

EFFECT OF Mn, Al, Ni, AND C CONTENT ON THE EQUILIBRIUM PHASE COMPOSITION OF ALLOYS BASED ON THE Fe–Mn–Al–Ni–C SYSTEM

L. M. Kaputkina, A. G. Svyazhin, D. E. Kaputkin,
V. E. Bazhenov, A. V. Bronz, and I. V. Smarygina

UDC 669.15'786-194

A Thermo-Calc program is used to calculate isothermal and polythermal sections of diagrams and phase composition for alloys of the Fe–Mn–Al, Fe–Mn–Al–Ni, and Fe–Mn–Al–Ni–C systems. Phase diagrams are used to study the effect of nickel, aluminum, manganese, and carbon on the equilibrium structure of alloys of the Fe–Mn–Al–Ni–C system. Concentration ranges are determined for existence of single-phase γ -alloys in the range 1000–1200°C. It is established that achievement of a considerable aluminum content (10%) and existence of increased specific strength for austenitic alloys of the Fe–Mn–Al–Ni–C system containing not less than 5% Ni is possible with a manganese content of not less than 20% and carbon not less than 1.4%.

Keywords: light steels, Thermo-Calc, phase diagrams, equilibrium phases.

High-manganese austenitic steels and alloys with a considerable aluminum content are new promising materials. These alloys exhibit a high level of ductility combined with good specific strength [1, 2]. Alloys based on the Fe–Mn–Al–C system with a high aluminum content may have lower (by 15–20%) density compared with high-strength complexly alloyed steels [3], and correspondingly greater specific strength comparable with that of light metal alloys. They may find extensive use as ultralight steels in aircraft and automobile manufacturing, as steels with special properties in chemistry and power generation, cryogenic technology, etc.

In a preceding article [4], it was demonstrated that the phase equilibrium diagram for alloys of the Fe–Mn–Al–C system may be used for predicting the structure of these alloys after heat treatment. They give a representation similar to the actual structure of alloys in the hot deformation temperature and high-temperature heat treatment range. In order to predict the structure at 500–550°C, it is also necessary to consider properties of excess phases and their inclination towards precipitation. Thus, preliminary alloy composition selection may be carried out on the basis of the equilibrium phase diagrams for whose construction a number of programs have been developed, for example, Thermo-Calc.

In this article, the phase composition of a number of alloys of the Fe–Mn–Al–Ni–C system has been analyzed using phase equilibrium diagrams.

Equilibrium phase composition of alloys of the Fe–Mn–Al–Ni–C system. Controlled formation of the structure of excess phases within steel by heat treatment (HT) and thermomechanical treatment (TMT) methods is possible from an original condition of single-phase and uniform solid solution. A necessary condition for this is the existence of quite a broad range of single α - or, what in many cases is preferable, γ -solid solution in this alloy at temperatures normally used for hot deformation (950–1250°C).

Isothermal and polythermal sections of the Fe–Mn–Al–Ni–C diagram are considered in this article with a variable content of one of the elements (Ni, Al, C) and constant content of the rest.

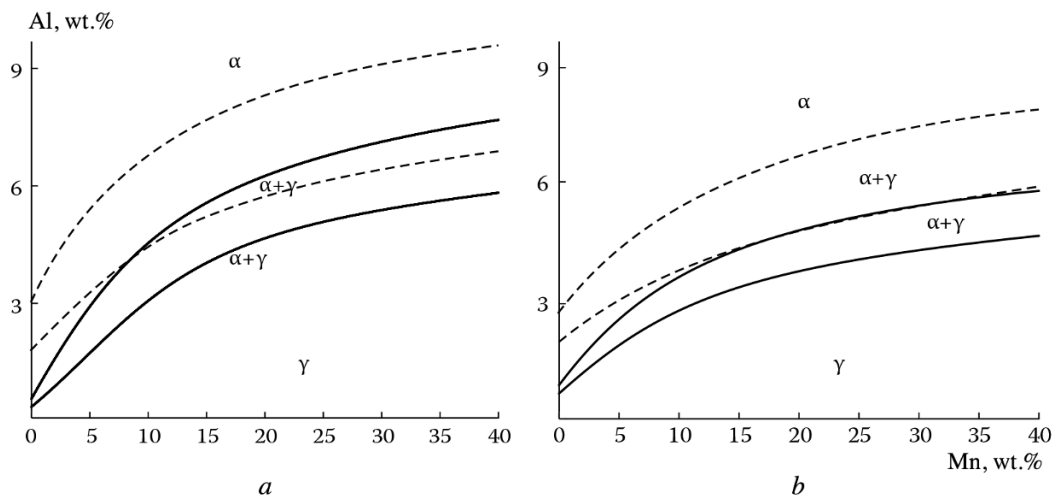


Fig. 1. Isothermal sections of Fe-Mn-Al diagram (solid lines) and Fe-Mn-5%Ni-Al (broken lines) at 1000°C (a) and 1200°C (b).

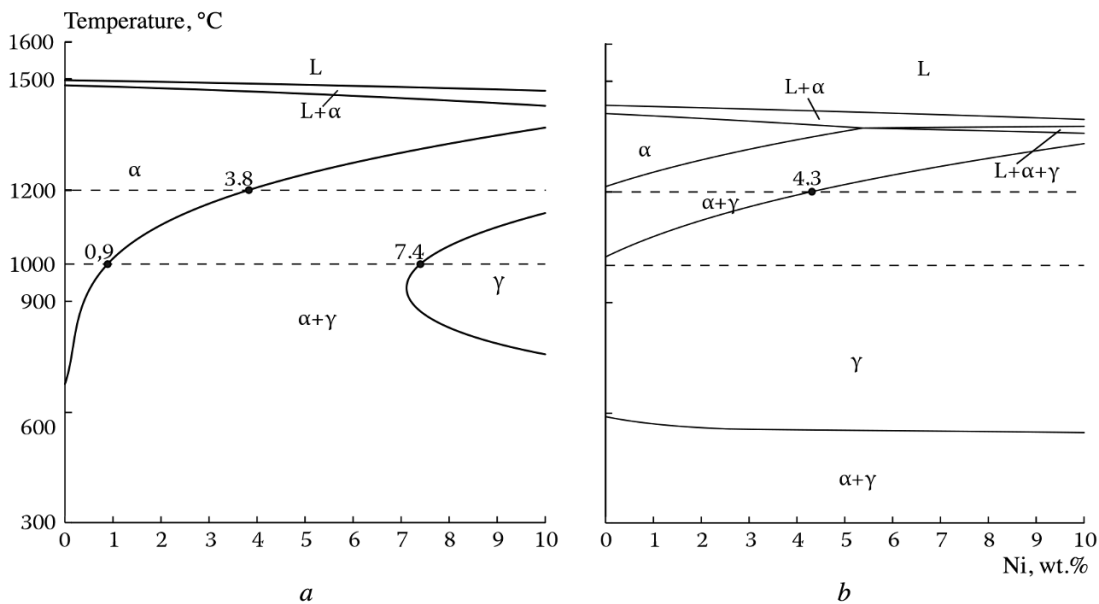


Fig. 2. Polythermal sections of alloy diagrams: a) (Fe-10%Mn-5%Al)-Ni; b) (Fe-25%Mn-5%Al)-Ni.

Effect of Ni on alloy structure. Isothermals sections of the Fe-Mn-Al and Fe-Mn-Ni-Al diagrams at 1000 and 1200°C are shown in Fig. 1. In Fe-Mn-Al alloys containing 30% Mn, the field of γ -solutions is limited by Al content of not more than 5.4% at 1000°C and Al not more than 4.5% at 1200°C, i.e., comparatively low aluminum content, and correspondingly a small reduction in alloy density. During melting of an alloy with 30% manganese, as a result of its strong evaporation production problems arise: considerable manganese loss, complexity of falling within a prescribed chemical composition, and atmosphere contamination, therefore, a high manganese content in alloys is undesirable. However, with a manganese content of 10% in order to obtain austenitic steel the permissible aluminum content is even less (3%), and the reduction in density comprises less than 4%. Introduction of 5% nickel makes it possible with all Mn contents to increase the Al content by about 1% (see Fig. 1).

TABLE 1. Content of Elements Bounding Single-Phase γ -Region at 1000–1200°C

Alloy	Content, wt.%			
	Mn	Ni	Al	C
Fe–Mn–Al	10	–	≤ 2.8	–
	20	–	≤ 3.8	–
	30	–	≤ 4.2	–
Fe–Mn–Ni–Al	10	> 10	5	–
	25	≥ 4.3	5	–
	10	5	≤ 3.8	–
	10	10	≤ 5	–
	25	5	≤ 5.1	–
	25	10	≤ 6.0	–
Fe–Mn–Ni–Al–C	10	5	5	≥ 0.26
	20	5	10	≥ 1.40
	25	5	5	≥ 0.00
	25	5	10	≥ 1.37

With any nickel content within the limits of 1–10%, all alloys crystallize as single-phase α - or two-phase ($\alpha + \gamma$)-solutions (Fig. 2). In the range 1000–1200°C, in the single-phase γ -region there are alloys containing more than 10% Ni with an Mn content of 10%, and alloys containing more than 4.3% Ni with an Mn content of 25%. The lower boundary of the γ -region is almost unchanged and is at $\approx 550^\circ\text{C}$, and the upper boundary increases from 1020 to 1350°C with an increase in nickel content from 0 to 10% (see Fig. 2).

With an increase in Al content to 15% in the (Fe–Mn–Al)–Ni system with an Mn content of 10 and 25%, all alloys crystallize with single-phase α -solution. In the range 600–1400°C with a nickel content within the limits 0–10%, all alloys are single-phase α -solutions. With a temperature below 500°C and nickel content not less than 9%, an $\alpha + \gamma$ solution forms, and below 450°C there is additional precipitation of Fe_3Al phase.

Thus, in alloys of the Fe–Mn–Al–Ni system the strongest effect on structure is caused by aluminum. In order to obtain single-phase γ -solution in the range 1000–1200°C, even with a comparatively low aluminum content (5%), quite a considerable concentration of Mn or Ni is required. Nickel in contrast to manganese does not create production problems. However, considering the extremely high cost of nickel introducing it into alloy composition without a reduction in its economic effect is only possible in small quantities, and therefore subsequently only alloys are considered with a nickel content of 5%.

Effect of aluminum on alloy structure. Polythermal sections of the diagram of (Fe–Mn–Al)–Ni alloys containing 5% Ni, and 10 and 25% Mn are shown in Fig. 3. It is seen that in both cases crystallization is possible by a $L \rightarrow \gamma$ scheme, i.e., without forming δ -ferrite, with small aluminum contents (up 1.5 and 3.5%, respectively). At 1000–1200°C, the boundary of the γ -region reaches an Al content of 3.8% and with an Mn content of 10%, and it reaches 5.1% Al with a content of 25% Mn. Single-phase α -solutions at 1000–1200°C exist with an aluminum content of more than 6.8 and 8.8%, respectively.

With an increase in nickel content to 10% in alloys (Fe–5%Ni–10%Mn)–Al, the boundaries of the phase regions shift in the direction of greater aluminum content. The boundary of the γ -region at 1000–1200°C reaches 5% Al. The boundary of the α -region at these temperatures exists with $\text{Al} \geq 8.5\%$. With an increase in nickel content in (Fe–5%Ni–25%Mn)–Al alloys to 10%, the form of the diagram presented in Fig. 3b is unchanged, and only the boundary of the phase region shifts. In this case, primary crystallization of γ -phase is observed up to an Al content of 4.5%, the boundary of the γ -region at temperature of 1000 to 1200°C reaches 6% Al, and the α -region in this temperature region exists with an aluminum content greater than 10.5% (see Table 1).

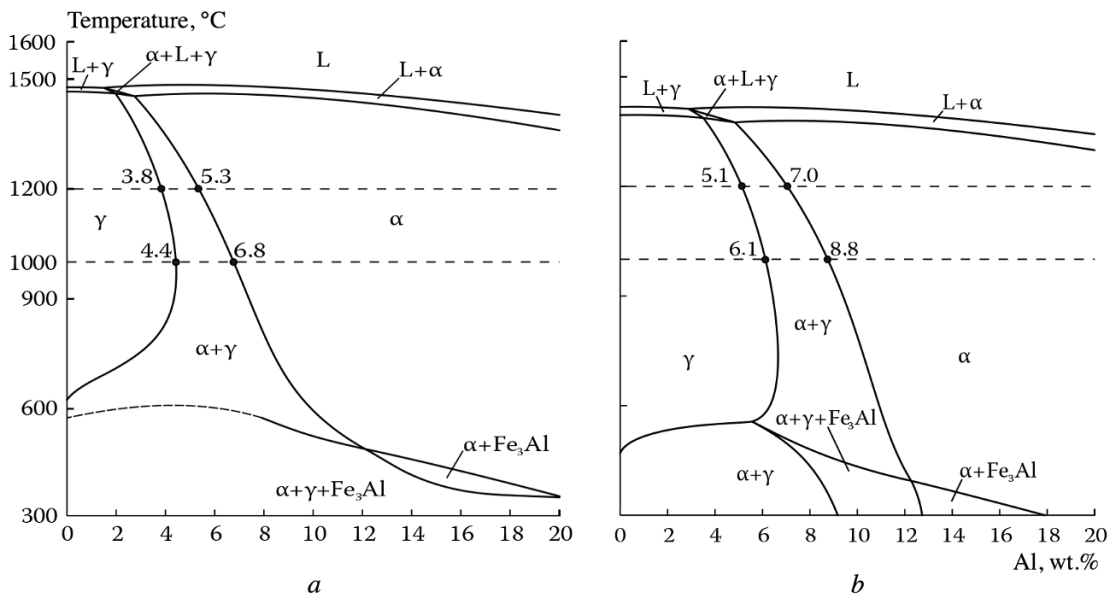


Fig. 3. Polythermal sections of alloy diagrams: a) (Fe-10%Mn-5%Ni)-Al; b) (Fe-25%Mn-5%Ni)-Al.

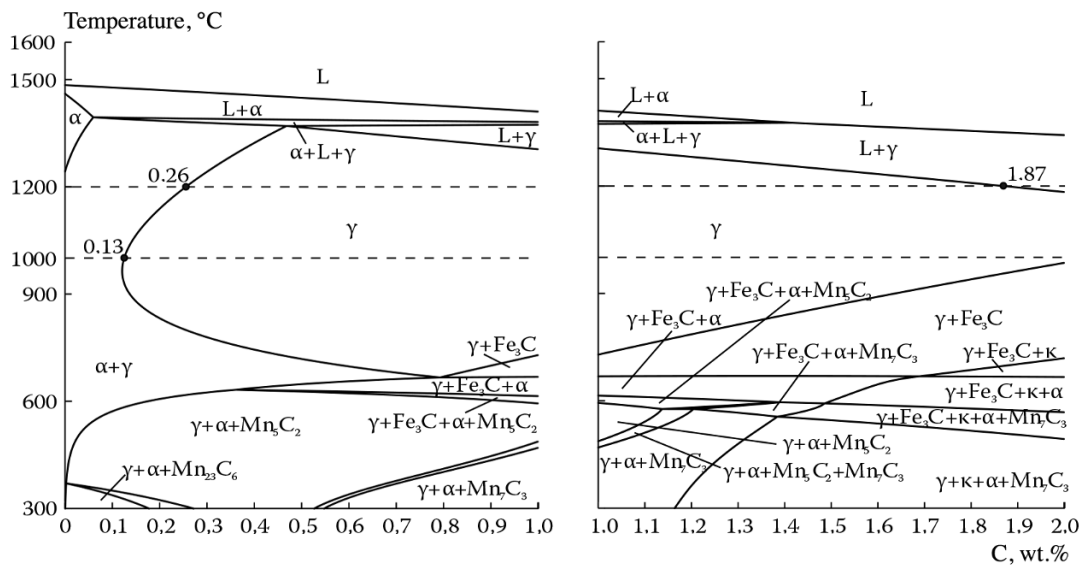


Fig. 4. Polythermal sections of alloy diagrams of the system (Fe-Mn-Al-Ni)-C containing 5% Ni, 10% Mn, and 5% Al.

Effect of carbon on alloy structure. Diagrams have been calculated and plotted for (Fe-Mn-Al-Ni)-C alloys containing 5% Ni; 10 and 25% Mn; 5, 10, and 15% Al. Diagrams are considered below for some promising alloys. A polythermal section is shown in Fig. 4 for the diagram of alloys of the system (Fe-Mn-Al-Ni)-C containing 5% Ni, 10% Mn, and 5% Al. The presence of carbon in the alloy significantly complicates the diagram. With a carbon content up to 1.45%, crystallization proceeds with the formation of α -phase, but in alloys containing carbon not less than 1.4% it proceeds by a $(L + \gamma) \rightarrow \gamma$ scheme, i.e., without forming δ -ferrite. The presence of carbon in alloys significantly expands the temperature range for alloy crystallization and the degree of element liquation. In the range 1000–1200°C, in the single-phase γ -region alloys will be found containing 0.26–1.87% carbon. With $C > 0.8\%$, cementite precipitates from γ -solution. At 550°C and a carbon content

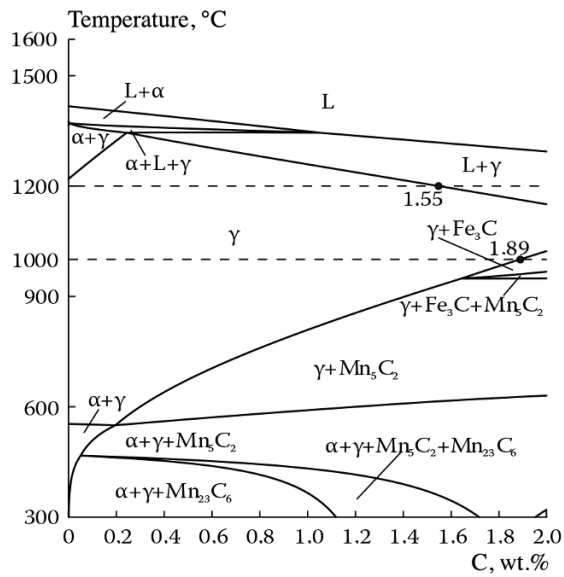


Fig. 5. Polythermal sections of alloy diagrams of the system (Fe–Mn–Al–Ni)–C containing 5% Ni, 25% Mn, and 5% Al.

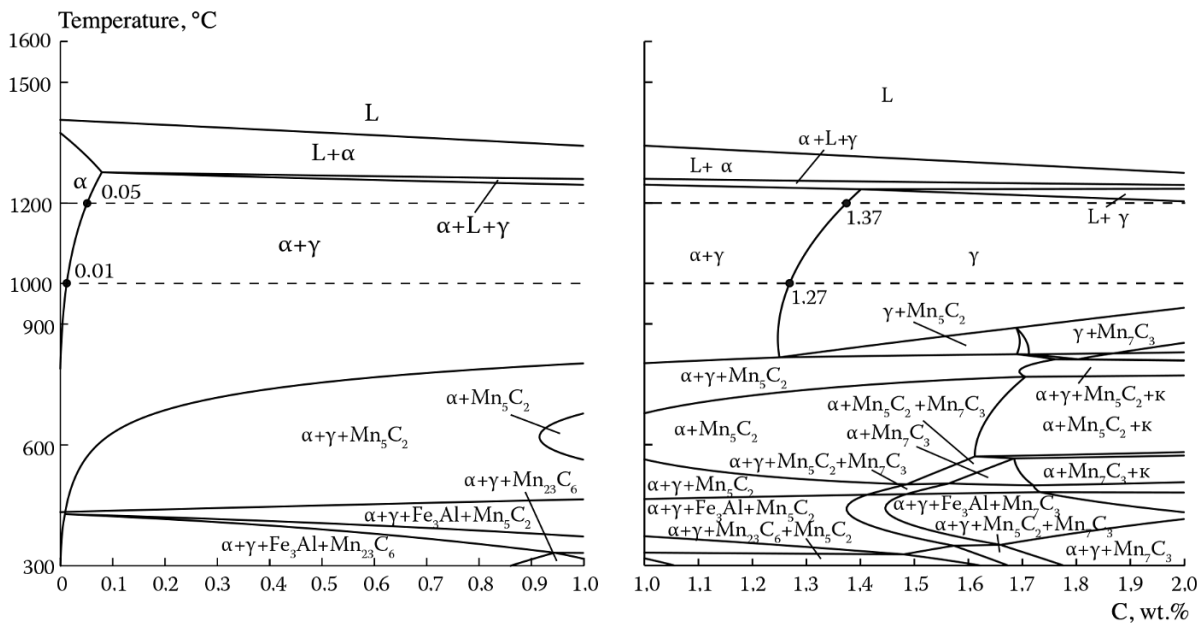


Fig. 6. Polythermal sections of alloy diagrams of the system (Fe–Mn–Al–Ni)–C containing 5% Ni, 25% Mn, and 10% Al.

up to 1.1%, γ -solution has a structure of $\alpha + \gamma + \text{Mn}_5\text{C}_2$; up to 1.4% C, a structure of $\alpha + \gamma + \text{Mn}_7\text{C}_3$; and above 1.4% C, a structure of $\alpha + \gamma + \kappa + \text{Mn}_7\text{C}_3$. The higher the carbon content, the higher is the temperature at which carbides appear in the alloy structure. With an increase in carbon content from 1.4 to 2%, the temperature for κ -carbide precipitation increases from 550 to 750°C (see Fig. 4).

It is seen from a polythermal section of the alloy diagram for the system (Fe–Mn–Al–Ni)–C containing 5% Ni, 25% Mn, and 5% Al (Fig. 5) that in the carbon content range up to 1% primary α -phase crystallizes first. With a carbon content

more than 1%, crystallization proceeds by a $(L + \gamma) \rightarrow \gamma$ scheme. With an increase in carbon content, the range of equilibrium crystallization for alloys expands. With this aluminum content in the range 1000–1200°C, single-phase γ -solution exists with a carbon content of 0–1.55%. At 550°C, the structure of alloy is $\alpha + \gamma + \text{Mn}_5\text{C}_2$. The temperature of the $\gamma \rightarrow \gamma + \text{Mn}_5\text{C}_2$ transformation increases from 550°C with a C content of 0.2% and to 950°C with 1.7% C.

A polythermal section is given in Fig. 6 for alloy of the system (Fe–Mn–Al–Ni)–C containing 5% Ni, 25% Mn, and 10% Al. All alloys containing more than 0.09% C crystallize by a $L + \alpha \rightarrow L + \alpha + \gamma$ scheme; with a carbon content more than 1.4%, crystallization proceeds with the formation of γ -phase. In the range 1000–1200°C, all alloys containing 0.05–1.27% C are in a two-phase region of $\alpha + \gamma$; with $C > 1.37\%$, they are in a single-phase γ -region. Transformation $\gamma \rightarrow \alpha + \gamma$ proceeds at 800°C, and up to $C = 1.7\%$ there is formation of a $\alpha + \gamma + \text{Mn}_5\text{C}_2$ structure, and a $\alpha + \gamma + \text{Mn}_5\text{C}_2 + \kappa$ with $C > 1.7\%$.

Of greatest practical interest are austenitic alloys of the Fe–Mn–Al–Ni–C system. Representation of the chemical composition of alloys having a single-phase γ -region with a hot deformation temperature (1000–1200°C) are given in Table 1, constructed on the basis of calculated phase equilibrium diagrams.

It is seen that it is impossible to prepare Fe–Mn–Al austenitic alloys with a sufficiently high aluminum content. Addition of 5 and 10% nickel makes it possible to increase the aluminum content by 1 and 2.2%, respectively. In order to increase the aluminum content to 10% with the presence of single-phase γ -structure in the range 1000–1200°C, in Fe–Mn–Al–Ni alloy it is necessary to add carbon.

Conclusions. The structure of the Fe–Mn–Al alloy is determined mainly by the manganese and aluminum contents. Achievement of a considerable aluminum content (10%) and consequently a marked increase in specific strength of austenitic alloys of the Fe–Mn–Al–Ni–C system is possible with contents of $[\text{Mn}] \geq 20\%$, $[\text{Ni}] \geq 5\%$, $[\text{C}] \geq 1.4\%$. Low-carbon austenitic alloys containing 5% aluminum may be prepared with an Mn content not less than 25% and not less than 5% Ni, or containing Mn not less than 10% and Ni not less than 10%.

This work was performed with financial support from the RF Ministry of Education and Science within the scope of the project part of State Assignment No. 11.1943.2014/K in the sphere of scientific activity.

REFERENCES

1. H. Kim, D. W. Suh, and N. J. Kim, “Fe–Al–Mn–C lightweight structural alloys: a review on the microstructures and mechanical properties,” *Sci. Technol. Adv. Mater.*, **14**, 014205 (2013).
2. M. Witkowska, A. Zielińska-Lipiec, J. Kowalska, and W. Ratuszek, “Microstructural changes in a high-manganese austenitic Fe–Mn–Al–C steel,” *Arch. Metall. Mater.*, **59**, No. 3, 971–975 (2014).
3. D. Raabe, H. Springer, I. Gutierrez-Urrutia, et al., “Alloy design, combinatorial synthesis, and microstructure–property relations for low-density Fe–Mn–Al–C austenitic steels,” *JOM*, **66**, No. 9, 1845–1856 (2014).
4. L. M. Kaputkina, A. G. Svyazhin, D. E. Kaputkin, et al., “Phase composition of light steels and alloys based on the system Fe–Mn–Al–C,” *Metallurg*, No. 10, 26–29 (2015).