed steels, primarily due to a decrease in nickel and alloying with copper and nitrogen [6, 22, 23]. However, the physicochemical principles of such developments are still unknown from the literature.

Therefore, the aim of this work was to create thermodynamic criteria for the focused development of new DSSs and optimization of existing compositions of duplex steels, taking into account the requirements for their mechanical, corrosion and technological properties.

Materials and Methods

Much of the work on the calculations was performed by thermodynamic modeling using the FactSage 7.3 software package [24–26] with latest SGTE (2017) database. Phase formation processes in liquid and solidifying steel were simulated under local equilibrium conditions.

Table 1. **Chemical Compositions of Experimental Steels (Wt.%)**

Steel	C	Si	Mn	Cr	Ni	Mo	N	Al	Cu	Ti	Nb	V	Fe
Cr21	0.015	0.64	1.58	21.1	6.1	0.48	0.1	0.02	0.18	0.007	0.04	0.017	balance
Cr23	0.019	0.69	1.63	23.4	6.0	0.48	0.1	0.04	0.17	0.008	0.04	0.016	
Cr26	0.021	0.61	1.49	26.2	5.9	0.50	0.1	0.02	0.16	0.008	0.05	0.017	

Table 2. **Chemical Compositions of Investigated Commercial Steels (Wt.%)**

UNS No.	Grade	C	Cr	Mn	Ni	Mo	N	Si	Cu
S32001	Lean	0.03	19.5–21.5	4.0–6.0	1.0–3.0	0.6	0.05–0.17	0.1	1.0
S32003	Standard		19.5–22.5	2.0	3.0–4.0	1.5–2.0	0.14–0.20		—
S31200	25 Cr		24.0–26.0		5.5–6.5	1.2–2.0			—
S32950	Super		26.0–29.0		3.5–5.2	1.0–2.5	0.15–0.35		—
S32707	Hyper		26.0–29.0	1.5	5.5–9.5	4.0–5.0	0.30–0.50		1.0
S33207	Hyper		29.0–33.0		6.0–9.0	3.0–5.0	0.40–0.60		

The experimental part of the work was performed on duplex stainless steel made in an open induction furnace. Cast samples were studied after heat treatment carried out by successive heating of the samples to different temperatures (1100, 1150 and 1200 °C), holding at these temperatures for 90 minutes and water quenching. Metallographic studies were performed using a Zeiss Axiovert 200 MAT motorized optical microscope equipped with a Thixomet image analyzer. To reveal the microstructure, electrochemical etching in a 60% aqueous nitric acid solution for 15 seconds was carried out using a Buehler PoliMat 2 device. The volume fraction of ferrite was estimated by the grid method.

Three steel specimens have been obtained for the experiment; their chemical compositions determined using the SPECTROMAX-F spectrometer are given in **Table 1**. The content of sulfur and phosphorus in all studied specimens did not exceed 0.01% for each element.

Development of thermodynamic criteria

Based upon the DSS definition [1, 27], we can formulate the requirements for the chemical composition of these steels as follows: the temperature at which austenite and ferrite are in equal fractions, $T_{50/50}^{\gamma/\delta}$, should be in the hot plastic deformation range, and the temperatures at which σ-phase, T_0^{σ} and chromium nitrides, $T_0^{Cr_2N}$ formation begins, must be below these temperatures to exclude the presence of these phases in the structure of the finished steel products. Let us examine how these criteria can be controlled by the example of hot rolling.

The analysis of phase formation processes in two experimental DSS of different compositions revealed that such a requirement needs to find a compromise as shown below (**Fig. 1**).

If the temperature at which austenite and ferrite are in equal fractions, $T_{50/50}^{\gamma/\delta}$, is in the temperature range of hot plastic deformation, then the temperature T_0^{σ} is too high (**Fig. 1, *a***). If we choose the composition so that the σ-phase begins to precipitate at low temperatures, then the $T_{50/50}^{\gamma/\delta}$ falls outside the temperature range of hot plastic deformation (**Fig. 1, *b***).

Let us focus on some well-known commercial steels to check how they correspond to these criteria. The chemical composition of these steels is given in **Table 2**.

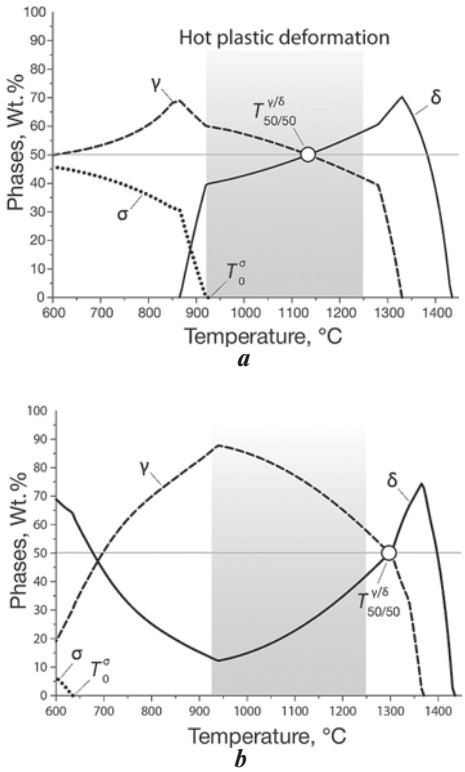

Fig. 1. The temperature of ferrite and austenite coexistence in equal fractions ($T_{50/50}^{\gamma/\delta}$) and the temperature at which σ-phase formation begins (T_0^{σ}) at two different chemical compositions of steels: Fe–0.03%C–29%Cr–1.5%Mn–8%Ni–3%Mo–0.15%N–0.1%Si–1%Cu (*a*); Fe–0.03%C–20%Cr–1.5%Mn–5%Ni–0.3%Mo-0.2%N–1%Si–0.3%Cu (*b*)

Table 3. **Critical Temperatures for Commercial Steels at Different Values of Cr_{eq}*) and Ni_{eq}**)**

Steel	Chemical composition	Criterion, °C		
		$T_{50/50}^{\gamma/\delta}$	T_0^{σ}	$T_0^{Cr_2N}$
S32001	Mean	1279	770	–
	$Cr_{eq}\uparrow$*, $Ni_{eq}\downarrow$**	1076	736	–
	$Cr_{eq}\downarrow$*, $Ni_{eq}\uparrow$**	1366	769	–
S31200	Mean	1079	790	880
	$Cr_{eq}\uparrow$, $Ni_{eq}\downarrow$	912	795	884
	$Cr_{eq}\downarrow$, $Ni_{eq}\uparrow$	1199	785	–
S32003	Mean	1105	674	900
	$Cr_{eq}\uparrow$, $Ni_{eq}\downarrow$	–	690	917
	$Cr_{eq}\downarrow$, $Ni_{eq}\uparrow$	1240	650	891
S32950	Mean	–	775	960
	$Cr_{eq}\uparrow$, $Ni_{eq}\downarrow$	–	781	995
	$Cr_{eq}\downarrow$, $Ni_{eq}\uparrow$	1185	764	937
S32707	Mean	–	964	1078
	$Cr_{eq}\uparrow$, $Ni_{eq}\downarrow$	1038	955	1104
	$Cr_{eq}\downarrow$, $Ni_{eq}\uparrow$	–	973	–
S33207	Mean	–	970	1161
	$Cr_{eq}\uparrow$, $Ni_{eq}\downarrow$	–	980	1210
	$Cr_{eq}\downarrow$, $Ni_{eq}\uparrow$	–	942	1091

*) $Cr_{eq}\uparrow$ и $Cr_{eq}\downarrow$ — chromium equivalents at the upper and lower levels, respectively.
**) $Ni_{eq}\uparrow$ и $Ni_{eq}\downarrow$ — nickel equivalents at the upper and lower levels, respectively.

Analysis of the compositions of these steels showed that $T_{50/50}^{\gamma/\delta}$ and T_0^{σ} changed significantly (**Table 3**) due to the alloying elements concentration changes within these grades (see **Table 2**).

UNS S32001 steel when changing the concentration of its alloying elements within the grade has the widest temperature range for the coexistence of ferrite and austenite in equal fractions, ($T_{50/50}^{\gamma/\delta}$), including the range of hot rolling, and relatively low temperature T_0^{σ}. Chromium nitrides are not formed in this steel.

Steels UNS S31200 and UNS S32003 have a favorable combination of $T_{50/50}^{\gamma/\delta}$, T_0^{σ} and $T_0^{Cr_2N}$ thus they can be considered as advanced DSS. With any changes in the concentration of alloying elements within a grade many compositions of these steels provide $T_{50/50}^{\gamma/\delta}$ inside of the hot rolling temperature range, while the temperatures T_0^{σ} and $T_0^{Cr_2N}$ remain quite low.

The other three steels have an unfavorable combination of $T_{50/50}^{\gamma/\delta}$, T_0^{σ} and $T_0^{Cr_2N}$. If in UNS S32950 steel the σ-phase is formed at a sufficiently low temperature for all combinations of its alloying elements, then in UNS S32707 and S33207 steels the temperatures T_0^{σ} and $T_0^{Cr_2N}$ become unacceptably high and close to the heating temperature for rolling. However, the main problem of these steels is that the equal fractions ratio of ferrite and austenite is not achieved at any temperature of solid steel, including hot rolling at any concentration of their alloying elements. Therefore, the successful production of these steels is possible only with multi-stage method of procedure and strict adherence to processing conditions.

Next, we deal with an influence of main alloying elements on the criteria $T_{50/50}^{\gamma/\delta}$ and T_0^{σ} taking into account the temperature range of hot rolling. With an increase in the chromium content in DSS at a constant nickel content, the temperature $T_{50/50}^{\gamma/\delta}$ significantly decreases, and T_0^{σ}, on the contrary, increases (**Fig. 2,** grey lines).

We have placed on these graphs the values of the criteria $T_{50/50}^{\gamma/\delta}$ (see **Fig. 2, *a***) and T_0^{σ} (see **Fig. 2, *b***) calculated for known commercial DSS at the limit concentrations of alloying elements within the grades of these steels. As follows from the analysis of these results (see **Fig. 2**), not all commercial steels satisfy the criteria $T_{50/50}^{\gamma/\delta}$ and T_0^{σ}.

The next thing for consideration is the influence of other alloying elements in the DSS commercial grades on the criteria $T_{50/50}^{\gamma/\delta}$ and T_0^{σ} (**Fig. 3**).

First, we select steel Fe–X%Cr–0.03%C–6%Ni–1%Mn–1.5%Mo–0.1%N–0.5%Si (see **Fig. 3**) as the basis and add 4% of manganese to this steel. In such steels, depending on the chromium content, the temperature $T_{50/50}^{\gamma/\delta}$ rises by 32–57 °C (Fig. 3a), and T_0^{σ} — by 17–83 °C (**Fig. 3, *b***). If to the initial composition of this steel 1.5% of molybdenum is added, then depending on the chromium content in it, the temperature $T_{50/50}^{\gamma/\delta}$ will decrease by 71–140 °C, and T_0^{σ} will increase by 40–50 °C.

Then, we choose steel Fe–X%Cr–0.03%C–1%Mn-8%Ni–1.5%Mo–0.1%N–0.5%Si as the basis (see **Fig. 3**) and add 0.5% of copper to this steel. In such steels, depending on the chromium content in it, $T_{50/50}^{\gamma/\delta}$ increases by 105–136 °C (see **Fig. 3, *a***), and T_0^{σ} increases by 9–12 °C (see **Fig. 3, *b***). If 0.15% of

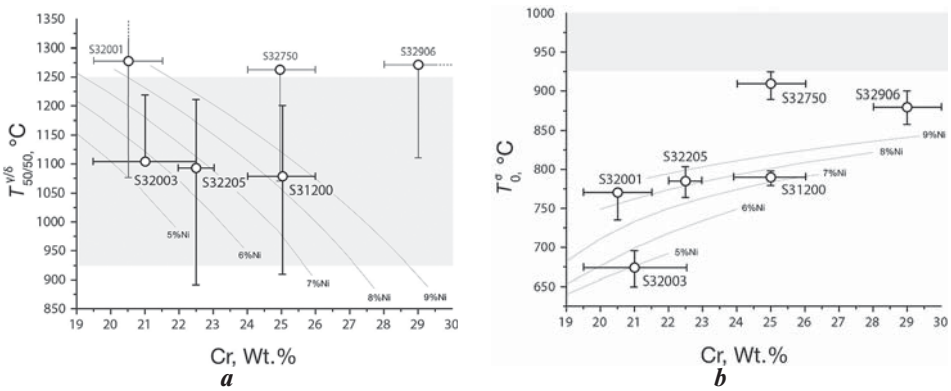

Fig. 2. The temperatures $T_{50/50}^{\gamma/\delta}$ (*a*) and T_0^{σ} (*b*) vs. Cr concentration for steel Fe–0.03%C–1%Mn–1.5%Mo–0.1%N–0.5%Si at a constant nickel (grey lines) and for commercial DSS

nitrogen is added to the initial composition of this steel, the temperature $T_{50/50}^{\gamma/\delta}$ raises even more (144-205 °C), and T_0^{σ} does not increase, but decreases by 7–8 °C.

Thus, by varying the alloying elements, we can change $T_{50/50}^{\gamma/\delta}$ and T_0^{σ}, ensuring their optimal values. In high nitrogen steels, along with these criteria, the temperature $T_0^{Cr_2N}$ should be taken into account.

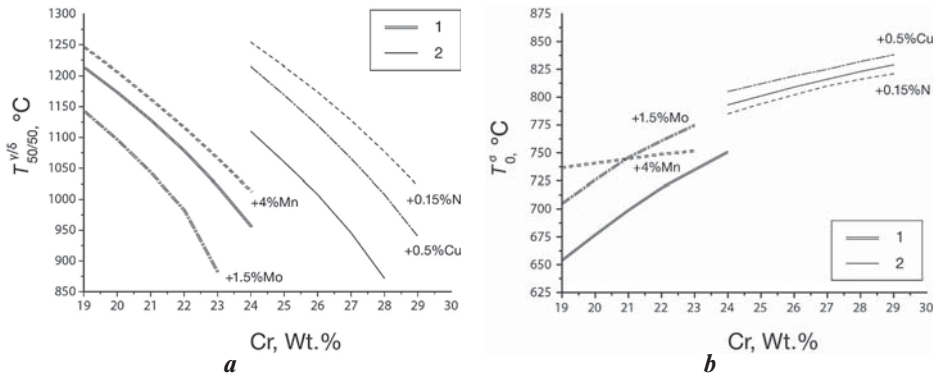

Fig. 3. The temperatures $T_{50/50}^{\gamma/\delta}$ (*a*) and T_0^{σ} (*b*) vs. secondary alloying elements concentrations in DSS: Fe–X%Cr–0.03%C–1%Mn–6%Ni–1.5%Mo–0.1%N–0.5%Si (*1*) –X%Cr–0.03%C–1%Mn–8%Ni–1.5%Mo–0.1%N–0.5%Si (*2*)

Calculations of Optimal DSS Compositions

Let's summarize the influence of chemical composition of steels on the main criteria $T_{50/50}^{\gamma/\delta}$, T_0^{σ} and $T_0^{Cr_2N}$ for all possible DSS compositions known from literature [1].

More than 400 calculations of different DSS chemical compositions were performed by thermodynamic modeling methods so as to cover all ranges of change of compositions of well-known commercial DSS (Wt.%): C — 0.01...0.1; Cr — 18...31; Mn — 1...10; Ni — 1...10; Mo — 1...5; N — 0.01...0.6; Si — 0.1...1; Cu — 0...1.25; Ti — 0...0.7; Nb — 0...2; V — 0...1.5.

As a result of the calculations, we have obtained a database of the chemical compositions of steels and the corresponding temperatures: $T_{50/50}^{\gamma/\delta}$, T_0^{σ} and $T_0^{Cr_2N}$. The calculation results of these temperatures were summarized using regression analysis performed by STATISTICA software. Equations of multiple regression have been obtained that adequately describe the influence of the chemical composition of steels on the criteria $T_{50/50}^{\gamma/\delta}$, T_0^{σ} and $T_0^{Cr_2N}$:

$$T_{50/50}^{\gamma/\delta} = 1644 + 902\cdot\%C - 46\cdot\%Cr + 76\cdot\%Ni - \\ - 45\cdot\%Mo + 1024\cdot\%N + 135\cdot\%Si \\ + 221\cdot\%Cu - 163\cdot\%Ti - 23\cdot\%Nb - 209\cdot\%V \quad (1)$$

$$T_0^{\sigma} = 453 - 207\cdot\%C + 7\cdot\%Cr + 26\cdot\%Ni - \\ - 3\cdot\%Mn + 24\cdot\%Mo - 8\cdot\%V - 29\cdot\%Si \\ + 33\cdot\%Cu - 39\cdot\%Ti - 13\cdot\%Nb \quad (2)$$

$$T_0^{Cr_2N} = 370 + 27\cdot\%Cr + 12\cdot\%Ni - 22\cdot\%Mo + \\ + 550N + 31Si - 126Nb - 25\cdot\%V \quad (3)$$

For each coefficient in equations 1 to 3, the *p*-value was below 0.05. **Fig. 4** shows the scattering diagram for the temperatures $T_{50/50}^{\gamma/\delta}$, T_0^{σ} and $T_0^{Cr_2N}$ calculated from

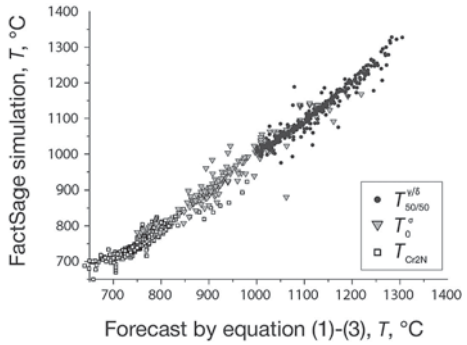

Fig. 4. Scattering diagram for temperatures $T_{50/50}^{\gamma/\delta}$, T_0^{σ} and $T_0^{Cr_2N}$: calculated by FactSage vs. predicted by equations 1 to 3

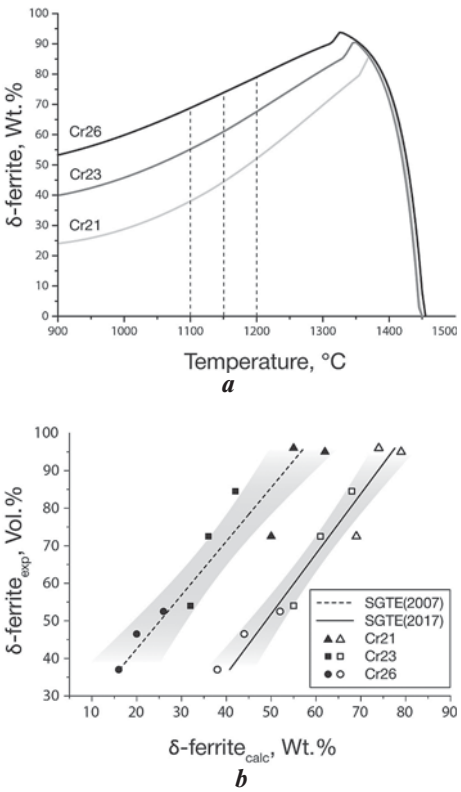

Fig. 5. δ-ferrite Wt.% in experimental steels (Table 1) at different heat treatment temperatures (*a*). Calculation results with SGTE (2017) database (*a*) and comparison of experimental and calculation results with SGTE databases from 2007 and 2017 (*b*)

these equations, on the one hand, and the temperatures obtained by thermodynamic modeling, with another. This diagram illustrates the high adequacy of regression equations 1 to 3: the coefficients of determination exceed 0.96.

For experimental verification of the reliability results of thermodynamic modeling, a hot physical experiment was carried out, including the duplex stainless-steel making, followed by quenching into water from temperatures of 1100, 1150 and 1200 °C. Different heat treatment temperatures of steels provided different Wt.% of δ-ferrite in the specimens (**Fig. 5, *a***).

As a comparison, calculations were performed using two SGTE databases from different years (see **Fig. 5, *b***). A comparative analysis of the δ-ferrite fraction in experimental steels of different chemical compositions after quenching from different temperatures confirms that the latest 2017 year databases [26] describe the experimental ferrite contents at different quenching temperatures much better (see **Fig. 5, *b***). However, a future improvement of thermodynamic databases is still required.

Let us show how the obtained multiple regression equations, 1 to 3, can be used to optimize the composition of known DSS and to search for the compositions of new steels.

We enhance the proposed above criteria defining the mechanical and technological properties with the PREN criterion, which characterizes the resistance of steel to pitting corrosion and is calculated by its chemical composition [28, 29]:

$$PREN = \mathrm{Cr} - 14.5\mathrm{C} + 3.3\mathrm{Mo} + 2\mathrm{W} + 2\mathrm{Cu} + 16\mathrm{N} \quad (4)$$

Optimization was carried out using the SOLVER function of the MS Excel spreadsheet processor by which the steel composition was calculated from equations 1 to 4 taking into account one of the criteria as an objective function and given restrictions on other criteria.

Steel Composition Optimization

We select the optimal compositions of the previously considered commercial grades, choosing PREN (4) as the objective function, then for the remaining criteria we introduce the following restrictions:

$$1150\ ^\circ\mathrm{C} < T_{50/50}^{\gamma/\delta} + \Delta T_1 < 1250\ ^\circ\mathrm{C} \quad (5)$$

$$T_0^{\sigma} < 900\ ^\circ\mathrm{C} \quad (6)$$

$$T_0^{\mathrm{Cr_2N}} < T_{50/50}^{\gamma/\delta} - \Delta T_2 \quad (7)$$

Here, in condition (5), 1150–1250 °C is the recommended temperature range for hot rough rolling, and the temperature $T_{50/50}^{\gamma/\delta}$ has been increased by ΔT_1 taking into account cooling of the plate during this operation. If the temperature of the end of the finish rolling is 900 °C, then inequality (6) sets the conditions for preventing the precipitations of the σ-phase in the finished steel product. It is known that the precipitate of unfavorable Cr_2N can occur only with prolonged isothermal exposure when the billet is heated for rolling [30–32]. This was taken into account by introducing condition (7), according to which the temperature $T_0^{\mathrm{Cr_2N}}$ should be lower by ΔT_2 than the temperature of austenite and ferrite existence in equal fractions, which determines the temperature of pre-rolling heating according to condition (5).

Table 4. **Optimization of Well-known Commercial Steels Compositions to Obtain Maximum PREN with Restrictions (5)–(6) at ΔT_1 = 20 °C, ΔT_2 = 30 °C**

Grade, UNS	PREN actual	Criterion, °C			Element, Wt.%					
		$T_{50/50}^{\gamma/\delta}$	T_0^{σ}	$T_0^{\mathrm{Cr_2N}}$	Cr	Mn	Ni	Mo	N	Cu
Successful optimization: wide "technological gates" found										
S32001	27.4	1230	707	820	21.5	6.0	1.0	0.6	0.17	0.8
S32003	29.3	1130	703	873	20.0	2.0	3.0	2.0	0.20	–
S31200	30.9	1130	762	874	24.0	2.0	5.5	1.3	0.20	–
S32707	55.1	1201	897	1154	29.0	1.5	5.5	5.0	0.50	1.0
Successful optimization: but the "technological gates" are narrow										
S33207	57.7	1230	881	1200	30.5	1.5	6.0	5.0	0.57	1.0
There are no optimal compositions among all given steels										
S32950	34.5	1070	736	978	26.0	2.0	3.5	1.0	0.35	–

Table 5. **Search for the Composition of Steel with Predetermined Properties 0.03%C–(18–29)%Cr–(1–2)%Mn–(3–8)%Ni–(1–6)%Mo–(0.1–0.4)%N–(0–1)%Cu–0.01%Ti–0.03%Nb–0.03%V**

Steel	PREN actual	Criterion, °C			Element, Wt.%					
		$T_{50/50}^{\gamma/\delta}$	T_0^{σ}	$T_0^{\mathrm{Cr_2N}}$	Cr	Mn	Ni	Mo	N	Cu
PREN → 30, 35, 40; ΔT_1 = 20 °C, ΔT_2 = 30 °C										
1	30.0	1130	670	903	18	4	1	2.5	0.26	–
2	35.0		683	964	18	4	1	3.7	0.33	
3	40.0		696	1024	18	4	1	4.9	0.40	
PREN → max; ΔT_1 = 20 °C, ΔT_2 = 30 °C										
4	45.9	1130	739	1058	19.1	4	1	6.0	0.40	0.5
PREN → max; ΔT_1 = 20 °C, ΔT_2 = 100 °C (line 5), 150 °C (line 6), 200 °C (line 7)										
5	45.4	1154	734	1054	18.7	4	1	6.0	0.4	0.5
6	44.3	1195	725	1045	18.0			5.9		
7	42.2	1230	715	1030				5.2		

The optimization results of known commercial DSS compositions for the target value of PREN are given in **Table 4**. Here and in all steels studied further, the carbon content is constant and equal to 0.03%.

The optimization was successful for steels S32001, S32003, S31200, the optimal compositions and the corresponding criteria are given in Table 4.

It was possible to find the optimal composition in S33207 steel, but the temperature $T_0^{\mathrm{Cr_2N}}$ = 1200 °C is close to the temperature $T_{50/50}^{\gamma/\delta}$ = 1230 °C, which will

lead to a significant narrowing of the "technological gate" during production.

No optimal compositions were found in S32950 steel. It is impossible for them to choose a composition for which the temperature $T_{50/50}^{\gamma/\delta}$ would be in the hot rolling range.

Let us consider the task of developing new steels with specified technological and operational properties.

Based on the analysis of well-known standards and publications [1, 33], we select the variation ranges of alloying elements of steels (**Table 5**). We will vary the contents of chromium, manganese, nickel, molybdenum, nitrogen and copper, and will define constant concentrations of micro-alloying elements (titanium, niobium and vanadium). Here, the lines *1*, *2*, and *3* show the results of optimizing the composition of steels for fixed target values of PREN (30, 35 and 40, respectively), and the line *4* the optimal compositions of steels with the highest PREN = 45.9.

We note that an increase in PREN in these steels was obtained, first of all, due to nitrogen content growth; therefore, the temperature at which the formation of Cr_2N starts rose almost to the limit value specified by condition (7). Therefore, for such steels, the "technological gate" of heating temperatures for rolling and the actual rolling process itself has significantly narrowed, with all the associated risks of defects. Therefore, to expand the "technological gate", which is formally regulated by ΔT_2, we will gradually increase it by: 100, 150 and 200 °C. For these temperatures, new optimal compositions were calculated (see **Table 5**, lines *5*, *6* and *7*, respectively). As follows from these results, at the cost of a slight decrease in PREN, it was possible to significantly expand the "technological gate" during the hot rolling of these steels.

Thus, the practical value of the developed criteria for optimizing existing compositions of commercial DSSs and developing new steels with desired properties has been shown.

Summary

1. Thermodynamic criteria have been developed for a reasonable choice of the chemical compositions of advanced duplex stainless steels (DSSs) based on the following requirements:
   - temperature at which austenite and ferrite are in equal fractions, $T_{50/50}^{\gamma/\delta}$, must be in the range of hot plastic deformation;
   - temperature at which σ-phase formation begins T_0^{σ} should be lower than the temperature of the end of hot plastic deformation to exclude its appearance in the finished steel product;
   - temperature at which the formation of chromium nitrides begins $T_0^{Cr_2N}$ should be lower than the heating temperature for rolling.
2. A thermodynamic analysis of the composition of existing DSSs shows that, when the alloying elements change within the grade, there is a significant scatter in the values of $T_{50/50}^{\gamma/\delta}$, T_0^{σ} and $T_0^{Cr_2N}$, therefore, at the maximum concentrations of alloying elements within the grade composition either temperature $T_{50/50}^{\gamma/\delta}$ is outside the range of hot plastic deformation temperatures, or temperatures T_0^{σ} or $T_0^{Cr_2N}$ are too high to avoid the precipitations of the σ-phase or chromium nitrides in the finished metal product.
3. A hot physical experiment shows that thermodynamics with the newest SGTE database well describes the phase composition of the studied experimental steels at different quenching temperatures.
4. The influence of the chemical composition of DSS on the developed criteria is generalized in the multiple regression equations, which can be useful for optimizing the chemical composition of known commercial DSS, as well as for developing new steel grades with predetermined properties. Examples of such optimizations have been discussed.

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