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FORMATION OF THE GRAIN BOUNDARY STRUCTURE OF LOW-ALLOYED STEELS IN THE PROCESS OF PLASTIC DEFORMATION

Sergey Shejko[1], George Sukhomlin[2], Valerii Mishchenko[3], Vadim Shalomeev[1], Valentina Tretiak[1]

[1]Zaporizhzhya National Technical University (Zaporizhzhia, Ukraine)
[2]Pridneprovsk State Academy of Civil Engineering and Architecture (Dnipro, Ukraine)
[3]Zaporozhye National University (Zaporizhzhia, Ukraine)

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Abstract

In this work, transmission electron microscopy was used to study the effect of variable factors (ε, τ, t) as well as that of relative number of special, in the CSL (coincidence site lattice) concept, low-energy boundaries, in the ferritic and martensitic components of low-carbon steels. The conditions for the appearance of the first large-angle boundaries in the polygonized hot-deformed matrix are determined. CSL boundaries of Σ 3, 9, 11, 33 types, which increase the plasticity index of the products are found in the ferrite and martensit Establishment of optimal thermoplastic deformation - the change in the configuration of the grain boundaries, the formation of small-angle boundaries and the interaction of large-angle ones with special boundaries in accordance with the von Neumann-Mullins theory. After the heat treatment, the structure of 10ХФТБч type steel (Standard of Ukraine) consists of ferritic grains, a small amount of perlite and spheroidized special carbides.

Introduction

Modern material science solves many technological problems facing the industrial production of a variety of products for a wide range of purposes, most of which are manufactured by hot and cold rolling, forging, extrusion, drawing, etc. At the same time, questions arise from related fields of knowledge such as solid-state physics, mathematics, namely, where the first nuclei of new phases appear in a given material, what physical parameters are most significant in the manufacture of products by hot deformation. In particular, when improving the technology of controlled rolling with the aim of improving the strength and plastic parameters of rolled metal, it is important not only to obtain fine grain of ferrite in the structure, but also to trace its development from the initial to the final stage of deformation under different temperature and time conditions.

The task of the present work was to refine the available data as well as to obtain the new data on the formation of a block (polygonal) structure under controlled rolling of low-carbon steels 10Г2ФБ and 10ХФТБч (Standard of Ukraine) to increase the strength and ductility of rolled products.

Experimental part

Deformation-thermal treatment was carried out under industrial conditions on the double-stand rolling mill according to the experimental controlled rolling regime: heating of the billet to 1200 °C → homogenization for 5 hours → rough rolling (ε ≈ 40 ... 50 %) with a temperature dropping to 950 °C → technological cooling (subcooling) in air up to the chosen temperature of the intercritical interval (ICI): 900 ... 700 °C → finish rolling (7 ... 12 cycles of 5 ... 10%) for grain grinding of the precipitated eutectectoid ferrite and formation of dispersed grain-subgrain structure → cooling in air.

A fine structure was studied on a transmission electron microscope - EM-125 with an accelerating voltage of 100 kV, a camera length of 510 mm, a selector diaphragm with a diameter of 2.5 μm on a sample scale. Thin foils were prepared by cutting the bar across in the direction of rolling and recessing the rod with a diameter of 3.2 mm from it according to the disk technique.

The light metallography is made on a Neofot-2 microscope with an immersion objective "H-100 × 0.95" and a digital camera "Olimpus-C-350Z". Sections were prepared according to the traditional technology, but with mandatory electropolishing (removal of a layer of work-hardened metal 10 ... 20 microns thick).

The Main Researches

In the work, the main attention was paid to samples whose deformation ended at temperatures of 750 and 770 °C, since they correspond to the lower part of the ICI, when up to 80 ... 85% of ferrite is precipitated (and deformed) in the structure and the deformation hardening of the ferrite - the low-strength component of steel, is implemented. That is why it is important to obtain the details of the structure formation during the period when the incoming of dislocations is over and the polygonization and recrystallization of ferrite begins (or rather continues), as well as the $\gamma \rightarrow \alpha$ transformation of the residual austenite.

The method of microdiffraction [1] allows obtaining approximate information about next quantities:

- φ – the angle of azimuthal blurring of reflexes in a certain area. In our case, it is 2.5 μm - the diameter of the selector diaphragm;
- φ' – the misalignment angle on one medium subboundary φ_{sub}; the result of dividing the total blur angle (φ) by the number of subreflexes k in one full reflex, $\varphi' = \varphi/k = \varphi_{sub}$.;
- d_{sub} – the size of subgrains (the average chord) located in the analyzed area.

The results for the samples deformed at 770 °C and cooled in air are shown in Fig. 1.

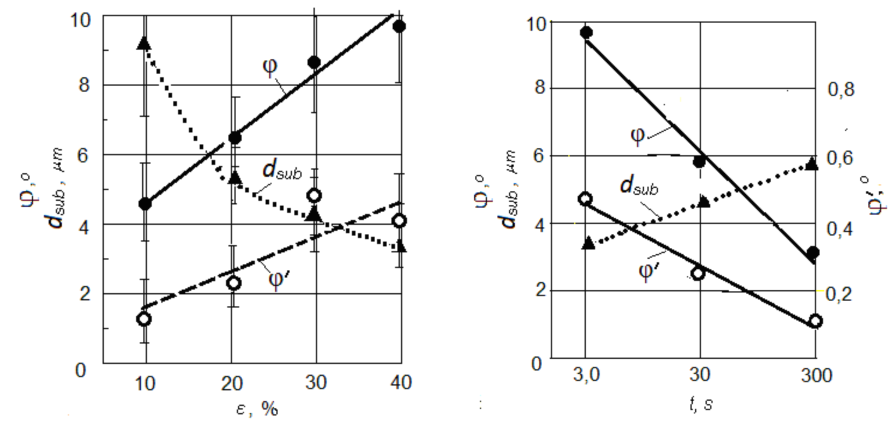
The structure of the strip, which received the maximum degree of deformation (ε = 42%), was fixed by quenching in parts: the first in 3 seconds, the second after 30 seconds, the third after 300 seconds of time-exposure.

The data shown in the diagrams (Fig. 1) show that with increasing of ε:

- The azimuthal disorientation angle φ is increased, and, as a result, the partial angle φ_{sub} on a single subboundary is increased as well;
- Subgrains are reduced to 3 μm.

During the time-exposure:

- The azimuthal disorientation angle φ is decreased, the post-deformation polygonization process begins;
- The azimuthal disorientation angle on a single subboarder $\varphi' = \varphi_{sub}$ is decreased;
- The sizes of subgrains are increased to 6 μm and their quantity is decreased.



a *b*

Figure 1. Characteristics of the subgrain structure of the hot-deformed ferrite after rolling at 770 ° C and cooling in air: *a* – changing of φ, φ' and d_{sub} from the degree of hot deformation; *b* – the same parameters in the post-deformation period.

ε

The results of the study of grain-boundary and polygonized structure and nucleation in hot-deformed ferrite. Fig. 2 shows the general structure formed in steel after 300 sec after the end of deformation and cooling in air.

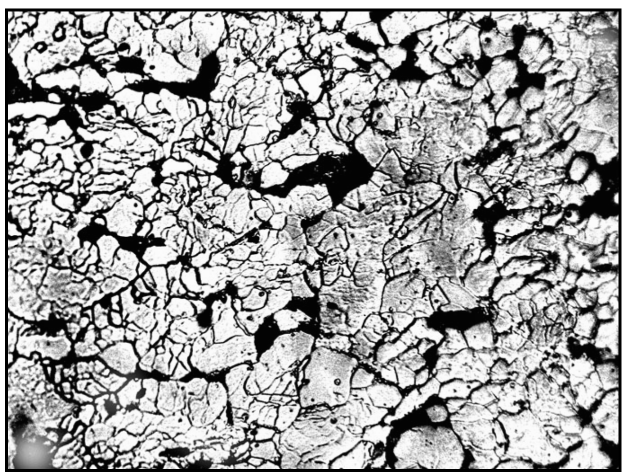


Figure 2. The structure of the hot-rolled steel 10ХФТБч (Standard of Ukraine). The end-of-deformation temperature is 750 °C, the time-exposure is 300 sec [2, 3]

It is noteworthy that the biggest part of ferrite has polygonized structure, but some larger subgrains are free from dislocations, that is, they are potential nuclei of recrystallization. In the structural sense, this phenomenon has not been completely investigated [4]. From the von Neman-Mullins concept, such grains are capable of growth if the number of sides *n* is more than six. In their reasonings, both von Neumann [5] and Mullins [6] proceeded from the assumption that all the large-angle boundaries are the same, that is, there is uniformity in terms of atomic structure, energy intensity and tension forces. Although this is not always true, we assume in this case that the polygonal (subgraine) boundaries exhibit similar properties and also obey the von Neumann-Mullins criterion based on the equilibrium of tension forces in triple junctions lying on the perimeter of n sides. Such approach is successfully used by researchers in their works [7, 14], studying the interactions of the large-angle and subgrain boundaries.

In Figure 3a, a subgrain with a number of sides of at least 12 is observed in the central part.

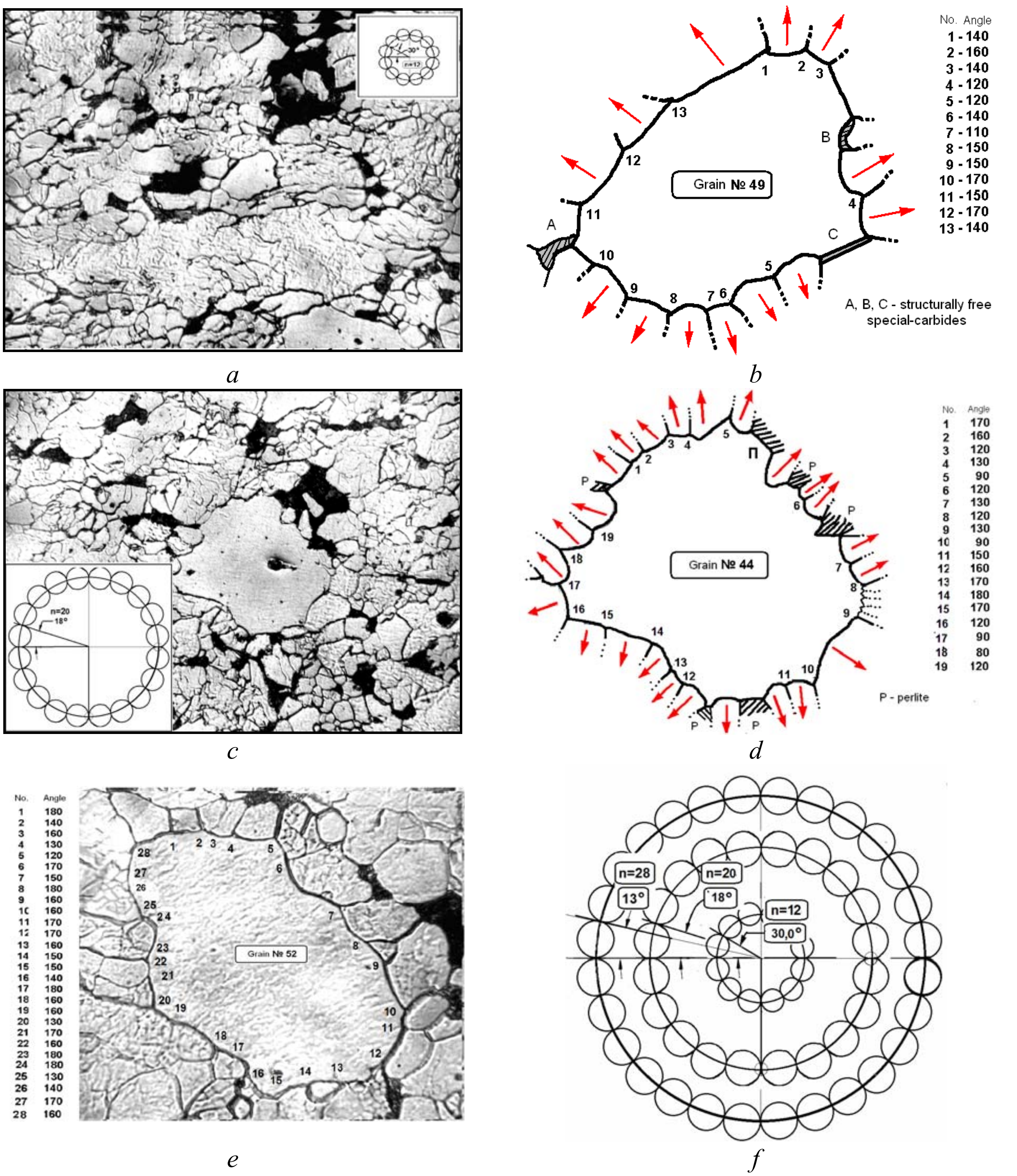


Figure 3. Enlargement of individual subgrains with an increased number of sides and the results of measurements of internal angles in triple junctions: a, c, e - images of polyhedral nuclei; b, d, f - schematic map of nuclei.

The internal angles between tangents to the boundary lines in triple junctions of polyhedral formations (nuclei) with the number of sides n = 12 (No. 49); *n* = 20 (No. 44) and *n* = 28 (No. 52) in 10ХФТБч steel (Standard of Ukraine) after hot rolling at 770 °C and cooling in calm air for 300 seconds were investigated (detected and measured).

At the same scale, these grains are shown in Fig. 3a, c, e. The corresponding schematic maps are shown in Fig. 3b, d, f. Next to the diagrams are tables of angles located on the numbered joints of the inner side of the growing grain (Fig. 3b, d). The curvature of the boundaries between the junctions was also considered, the arrows indicate the direction to the center of the curvature of the boundary, that is, the direction of its migration at a given moment.

Some morphological features of these subgrains-nuclei are revealed as the number of sides in them increases.

Grain No. 49 grows, the curvature centers of most segments are directed outwards, therefore the area increases in size, although on the sections A, B and C the boundaries are fixed by relatively large particles of special carbides. It can be assumed that these particles are not random, since they tend to repeat the bends of the growing polygon, and the film morphology, increased etching confirm that the carbides precipitate at the forming boundaries, and not the boundaries are stopped by the already formed particles. In addition, it should be taken into account that Suzuki's carbon atmospheres exist on the subgrain boundaries, and the growing grain, while absorbing polygonal boundaries, releases carbon and displaces it to the outside of the nuclei. Therefore, in the initial hot-deformed ferrite, near the perimeter of the nuclei, local microinhomogeneities supersaturated by carbon commensurate with the size of the polygons appear. As the "non-carbon" nucleus grows, the migrating nucleus-matrix border is enriched with carbon and at some point a cementite particle nucleates that rapidly grows along the most large-angle segment of the boundary until all excess carbon is spent on building a cementite single particle [8].

A similar phenomenon accompanies practically all growing nuclei, they can be seen in the figures containing nuclei, but they are almost not observed in the final, completely recrystallized ferrite-pearlite mixture.

The measurements showed that there are only two equilibrium 120-degree joints (see the table in Fig. 3b). This means that the inner boundaries of the nucleus in the majority already differ from the small-angle subgrain boundaries, by their greater tension, as their misalignment angles have already been increased by "inheriting" misalignments of the surrounding outer (already absorbed) polygon subboundaries.

Grain No. 44 (Fig. 3c, d) contains 20 border segments that tend to move to the outside, increasing the size of the subgrain nucleus, although along the inner perimeter there are five more segments belonging to pearlite colonies, which, as is known, do not move under the effect of the tension of external intraphase subboundaries or large-angle boundaries. The center of curvature of the segment 8-9 is located (at first glance!) inside the grain, but with a larger magnification, it is revealed that the segment 8-9 consists of five smaller segments that are turned by the centers of curvature to the outside. When analyzing 20 triple junctions it turned out that the number of 120-degree joints increased to 5, in addition, one 180-degree joint appeared (No. 14). Its appearance indicates the presence of two large-angle high-energy boundaries on the section 13-14-15 (Fig. 3c, d), which confirms the validity of coalescence mechanisms of the subgrains rotations during the formation and growth of nuclei of recrystallization of hot-deformed metals [9-13, 15].

Grain no. 52 is the largest (Fig. 3e, f), 28 triple joints were analyzed in it, which do not contain inner angles of less than 120 degrees, but contain 180 degrees angles (five cases). This means that the number of boundaries with an extremely high tension (with a large specific surface energy) increased, and the grain is a full member of the network of large-angle boundaries. Both positive and negative curvature were observed. Such boundaries also indicate a gradual transition of the nucleus to the category of large-angle grain boundaries.

The development of nuclei can be traced on the histograms of the distribution of inner corners opposing the outer small-angle subgrain boundaries (Fig. 4). They are constructed on the basis of the analysis of a small number of cases in each individual experiment, as the number of sides is limited by the very nature of nucleation. Despite this, the nuclei contain interesting information about the nuances of migration and the interaction of small-angle and large-angle boundaries during the recrystallization of hot-deformed materials.

The lower limit of cases is limited to 7, that is, the number that is theoretically required by the Neumann-Mullins concept for a growing nucleus. It is obvious that the theoretical diagram for a 6-sided "nucleus" will have a peak (mode) of 120°, (Fig. 4, curve 1)

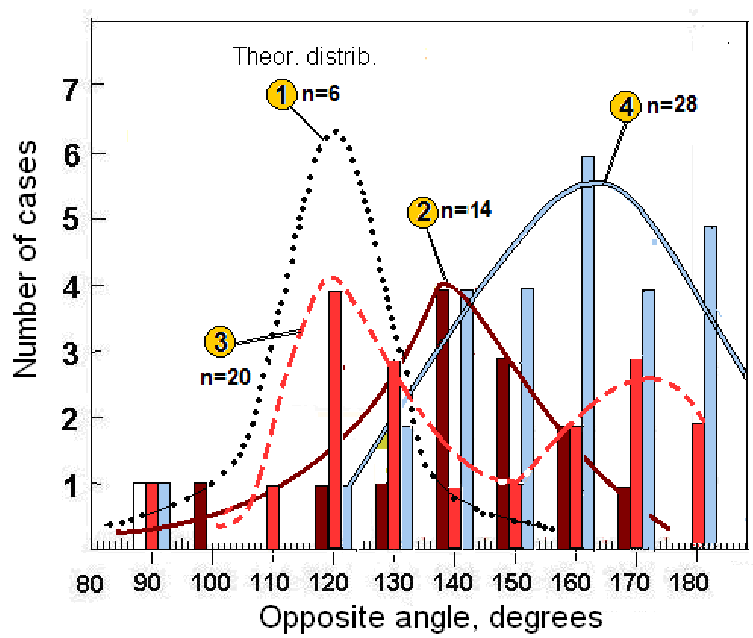


Fig. 4. Development of the nucleus of recrystallization in hot-deformed ferrite after deformation. Each grain is represented by its histogram.

The histogram of grain No. 49 (Fig. 4, curve 2) shows that the angles are distributed uniformly within 100-170°, and the peak is located at 140°, which shows a significant increase in misorientation at the boundaries of the nucleus, but their tension is not much different from tension of polygonal boundaries.

It should be recognized that even at this early stage the nucleus already has an individuality, almost all its boundaries are distinguished by more significant misalignment angles and generating capacity.

On the assumption of the larger the nucleus, the longer was its existence, it can be seen that the early formed grain No. 44 containing 20 sides exhibits a somewhat unexpected distribution of internal angles with two modes at 120 and 170° (Fig. 4, curve 3). If we take into account that the peak is observed at around 160° for grain No. 52 (Fig. 4, curve 4), while 120-degree joints are not even observed, it becomes clear that the large nucleus has practically reached the limiting state, contains only large-angle boundaries, it is surrounded only by small polygons, so if it grows, it happens very slow, while nucleus No. 44 is at the intermediate stage of development, when full-scale large-angle boundaries have already appeared (170-degree peak), and low-energy segments of boundaries (120-degree peak) are still encountered.

If the nuclei are represented by circles that are equal in area to the corresponding polygons and the subgrains are also circles with a diameter d_{sub}, (see the insets in Fig. 3a and 3c), we get a clear idea of the nature of the development of the recrystallization nuclei in the polygonized hot-deformed matrix (Fig. 3f)

Conclusions

1. Based on theoretical and experimental studies, a methodology and a scheme for the formation and growth of nuclei of the recrystallization of ferrite grains in a polygonized structure of ferrite-perlite steels after controlled rolling are proposed.

2. New data was obtained on the dependence of the parameters (misalignment angles and sizes of subgrains) of the block (polygonal) structure on the degree of deformation during hot rolling of 10Г2ФБ and 10ХФТБч steels, as well as their behavior during time-exposure after the end of deformation.

3. The development allows us to predict the processes of recrystallization and the formation of mechanical properties at the hot deformation of ferrite-pearlitic steels.

4. It is shown that the hardening of the rolled stock of ferrite-pearlite steels can also be achieved by forming a rational grain-boundary structure, by forming special grain boundaries during thermoplastic treatment.

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