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EFFECT OF HIGH STRAIN RATE ON THE DISLOCATION STRUCTURE OF MICROALLOYED AND IF STEELS

WPŁYW DUŻEJ PRĘDKOŚCI ODKSZTAŁCENIA NA STRUKTURĘ DYSLOKACYJNĄ STALI MIKROSTOPOWEJ IF

The problem of quality and quantity evaluation of dislocation structure under very high strain rates was analyzed. The investigation was performed for two steels of common application: high strength microalloyed Nb(Y) steel and interstitial free (IF) steel. Investigation of microalloyed steel allowed the analysis of dislocation structure evolution in strengthened material (both via precipitations and solid solution). In such conditions, the dislocation movement is difficult and forming substructures are significantly different from those observed in IF steel. In present studies, for suitable evaluation of dislocation structure, an attempt of modification of existing relationships was made. Bergström's proposition was utilized and relationships between dislocation cell size and mean dislocation density were determined.

The axisymmetrical compression tests were performed with different strain rates at room temperature using static and dynamic testing machines and dropweight. The analysis of microstructure of deformed materials was also performed using transmission electron microscopy (TEM). The estimation of the effect of strain rate on microstructure evolution and, first of all, on dislocation cell structure, was made. It was observed that dislocation structure evolution depends on thermomechanical history of deformed material, strain and strain rate.

On the basis of measurements and characteristics of dislocation structure and using Bergström's model it is possible to determine the total dislocation density, taking into account basic process parameters including strain rate under dynamic loading conditions. Obtained results showed a good accuracy of established model to estimate dislocation density on the basis of dislocation cell size.

Keywords: high strain rate, dislocation structure, dislocation density

W pracy podjęto problem oceny jakościowej i ilościowej struktury dyslokacyjnej powstałej w wyniku zastosowania bardzo dużych prędkości odkształcenia. Badania przeprowadzono dla dwóch szeroko stosowanych gatunków stali: mikrostopowej o podwyższonej wytrzymałości (Nb(Y)) oraz IF. Badanie stali mikrostopowej umożliwiło przeprowadzenie analizy rozwoju struktury dyslokacyjnej w materiale umocnionym wydzieleniowo oraz przez roztwór stały. W takich warunkach przemieszczanie się dyslokacji jest utrudnione, a tworzące się podstruktury różnią się znacząco od tych obserwowanych w stali IF. Dla właściwej oceny struktury dyslokacyjnej w obecnych badaniach podjęto próbę modyfikacji istniejących zależności. Wykorzystując propozycję Bergströma, wyznaczono związki pomiędzy wielkością komórek dyslokacyjnych a średnią wartością gęstości dyslokacji.

Przeprowadzono testy osiowosymetrycznego spęczania z różnymi prędkościami odkształcenia, w temperaturze pokojowej przy użyciu statycznej i dynamicznej maszyny wytrzymałościowej oraz młota spadowego. Odkształcony materiał poddano badaniom mikrostruktury z wykorzystaniem mikroskopii elektronowej. Ocenie poddano wpływ prędkości odkształcenia na rozwój mikrostruktury, w tym przede wszystkim na strukturę komórkową. Zaobserwowano, że rozwój struktury dyslokacyjnej uzależniony jest od rodzaju odkształcanego materiału oraz wielkości i prędkości odkształcenia.

Na podstawie pomiarów i charakterystyki struktury dyslokacyjnej oraz wykorzystując wzór Bergströma można wyznaczyć całkowitą gęstość dyslokacji z uwzględnieniem podstawowych parametrów procesu, w tym z uwzględnieniem prędkości odkształcenia w dynamicznych warunkach obciążenia. Otrzymane wyniki wskazują na poprawność przyjętego modelu do oceny gęstości dyslokacji na podstawie pomiarów wielkości komórek dyslokacyjnych.

1. Introduction

There are many benefits that can be obtained from refining the microstructure in metallic alloys. The grain size controlling towards its refinement is one of the most attractive ways of improvement of the mechanical properties. The yield stress, hardness, ductile-brittle transition temperature and ductility can be significantly enhanced thanks to this strengthening mechanism. Moreover, this method seems to be especially attractive

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because it doesn't require any expensive alloying additions and existing production technology can be used. Microstructural refinement of steel is usually achieved by thermomechanical processing and alloying. Microalloyed elements (Nb, Ti) can interact with the microstructure evolution in different ways depending on the reheating conditions, deformation history and parameters, as well as cooling conditions. As a result of these interactions, an evolution of dislocation structure and finally a various refinement of the microstructure is achieved [1, 2]. The quality of grain boundaries and dislocation boundaries directly determines the mechanical properties of deformed material. The situation is more complex, when high strain rate of deformation is applied. It is difficult to describe material behavior during deformation at high strain rates using "general" flow formulation. The proper description of correlations among high strain rate and mechanical and microstructural behavior of the material needs multiscale analysis where dynamically changed, during and between forming operations, microstructure and dislocation arrangement are adequately represented. It has been determined that in many metal forming processes (drawing, rolling of long products, forging) the strain rates in the deformation zones are very high (up to 4000 s^{-1}). It is, therefore, clear that the influence of strain rate in modeling of such metal forming processes should be taken into account. There is a number of ideas that have been proposed and successfully employed to describe the mechanical behavior and microstructural evolution as a function of strain rate. However, there is a lack of information representing the evolution of dislocation structures from conventional strain rates to the dynamic conditions. Additionally, the chemical composition and processing history would be expected to have significant effect on the evolution of dislocation structure. In the present study the aim is to emphasize the role of high strain rate in the arrangement process of dislocation structures, based on the observations of deformed microstructures and modeling procedures.

2. Experiments

The objective of the experiments was to produce deformed microstructures and then, to study the correlations between dislocation structure of such materials as a function of strain rate. The basic chemical compositions (wt.%) of the investigated steels are presented in Table 1. Both steels were supplied in hot rolled condition. These steels are widely used in the automotive industry due to their ability to generate very useful combination of strength (Nb(Y) steel), ductility and weldability. In addition, the interstitial free steel (IF) can be treated as a reference material because of its good ductility and low carbon content (clear ferritic structure). Axisymmetrical compression tests were performed in order to study the effect of high strain rates on the material mechanical and microstructural behavior. The compression tests were carried out under various strains and strain rate conditions at room temperature. The evolution of the microstructure, as well as the mechanical response of the material affected by the strain rate, strain and generated heat, were observed and analyzed. The tests were performed using the tensile-compression testing machine (strain rate = 0.001 s^{-1}), dropweight (strain rate = 200, 400, 600, 800 s^{-1}), and Schenck servo-hydraulic compression testing machine (strain rate = 150 s^{-1}). Subsequently, from one half of each deformed sample, TEM analysis was carried out. The tests scheme and the basic chemical compositions of the investigated steels (in wt %) are shown in Fig. 1 and Table 1, respectively.

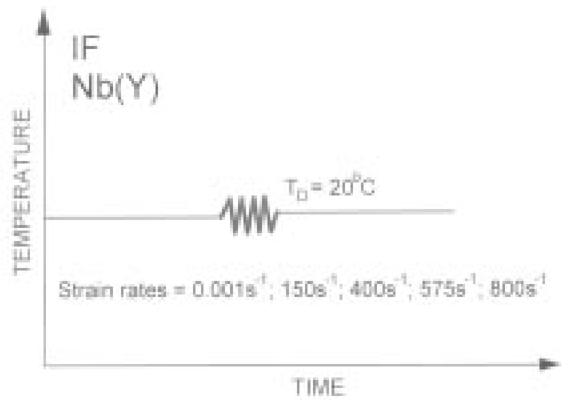

Fig. 1. The scheme of compression tests

TABLE 1

Basic chemical composition of investigated steels

Steel	C	Mn	Si	N_2	Ti	Nb	B
IF	0.022	0.112	0.009	0.0034	0.037	–	–
Nb(Y)	0.07	1.36	0.27	0.0098	0.031	0.067	0.003

3. Results

At high strain rates slip is restricted and the evolution process of dislocation structure can be significantly different than in the quasi-static conditions. Very high strain rates, appearing in more and more intensified metal forming processes, and application of studied steels for products that may be subjected to dynamic loading, are the reasons for study of the strain rate effect on dislocation substructure evolution.

In order to evaluate the effect of high strain rate on microstructural evolution, comparison of developed dislocation structures in the present steels were carried out by TEM microscopy. Basing on the obtained results it can be seen that very often no arrangement of dislocations was observed, especially in Nb(Y) steel. In such structures, the dislocation density – as an internal variable – can be treated as a sufficient representation of material response to plastic strain. However, at higher strains, grains became subdivided by the arrangement of trapped glide dislocations into cell boundaries. This needs another, additional method of valuation of the dislocation density. At low and medium strains, Hughes et al. [3–4] classified the deformation induced boundaries into two categories: incidental dislocation boundaries (IDBs) and geometrically necessary boundaries (GNBs)

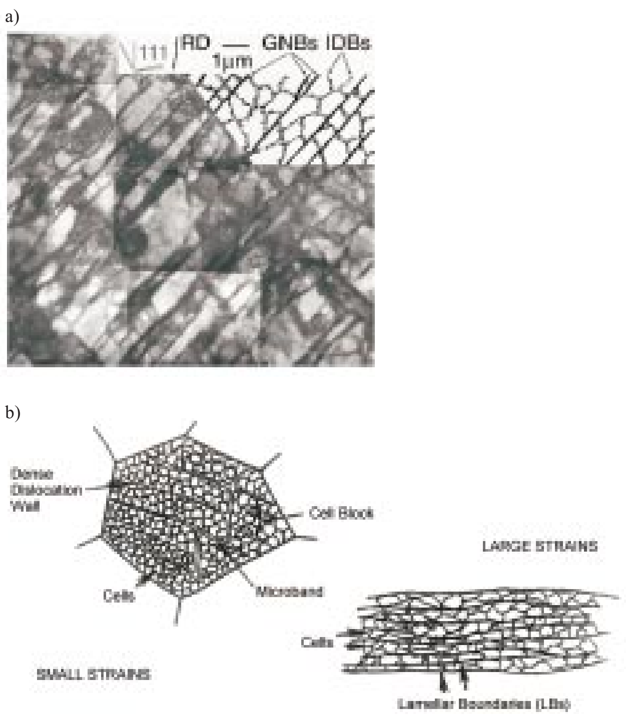

Fig. 2. a – TEM micrograph showing the arrangement of dislocation boundaries developing in pure Ni deformed to a rolling reduction of 20% [3], b – Schematic drawing of deformation microstructures and grain subdivision (small and large strains) [4]

separating crystallites that deform by different selections of slip systems and/or different strain or strain amplitudes and incidental dislocation boundaries (IDBs) formed by trapping of glide dislocations (Fig. 2). It has been observed that with increasing strain, the misorientation angle across the two types of boundary increases and that the spacing between the boundaries decreases [4]. It can be expected that by applying very high strain rate this behavior will be significantly changed. With increasing strain it is also observed that there is an interesting tendency for the dislocation boundaries to reorient from a typical cell block structure into a lamellar structure (as showed in Fig. 2b). In the typical cell block structure the GNBs include microbands (MBs) and single dense dislocation walls (DDWs) that surround blocks of equiaxed cells [4, 5]. At high strains and low strain rates flow softening can lead to concentrated slip occurring in shear bands [6]. This can lead to the rotation of the material within the shear band and create additional high angle boundaries. In the case of dynamic conditions of deformation there is no time for such microstructure organization. In addition, microalloying elements and fine precipitates would be expected to have an important effect on the microstructural evolution and dislocation arrangements.

Although the general principals mentioned above are fairly well established, there is a lack of published results encompassing the effects of high strain rates on the deformation structures. In the present study, the microstructural evolutions during compression at different strain rates and strains were investigated for two grades of steel. The arrangement of dislocation boundaries that occurs as a result of static and dynamic deformations were discussed by observing the TEM micrographs.

Fig. 3 shows TEM microstructures of the IF steel specimens deformed with various strain rates. The initial microstructure (grain diameter of 100 μm, in average) exhibited a relatively low dislocation density. After a compression test with strain of 0.53 at quasi-static conditions (Fig. 3a) the microstructure consisted mainly of parallel bands and grains with regular cells.

The microstructures of the specimens compressed with high strain rates are clearly different from the statically deformed ones. The lamellar structure can be observed in Fig. 3b, for example. In the specimen deformed in quasi-static conditions (strain rate = 0.001 s^{-1}), Fig. 3a, the equiaxed cells with the mean diameter of 0.52 μm form in the most of the observed areas. In general, in the case of lower strain rates more regular microstructures were observed. It was clearly shown in the present study that by increasing strain rate, for the same amount of deformation, there is a tendency for the dislocation boundaries to reorient from a typical cell block structure into a lamellar structure (see Fig. 3a and Fig. 3b). However, it can be also stated that very high strain rate, Fig. 3d, causes that a typical lamellar structure starts to be more inhomogeneous and thin layers of cells and subgrains are more dispersed.

The illegible, inhomogeneous deformation microstructures were observed in most of Nb(Y) steel specimens deformed at high strain rates. The starting microstructure in the present experiments was a typical ferrite-pearlite mixture with mean grain diameter of 12 μm. Comparing the quasi-static and high strain rate testing data of the specimens deformed with similar strains in Fig. 4a and c, it can be observed that the effect of strain rate on dislocation structure is really weak. Fig. 4b and d represents TEM micrograph showing the deformed microstructures in the Nb(Y) steel after compression with lower and higher strain and strain rates, respectively.

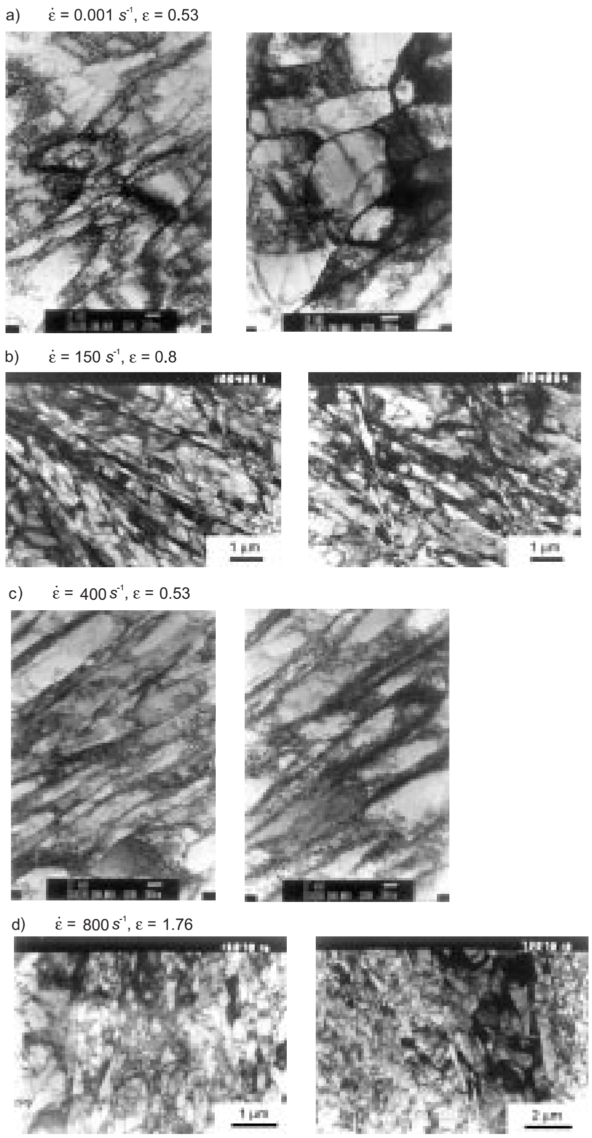

Fig. 3. TEM micrographs showing the compression deformed microstructure, with various strains and strain rates, in IF steel

The size and shape of cells and dislocation walls are very diversified and it also can be observed that whole microstructure of dynamically deformed specimen (Fig. 4d) is very inhomogeneous. It is well known that the unclear grain boundaries and dislocation substructures in microalloyed steels are, first of all, a result of presence of microalloying elements in solution and fine precipitates that retard the dislocation movement. It can be expected that this effect will be more pronounced when the deformation conditions change from quasi-static to the dynamic. Another noticeable source of dislocation movement retardation in the Nb(Y) steel, compared with the IF steel, is the presence of pearlite. Qualitative and especially quantitative evaluation of all mentioned interactions is extremely difficult. However, a possibility of such evaluation is necessary for the study of modern severe plastic deformation processes. The complex influence of the deformation conditions on the dislocation structure development can be controlled by adequate, physically based model.

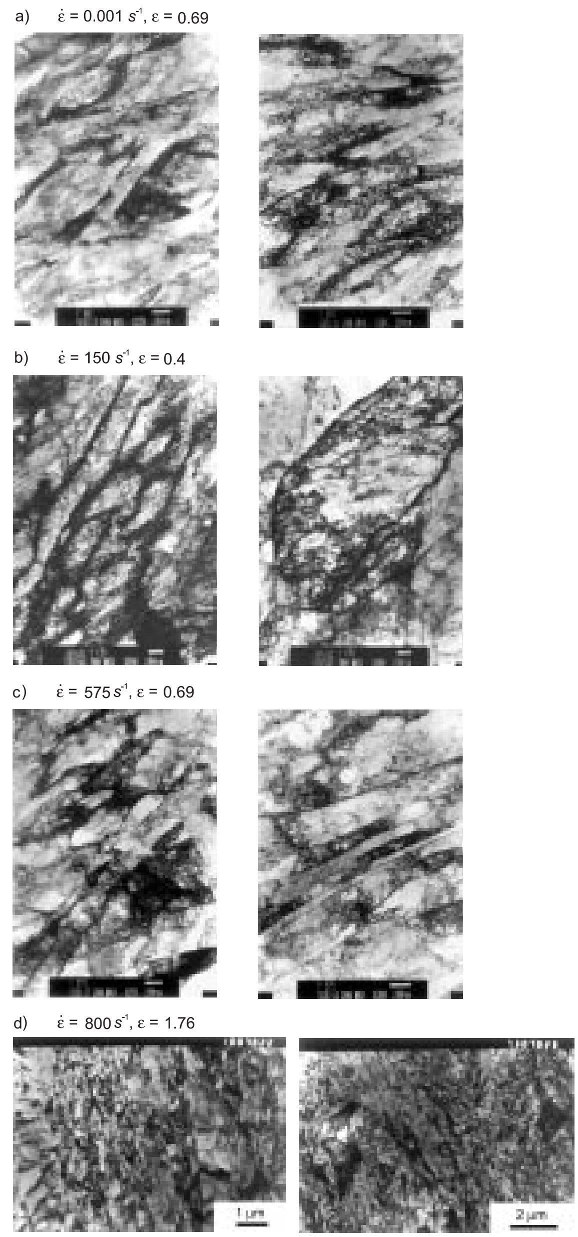

Fig. 4. TEM micrographs showing the compression deformed microstructure, with various strains and strain rates, in Nb(Y) steel

4. Modeling

B e r g s t r ö m's model, proposed in [7–8] is one of the most established ways of the plastic flow mechanics analysis basing on dislocation structure evolution. This model takes into consideration factors affecting the dislocation hardening rate as possible dislocation annihilation and heat effects causing decrease in strengthening through dynamic recovery. Bergström's model is characterized by the simplicity of analysis and wide range of applications – these facts have decided of using it in the further part of theoretical analysis of the present work.

Change in the total dislocation density with strain is determined by four processes i.e. generation, immobilization, re-mobilization and annihilation of dislocations.

B e r g s t r ö m [7–8] proposed that the dislocation density can be determined using following relationship (look also Table 2):

$$\rho = \frac{U}{\Omega}\{1 - \exp(-\Omega\varepsilon)\} + \rho_0 \exp(-\Omega\varepsilon), \tag{1}$$

where: U – is a measured rate at which the density of mobile dislocations is increased by creation and/or re-mobilization (is the composed rate at which mobile dislocations are immobilized or annihilated), Ω – the probability of remobilization and annihilation through reactions between mobile and immobile dislocations, ε – effective strain, ρ_0 – dislocation density in annealed material.

For small values of Ω or strain, equation (1) is approximated with

$$\rho \cong U\varepsilon + \rho_0. \tag{2}$$

Constant U occurring in equation (1) may be calculated from the following relationship [9]:

$$U = \frac{M}{bk_c d_c}, \tag{3}$$

where: M – Taylor's coefficient, k_c – constant, b – Burger's vector, d_c – dislocation cell size, whereas Ω, assuming that consists of an athermal and a thermal component, from the following equation [10]:

$$\Omega = \Omega_0 + \Omega(\dot{\varepsilon}, T) = \\ = \Omega_0 + \left\{k' n_0 (2D_0)^{1/2}\right\}^{2/3} \exp\left(-\frac{Q_m}{3RT}\right)\dot{\varepsilon}^{-1/3}, \tag{4}$$

where: Ω_0 – athermal component of Ω (= 6), $k'n_0$ – k' is a constant, n_0 is a number of vacancies per unit volume (= 1.85×10^{-3}), D_0 – the diffusion coefficient (= 2 cm^2/s), Q_m – the activation energy of grain boundary migration (= 30000 cal/mol), b – Burger's vector (= 2.48×10^{-10} m), R – gas constant, T – temperature, $\dot{\varepsilon}$ – strain rate.

Additionally, dislocation cell size may be calculated from relationship [11]:

$$d_c \approx \frac{2K}{\sqrt{\rho}} = \frac{k_c}{\sqrt{\rho}}, \tag{5}$$

where: K – empirical constant (»10), k_c – experimental constant, ρ – dislocation density.

Fig. 5 shows the relationship between dislocation density and dislocation cell size. On the basis of the carried out investigation it can be seen, that in case of steel, the best consistence of calculated and measured results is for k_c = 23.

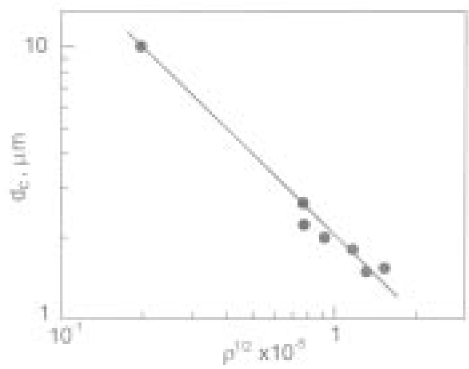

Fig. 5. Relationship between dislocation cell size and dislocation density [12]

Presented B e r g s t r ö m's model points to the direct implementation possibilities of the dislocation structure characteristics into the plastic flow mechanics description. Additionally, taking into consideration the difficulties connected to the precise determination of dislocation density in steels, especially with microalloyed elements, the representation of the dislocation structure by dislocation cell sizes and general assessment of their quality, has been decided to be proper in the analysis of the problem of strain rate effect on plastic flow process.

B e r g s t r ö m's model allows to estimate the relationship between dislocation density and dislocation cell size. The verification of basic relationships, describing by Eq. (1), was carried out on the basis of results from quasi-static and dynamic strength machine and dropweight for IF and Nb(Y) steel. Experimental conditions and results of dislocation structure evaluation are collected in Table 2. Dislocation cell size of microstructures was determined by secant method. In case of strong change of width/length ratio the mean cell diameter was considered. On the basis of measurement and characteristics of dislocation structure (size and quality of dislocation cells) and using B e r g s t r ö m's model (Eq. (1)) and Eq. (5) it is possible to determine the total dislocation density taking into account basic process parameters, in particular strain rate under dynamic loading conditions.

TABLE 2

Results of measurements of dislocation cell size and calculations of dislocation density for investigated steels

Steel	$\dot{\varepsilon}$, s^{-1}	ε	T_D, °C	d_c, μm	ρ, m^{-2} Eq. (1)	ρ, m^{-2} Eq. (5)	Cells features
IF	0.001	0.53	20	0.52	1.46×10^{14}	1.96×10^{15}	sharp, flattened
IF	400	0.53	20	0.8	9.74×10^{13}	8.27×10^{14}	thick, flattened
Nb(Y)	0.001	0.69	20	0.6	1.3×10^{14}	1.47×10^{15}	blurry, flattened
Nb(Y)	575	0.69	20	0.71	1.13×10^{14}	1.05×10^{15}	sharp, flattened
IF	150	0.8	20	0.68	1.84×10^{14}	1.44×10^{15}	sharp, flattened
IF	800	1.76	20	0.86	9.44×10^{13}	7.15×10^{15}	sharp, flattened
Nb(Y)	150	0.4	20	0.8	1.94×10^{14}	3.66×10^{15}	thick, flattened
Nb(Y)	800	1.26	20	0.48	1.69×10^{14}	2.3×10^{15}	sharp, flattened

Comparing the static and dynamic deformation conditions (Table 2) it can be noticed that increased strain rate causes increasing of cell diameter. This collaboration was observed for both of investigated steels. Generally, in case of Nb(Y) steel, the cell structure is less visible, then the quantitative analysis is more difficult. IF steel is characterized by clearly defined cell structure (Fig. 3), therefore the general conclusions can be formulated mostly basing of its analysis.

5. Conclusions

Carried out theoretical and experimental research can be concluded as follows:

1. The nature of dislocation structure depends on the deformation process parameters and chemical composition of investigated steels.
2. Quasi-static deformation causes formation of the cell structure. However, the size and shape of cells are not homogeneous. Very often dislocation walls are diversified.
3. The microstructures of dynamically deformed specimens of Nb(Y) steel are very inhomogeneous and cell structure is less visible.
4. Lamellar structure is more likely formed in increased strain and strain rate conditions. However, it can be also stated that very high strain rate causes, that a typical lamellar structure starts to be more inhomogeneous and thin layers of cells and subgrains are more dispersed.
5. Measurements of dislocation cells size and implementation of modified Bergström's equation allow the determination of the total dislocation density that takes into account basic processing parameters, also strain rate.

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