Peculiarities of Formation the Microstructure of Ferritic Steels during Cooling

A.I. Yatsenko[1], I.P. Fedorova[1], N.I. Repina[1], V.E. Khrychikov[2], V.G. Zarenbin[3], A.V. Tatarchuk[3]

[1]*Institute of Ferrous Metallurgy, National Academy of Sciences of Ukraine*
[2]*NMetAU*
[3]*PSACEA*

The peculiarities of formation of austenite during cooling of steels with ferritic structure are studied. It is shown that the initial austenitizing goes on the diffusion-shear mechanism of the ordered crystalline phase transition. High-temperature poly-morphic transformations of δ-ferrite $\rightarrow \gamma$ induce the formation of a special morphological form of austenite. Its composition and structure are inherited by subsequent solid-phase transformations and the formation of finite structures with hereditary constructional and structural steel base.

Keywords: STEEL, LOW CARBON, FERRITE, POLYMORPHIC TRANSFORMATION, AUSTENITIZING, THE MORPHOLOGICAL FORM

Introduction

Polymorphic transformation $\alpha(\delta) \rightarrow \gamma$ is the least studied for steels with the primary structure of ferrite (δ) or peritectic type with full or partial crystallization of δ-ferrite. Individual results of similar studies are given in [1, 2]. Therefore, the aim of the paper is to discuss some of the features of this process on the experimental data for Fe-Mi (Mi - impurities, stabilizers of phases α and γ) and engineering steels (carbon content up to 10^{-3} %, impurities up to 10^{-2} %, cooling the temperature below 1500 ° C, quenching in the temperature range 1450-750 ° C in increments of 50-20 ° C, the method of analysis is comprehensive metallographic).

Results and Discussion

Depending on the composition and conditions of formation of dendrites morphology reflects the surface and bulk, limited and free growth, symmetry, axial order, etc. With changes of hypothermia of the matrix melt, physical and chemical heterogeneity of the interacting phases' concentration and structural features of dendrites - branching and crystallographic growth model are associated. At different cooling rates "thickness" of branches and their profiles, coalescence, splicing or fragmentation can be changed, as well as changes in the number, distribution and shape of the residual interdendritic liquid. In the form of the many structural distinguish this appears and can be observed after solidification. Sometimes solid phase concentration and recrystallization effects mature in dendritic matrix before the end of crystallization (**Figure 1**).

During cooling from the liquid-solid state ferritic dendrites pass through the intervals of state ж+δ→δ→δ+γ, etc. Also option ж+δ→ж+δ+γ→δ+γ, with the formation of austenite inside the dendrite (not by peritectic method, but using independent reactions δ→γ, without peritectic and therefore in a polymorphic way can be used. Capturing the difference can be difficult. Without considering the specific features of the growth of austenite in peritectic alloys in the interaction of aggregate phases, it can be noted that the greatest importance in this process can have a phase to phase distribution of impurities in its first - preparatory stage of crystallization ж→δ+жостр.

The distribution of carbon and other impurities (with the equilibrium ratio $K^{\gamma,\delta}_{ж \rightarrow \delta} < 1$) in the dendritic structure is similar in direction: from the axes of the branches to the borders and in the interdendritic liquid. At solid-state reaction are also important content and effectiveness of the influence of impurities. For example, in the alloys Fe-C-Si and Fe-C-Mn (or Si+Mn) stability δ-ferrite and austenite depending on the content and ratio of impurities in the direct segregation - γ stabilizers (C, Mn) is stimulated δ→γ

by transformation outside δ-dendrites, and in the joint segregation (C, Si and C+Si+Mn), respectively, the quantitative difference. So there may be different versions of austenitizing: 1 - around the dendrites (Si+Mn> Si), 2 - inside and in liquid, 3 - (Si+C+Mn) - only in the axes of the branches (**Figure 2**). After complete cooling one can obtain different scales of structures on the ferrite-carbide, martensitic basis.

a   b   c
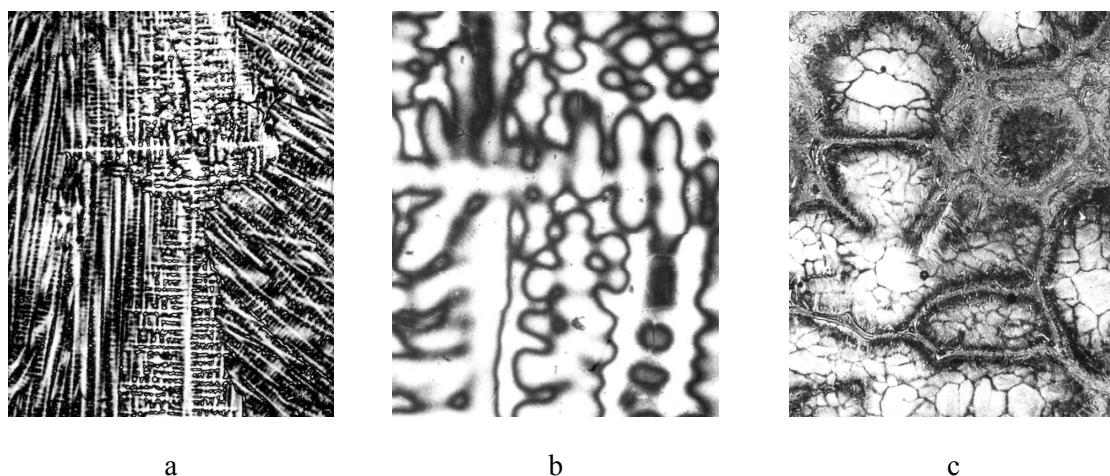
Figure 1. Primary alloy microstructure - 0.01% C, 1.25% Si, 1.15% Mn: a-x12,5; b - x50; c - x400, etching with sodium picrate

a   b

c   d
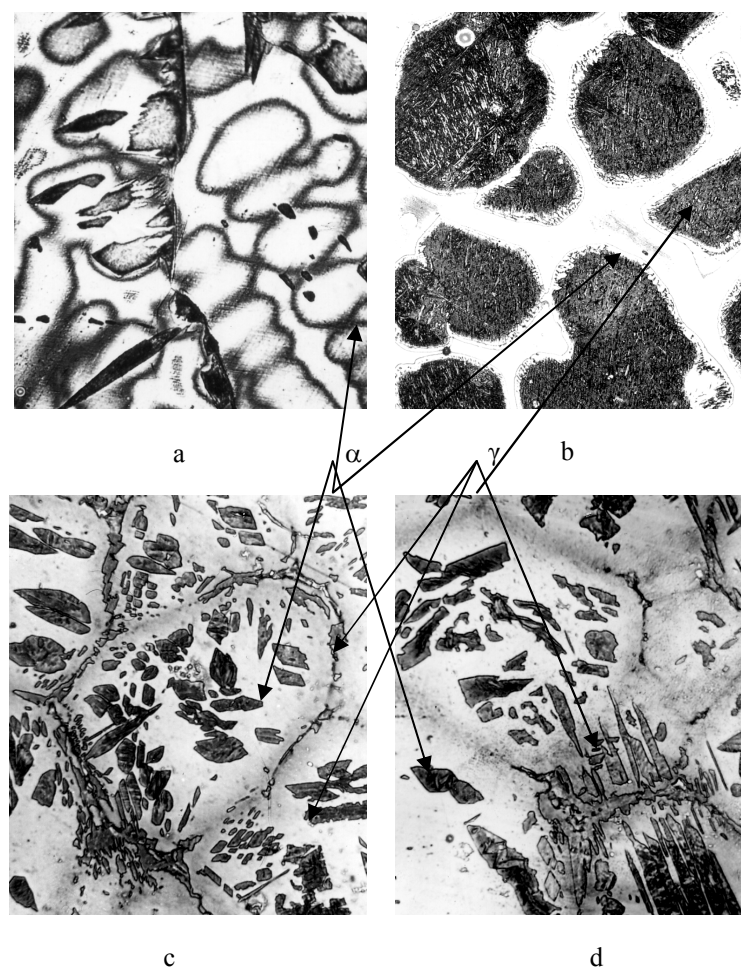
Figure 2. Microstructure of alloys after quenching from circum-liquidus temperature,%: a – 0.07 C, 2.72 Si, x400; b – 0.060 C, 0.016 Si, 0.55 Mn, x200; c – 0.10 C, 0.80 Si, x600; d – 0.10 C, 0.95 Si, x600; etching with sodium picrate
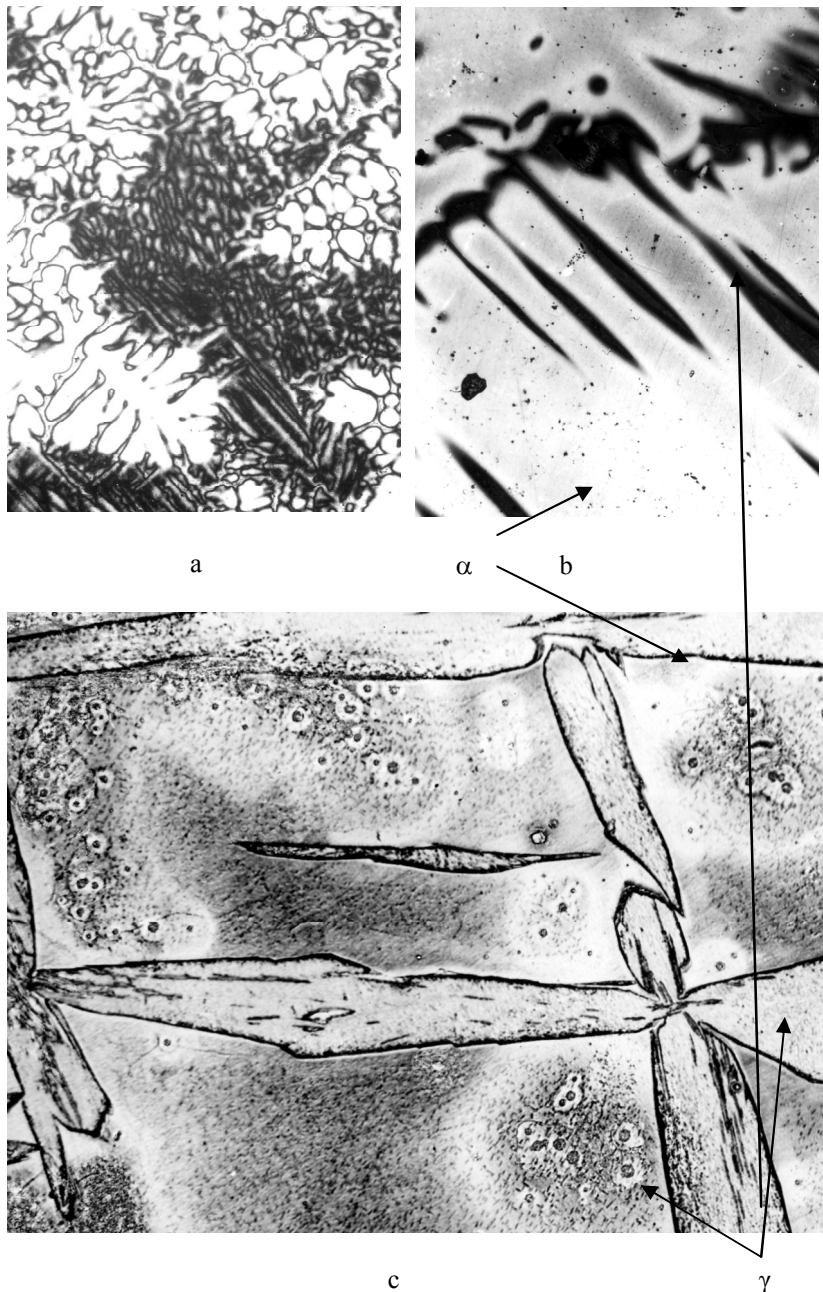
Figure 3. Microstructure of alloys after quenching from the temperatures in the crystallization range and below, %: a –0.012 C, 1.25 Si, 1.15 Mn; b – 0.04 C, 0.80 Si, 0.60 Mn; c –0.37 C, 4.50 Si; x500; etching with sodium picrate

The most important characteristics of changes in the structure during solid-phase rotation are phase morphology, topographic connection, concentration differences. According to experimental data, the main morphological form of austenitic crystals during the growth of the grain boundaries and within δ-ferrite grains is plane plate or rods (angular sections) with different ratio of axes formed under conditions of cooling - from quenching from the liquid solid state to cooling the casting with the furnace. Even in favorable thermokinetic and structural conditions sufficient to complete austenitization, fragmentation or coalescence of austenite in the two-phase state δ+γ is unnoticeable until the full connection of its individual plates. But their "constructive parameters - the shape, size, location in the heterogeneous (liquation) δ - matrix, of course, can vary greatly.

Connection of nucleation and selective growth of austenite with the state of the initial ferrite appears quite clearly. The transformation begins in areas of high-energy intergranular and interphase - intragrain boundaries, as can be seen structurally,
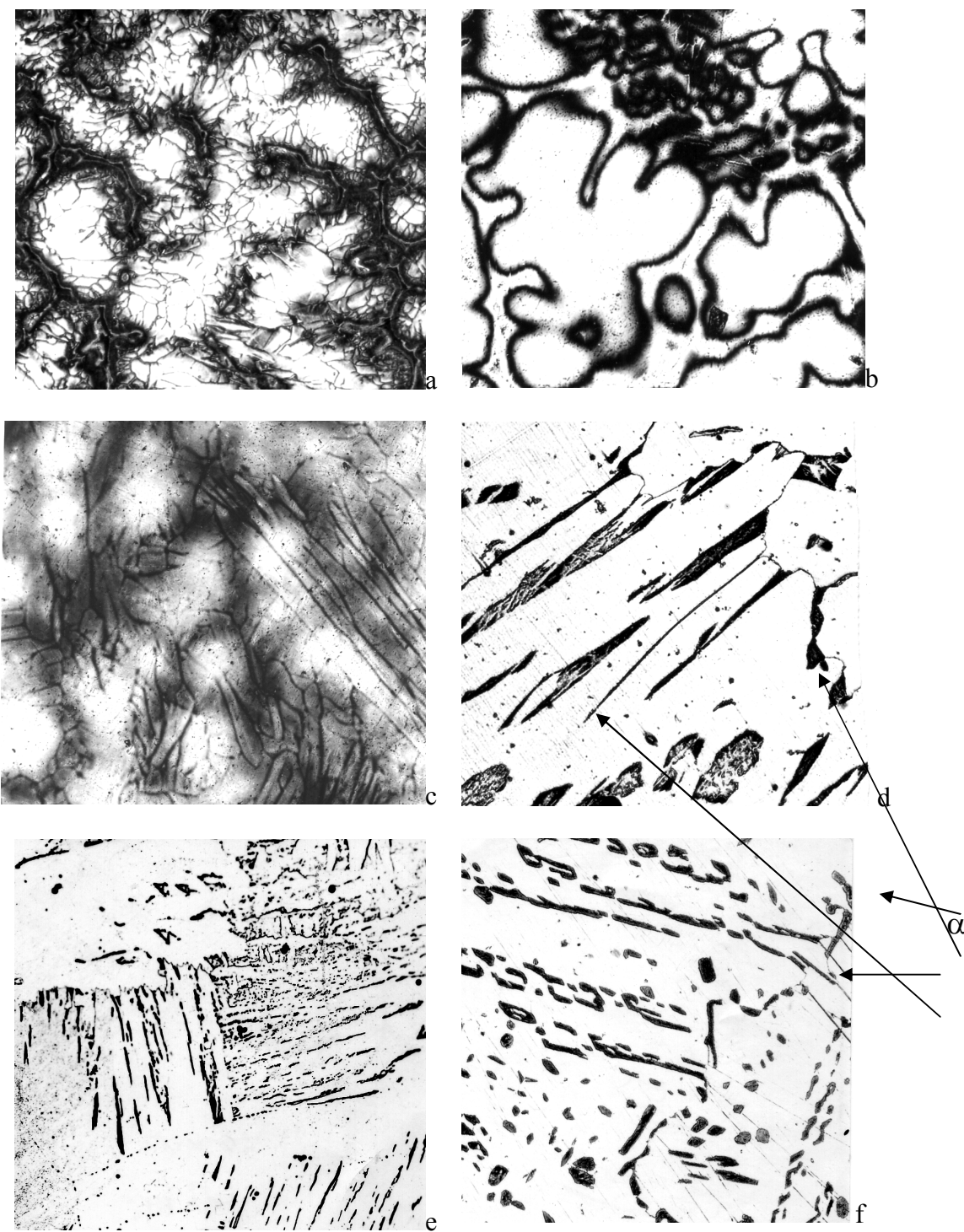
Figure 4. Alloy microstructure after crystallization and solid phase transformations,%: a – α- alloy with 0.02 C, 0.20 Mn, 12.25 Si; b – 0.04 C, 1.25 Si; c – 0.10 C; 0.8 Cr, 0.5 Si; d – 0.05 C, 1.73 Al; e – 0.10 C, 2.65 Al; f – 0.10 C, 0.5 Si, 0.5 Ce; a, b, c, f etching with sodium picrate; d, e – etching with nital; a – x125; b – x185; c, e – x200; d – x300; f – x50

although it is impossible to divide the role of crystal geometry and segregation factors - targeting, distribution of atomic defects, impurity diffusion.

High-temperature austenitizing as other polymorphic transformations, in principle, should provide equilibrium phase-concentration condition and, therefore, it is associated with redistribution of components in solid solutions in nonequilibrium processes. This can manifest itself in physical and chemical effects and their consequences, such as changes in the thermal stability of phases, chemical

and mechanical properties. In some favorable cases, when using conventional metallographic technique one can see the relevant changes in the structure, increasingly using new modern means of study (radiography, microroentgen etc.).

For the basic alloys graphic qualitative results are obtained by selective microetching, quantitative - roentgen-structural method of analysis of used series of concentration and temperature alloy groups of different phase composition. One can clearly identify the single and multiphase traces of matrix-based structure, the boundaries of the ferrite-austenite (martensite, eutectoid), the distribution of individual elements, crystallite changes. In normal variants of structure microphotography they can often distort what is impossible with electron diffraction.

Due to the sensitivity of the effect of microetching traces high temperature condition may occur sometimes after quenching from circum-liquidus temperatures (**Figure 2**), and, of course, in the crystallization range and below (**Figure 3**). Here (**Figure 3a**) in the structure after quenching from the condition ж+δ, one can observe traces of heterogeneity of liquid around dendrites, with cooling from 1250 ° C in air (**Figure 3b**) one can see the ferrite and darkening - traces of austenite, with quenching from 1300 ° C (**Figure 3c**) ferritic base is formed, austenite (martensite) - plates and rims around the inclusions SiO_2.

Low carbon structural steels iron solutions with impurities that define their behavior as doped alloys. The final morphology of their structures is a consequence of the crystallization and solid-phase changes, especially transformations $\alpha(\delta) \leftrightarrows \gamma$ (**Figure 4**).

The seemingly chaotic distribution of martensitic, eutectoid sites, dispersed carbide precipitates in ferrite is uniquely connected with the uneven distribution of active impurities, even in small doses of dissolution of primarily carbon, manganese, silicon. Given the differences in their solid solubility and kinetics of segregation $\alpha(\delta) \leftrightarrows \gamma$, one can expect a change of intergranular and intragranular ferrite and austenite, which correlate with the liquation state of the primary structure. The observed random structural and topographical chaos turns into coherent clear system with manifestation of morphological and concentration traces of $\alpha(\delta) \leftrightarrows \gamma$ transformation. This is particularly obvious in the Fe-C alloys of high level of α-stabilizers - silicon, aluminum. With the growth of austenite layers, plates the concentration

of these elements and carbon in the interlayer of residual interplate ferrite and inside austenite. Therefore, during cooling these structures complex plots (inclusions) of martensite or fine α+κ eutectoid are formed. Microstructural analysis is confirmed by electron probing for Si, Mn, Cr, Mo, P. For example, for phosphorus coefficient of distribution with an average content of 0.10% was $K^P_{\alpha/\gamma} = 1.25-2.30$, C^P_{max} spread from 2.05 to 3.0. The detected concentration differences correspond to the directions of the equilibrium interphase distribution, but vary greatly, even within a single sample, making it difficult to compare them yet.

As a reliable fact it should be noted that in parts of ferrite matrix of the same initial composition austenite can vary in structure and composition, depending on the transformation thermokinetics $\delta \rightarrow \gamma$. Example: alloy with (%) 0.038 C; 0.50 Mn; 1.20 Si; 0.7 Ti; 0.02 Al; quenching from 1300 ° C. It is fixed that $\delta \rightarrow \gamma$ transformation is complete; the morphology of austenite is double. The first type is dendrite grain boundary crystallites, the second - intragranular plate blocks. The content of dopants in both groups (average) makes (%): Mn 0.60 and 0.75; Si 0.70 and 0.95; Ti to 0.05 and 0.07 (**Figure 5**).

With all probability of disparate measurements (instrumental inaccuracies phase and chemical heterogeneity of objects, etc.) - the total output is that the possibility of concentration phase segregation of impurities, especially hard-mortar, which qualitatively matches the direction of equilibrium phase relations at $K_0<1$ or $K_0>1$.

It is difficult to assess this conclusion outside the ideas about the structure of the object of research - crystallite morphology of ferrite and austenite in their interaction. Recalling what was said earlier, we emphasize that for austenitizing of primary ferritic steels such two groups of factors of structure formation are essential - crystallization and solid-phase . First is the structure of dendrites, inside dendritic segregation, liquation, and the second is the primary recrystallization, inter-crystallite segregation and microheterogenization. Full or partial formation of austenite ($\delta \rightarrow \gamma$, $\delta \rightarrow \gamma + \delta_{ocr}$) of different composition and structure is possible, often with traces of morphological arrangement (block-plate subgranular structure), which may be linked to the morphology of dendrites.

Sometimes selective conversion connection with local concentration of impurities α(δ) or γ - stabilizers are noticeable. For example, in the alloy Fe-C-Si (with Si>>C) austenite is formed earlier
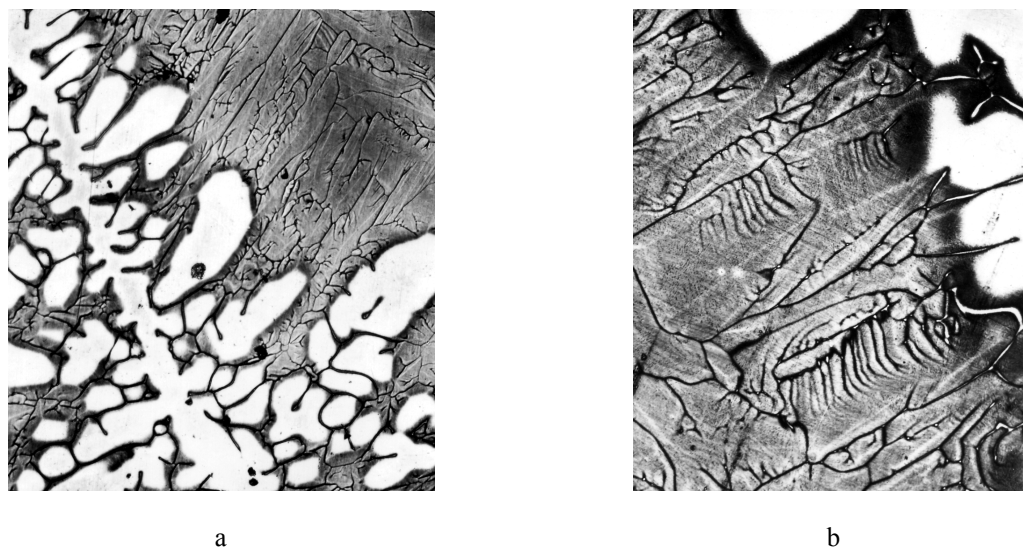
Figure 5. Alloy microstructure with (%) 0.038 C, 0.50 Mn, 1.20 Si, 0.07 Ti, 0.02 Al after quenching from 1300 °C; a – x50; b – x250; with sodium picrate
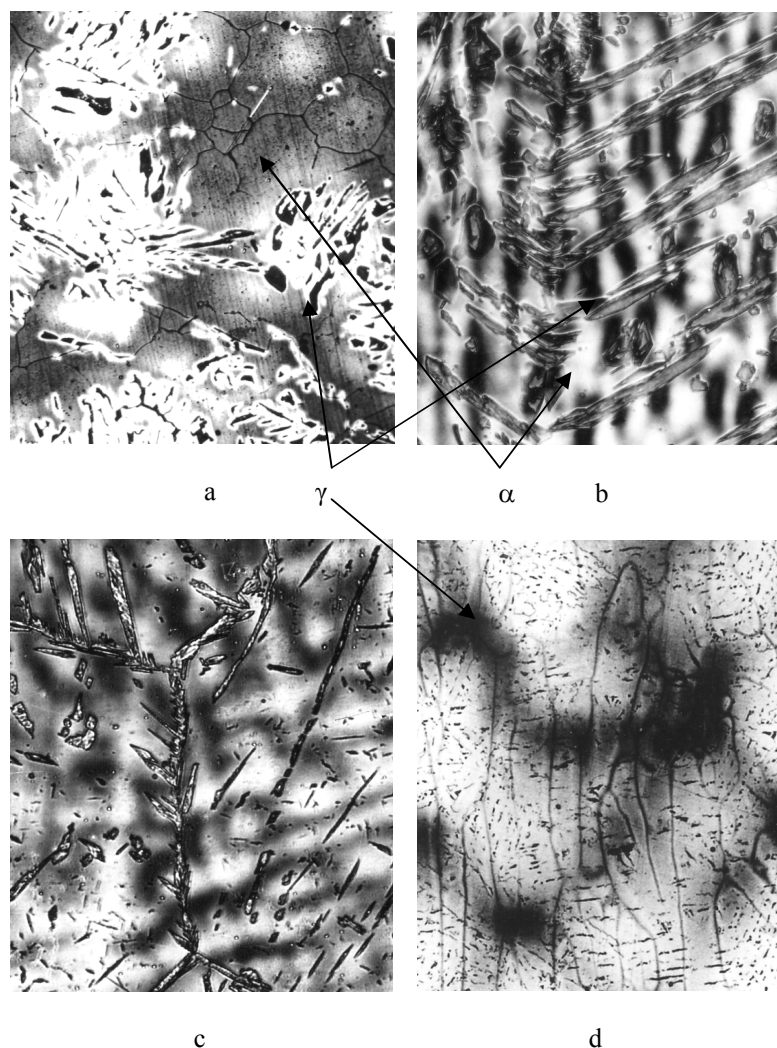

Figure 6. Microstructure of alloys: a – 0.04 % C, 0.8 % Si, 0.6 % Mn, $V_{cool.}$ = 100°/min; b – 0.15 % C, 2.0 % Si, 2.0 % W; c – 0.17 % C, 5.31 % Si, quenching from 1400 °C; d – 0.06 % C, 0.50 % Si; a, b – x50; c – x320; d – x100; etching with sodium picrate
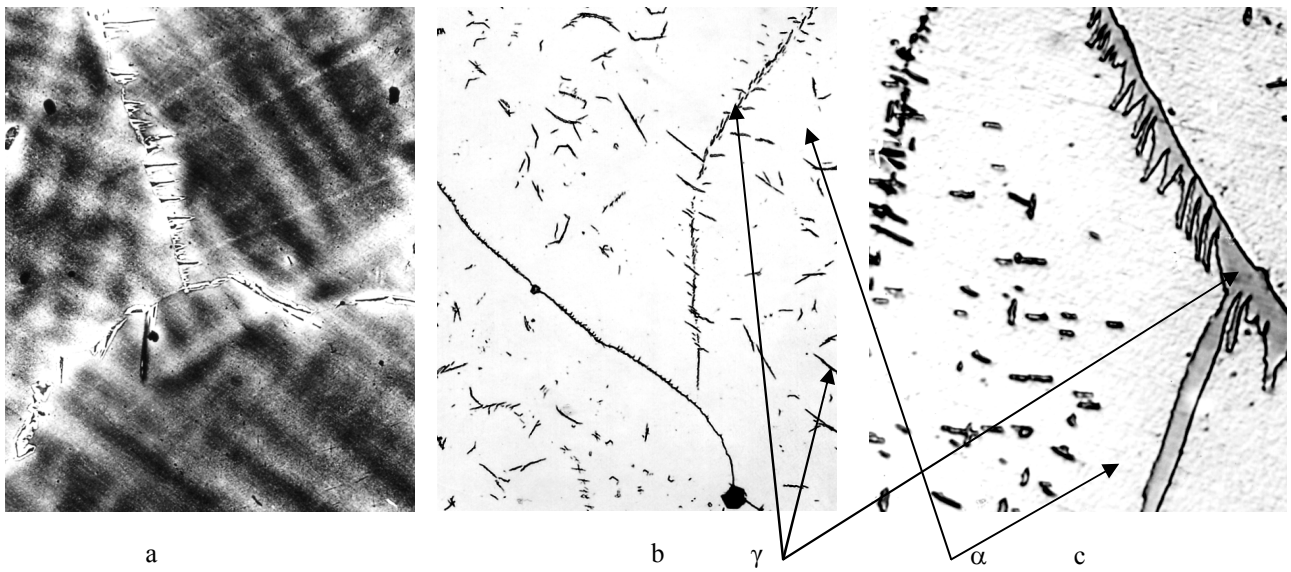
Figure 7. Microstructure of low-carbon alloys after quenching from undersolidus temperatures, %: a – 0.05 C, 0.50 Si, 2.80 Al; b – 0.05 C, 0.50 Si, 4 Al; c – 0.08 C; 3.4 Si; a, b – x200; c – x1000; a - etching with sodium picrate; b, c – etching with nital
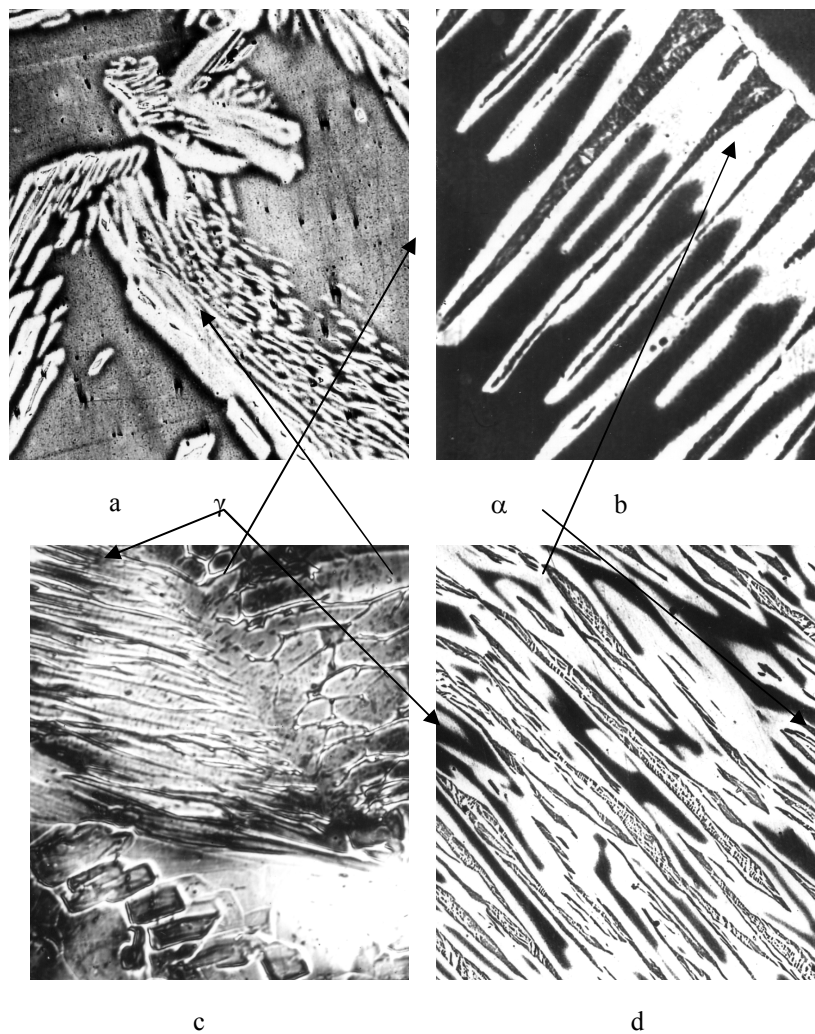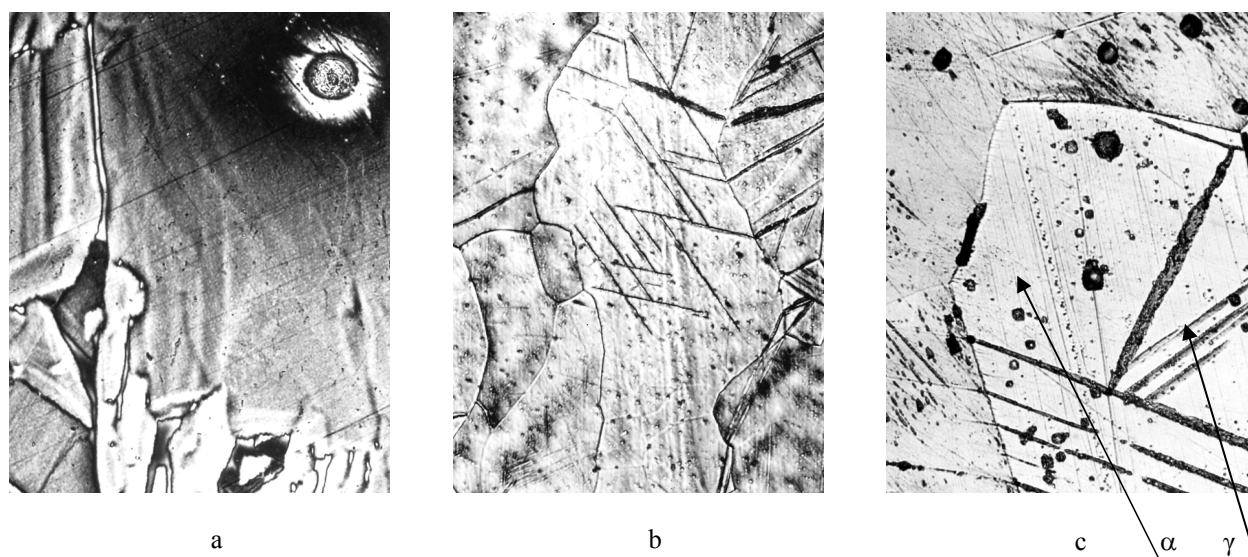

Figure 8. Microstructure of low-carbon alloys, %: a – 0.05 C, 1.75 Al; b – 0.10 C; 2.64 Al; c – 0.05 C, 1.53 Si; d – 0.27 C, 2.45 Al; a, c – x125; b – x600; d – x250; etching with sodium picrate

Figure 9. Microstructure of low-carbon alloys with high content of δ-stabilizers, %: a – <0.05 C, 2.0 Si; b, c – <0.02 C, 5.0 Si, 0.10 P; a – x250; b – x63; c –x400; a, b – etching with sodium picrate; c – etching with nital

in the axial parts of the dendritic branches with relatively lower content of C and Si, than in the interbranch area where because of liquidity of Si>C ferrite is also more stable (**Figure 6a, b**).

The transformation can begin in interdendritic layers, spreading through the inside and adjacent branches and dendritic interbranches of favorable composition (**Figure 6d**).

We have already noted that the plate-rod form of austenitic "sprouts" is the basis for the analyzed alloys at δ→γ transformation. Consider some of the features of its formation by the example of two series of alloys with additives of Si, Al and/or P. The typical structure is shown at the beginning of the transformation from the first series of samples (0.02-0.08% C; 3-5% Si (or Si + Al). Structure during the transformation is from the second series (0.10-0. 15%; 1.5-2.5-5.0% Si (or Si+P, Al).

Primary ferritic matrix is multi-axis "reticulate-lattice" dendrites. At hardening cooling from undersolidus temperatures it is possible to allocate from the δ-ferrite dispersed carbide inclusions, ranked within the grains and at the individual boundaries to form separate "scales" or films (**Figure 7**).

Apparently, such structural training here makes the emergence of austenite in the form of areas of intergranular film with non-smooth surfaces δ/γ and serrated steps - the future plates (wedges or rods).

In the second series of samples there are clearly visible features of δ+γ structure - form of austenitic plates (from initial intergranular layers), their organized orientation of "ridge" growth in the

form of packets of the intragrain pointed γ-strips, with layers in the intervals - the residual d-ferrite. Often, they are complex inter-and intragranular spatial compositions (Figure 8a). Often, especially in the early stages of transformation, one can clearly see selective direction of intragrain growth (single, mostly groups) of such γ-fasciation in the δ-base, which is caused by connections to intragranular texture of the original δ-ferrite (**Figure 8b**).

During the transformation it is possible to observe the different forms and structure combinations (**Figure 8b, c**). It ends while preserving expressive traces of ordered structural mosaic that also can be seen in the microstructure of low-carbon alloy with high content of δ-stabilizers (**Figure 9**). Of course, depending on the conditions of the transformation (composition of the original structure, processing modes) it is possible to obtain many options of secondary macro-and micro-structure after transformation, but they are united by the unity of the concentration and crystallomorphic ties, which are not easier to be managed than the crystallization.

Observable facts allow us to represent the probability of a general type of structure genesis. The mosaic structure of polymorphic austenitizing as the phase of secondary - post-crystallizational transformation, may reflect signs of two ways of metallophysical reaction - cristal-geometrical ordered lattice reconstruction of the coherent phases or diffusion directional transfer of the interacting components of these lattices. This is reflected in the elementary acts of intracrystalline

Foundry

complex shifts - shifts and changes in the chemical composition, combined with different intensity in a single phase transition. The relative intensity of them depends on a combination of many factors.

Traces of the shear-block structure, including twins (after primary recrystallization of polymorphic austenite) can be seen in the structure of alloys with high content of alloying δ-stabilizers with low carbon (**Figure 9**).

As can be seen, in a large range of compositions of primary ferrite (in non-peritectic steels) polymorphic transition δ(α)→γ can occur with morphological and concentration changes of solid basis, the structure of which can be several orders lower than that of a usual - grain one. These peculiarities of the structure of alloys require a special investigation.

Conclusions

1. The primary structure of low carbon steels of peritectic alloys based on iron and structural steels is produced by dendritic crystallization of δ-ferrite.

2. When cooling a casting recrystallization of ferrite and polymorphic transformation of δ-ferrite into γ, according to the composition and solid-phase process thermokinetics δ→γ (or γ+δ$_{ост}$) takes place.

3. Primary austenitizing goes on diffusion-shear mechanism of crystalline ordered phase transition.

4. Structural and concentration changes during austenitizing depend on the influence of basic ferrite state.

5. High temperature polymorphic transformations of δ-ferrite→γ cause the formation of specific morphological form of austenite. Its composition and structure are inherited during subsequent solid-phase transformations and formation of finite structures with hereditary constructional and structural basis of steel.

References

1. Yatsenko A.I., Khrychikov V.Ye., Khokhlova T.S. i dr. Kristallizatsiya i per-vichnaya struktura konstruktsionnykh staley, Uch. Posobiye, Dnepropetrovsk: Zhur-fond, 2010, 225 p. *

2. Kalinushkin Ye.P. Pervichnaya kristallizatsiya legirovannykh splavov na osnove zheleza, Dnepropetrovsk: Porogi, 2007, 172 p. *

* Published in Russian

Особенности формирования микроструктуры при охлаждении сталей ферритного класса

Яценко А.И., Федорова И.П., Репина Н.И., Хрычиков В.Е., Заренбин В.Г., Татарчук А.В.

Изучены особенности образования аустенита при охлаждении сталей с ферритной структурой. Показано, что первичная аустенизация идет по диффузионно-сдвиговому механизму кристаллически упорядоченного фазового перехода. Высокотемпературные полиморфные превращения δ-феррит→γ вызывают образование особой морфологической формы аустенита. Его состав и строение наследуются при последующих твердофазных превращениях и образовании конечных структур с наследственной конструкционно-структурной основой стали.