ARCHIVES OF METALLURGY AND MATERIALS
Volume 56 2011 Issue 2
DOI: 10.2478/v10172-011-0048-2

H. DYJA*, M. KNAPIŃSKI*, M. KWAPISZ*, J. SNOPEK*

PHYSICAL SIMULATION OF CONTROLLED ROLLING AND ACCELERATED COOLING FOR ULTRAFINE-GRAINED STEEL PLATES

FIZYCZNE SYMULACJE WALCOWANIA REGULOWANEGO I PRZYSPIESZONEGO CHŁODZENIA BLACH GRUBYCH Z ULTRADROBNOZIARNISTEJ STALI

The work shows the possibilities of obtaining ultrafine-grained ferrite-pearlite and ferrite-bainite structures in the process of controlled rolling of sheet metal using immediate accelerated cooling after the final pass. Low-carbon steel without micro-alloy additives was analyzed. The analysis was conducted using the Gleeble 3800 device with Hydrawedge II MCU module which enabled a multiple cycle of fast compression of the material. During the test, 10x15x20 mm rectangular parallelepiped specimens were deformed in flat anvils gaining the flat state of deformation in the zone of compression. Then the influence of the used scheme of deformation, cooling rate, time of break between the last deformation and the beginning of the accelerated cooling was analyzed as well as the temperature at the end of accelerated cooling of the structure and the mechanical properties of the final item.

Keywords: plate rolling, physical simulation, super fine-grained steel

W pracy przedstawiono możliwości uzyskiwania superdrobnoziarnistych struktur ferrytyczno-perlitycznych i ferrytyczno-bainitycznych w procesie regulowanego walcowania blach grubych z zastosowaniem bezpośredniego przyspieszonego chłodzenia po ostatnim przepuście. Analizie poddano niskowęglową stal, która nie zawiera dodatków mikrostopowych. Badania prowadzono za pomocą urządzenia Gleeble 3800 z przystawką Hydrawedge II MCU, które umożliwia wykonywanie wielokrotnych szybkich cykli ściskania materiału. Podczas badań odkształcano prostopadłościenne próbki o wymiarach 10x15x20 mm w płaskich kowadłach, uzyskując płaski stan odkształcenia w strefie ściskania. Analizowano wpływ zastosowanego schematu odkształceń, szybkości chłodzenia, czasu przerwy pomiędzy ostatnim odkształceniem i początkiem przyspieszonego chłodzenia oraz temperatury końca przyspieszonego chłodzenia na strukturę i własności mechaniczne uzyskanego wyrobu.

1. Introduction

Intensification of the production processes which take place nowadays globally involves the necessity of producing new steel materials characterized by relatively high mechanical properties in comparison to their price. The items in which the fine-grain structure was achieved during the production process (the diameter of the ferrite grain in the ready item is less than4 μm), have a lot of success in the steel market, which due to this structure guarantees excellent lasting as well as plastic qualities (including impact hardness) [1].

Achieving that kind of structure in low-carbon constructional, non-alloy steels (likely with micro additives) is possible with thermomechanical processing, and this guarantees production of items with excellent properties (with the lasting quality more than 700 MPa) and a low price as well as much amenability to recycling. One of the ways of obtaining of ultrafine-grained structure in low-carbon, non-alloy steels after hot rolling is to use a large value of deformation in the last press which takes place in the temperature close to the temperature at which austenite changes, or in the two-phase range $\gamma + \alpha$ ith the following accelerated cooling to the surrounding temperature [2,3]. The work shows some research results which aim at defining the optimal hot rolling conditions and cooling of the sheet metal of the analyzed steel which guarantee maximum grain refinement and obtaining the ferrite structure with equiaxial ferrite grains with formation of pearlite and/or bainite.

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* CZĘSTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF MATERIAL PROCESSING TECHNOLOGY AND APPLIED PHYSICS , INSTYTUTE OF MODELLING AND AUTOMATION OF PLASTIC WORKING PROCESSES, 42-200 CZĘSTOCHOWA, 19 ARMII KRAJOWEJ AV., POLAND

2. The description of the material and the course of tests

The subject of the research described in this work was ultrafine-grained constructional steel the chemical composition of which was worked out in the Institute for Ferrous Metallurgy. At the same Institute, experimental smelts were made and 100x100x700 mm ingots were casted. The results of the chemical composition of the ingots are shown in Table 1.

TABLE 1

The chemical composition of the steel under analysis

C	Mn	Si	P	S	Cr	Ni
0.13	0.83	0.17	0.012	0.011	< 0.02	0.02
Mo	Co	V	Ti	Al	Cu	
< 0.01	0.01	0.1	0.024	0.023	0.02	

In order to eliminate the dendritic structure, which is typical of the ingots, and eliminate some possible casting defects, the steel was subjected to preliminary hot forming. The flats of the dimensions 27.5×16.5 mm were made from the ingots and then were subjected to the annealing operation. The material prepared in this way was delivered to perform physical simulation of the process of plate rolling taking into account accelerated cooling after rolling. Physical modeling of the steel rolling process was conducted using the GLEEBLE 3800 simulator. This device enables to conduct the following physical processes simulations: continuous steel casting, rolling, drawing, forging, squirting and welding. The system also allows to perform tests of ductility of the materials for the processes of forming, structural tests of deformation mechanisms and to describe material characteristics. Using the multipurpose character of the device it is possible to perform the following tests: the hot tensile test, the uniaxial compression test, the compression test in the plane state of deformation [4, 5].

The research has been divided into two main stages in which the following has been analyzed: the influence of the accepted schemes of deformation and the temperature of the end of rolling on the microstructure development after cooling with the given cooling rate to the surrounding temperature as well as for the chosen optimal scheme of deformation – the influence of cooling parameters on the final structure of the steel. During the first stage of the research the specimens were heated to the temperature of 1000°C at the rate of 5°C/s and then soaked at the same temperature for 5 s in order to obtain homogeneous distribution of temperature in the deformed part of the specimen. Then the specimen was cooled at the rate of 3°C/s to the surrounding temperature and compressed according to the schemes presented in Table 2. After the deformation the specimens were

TABLE 2

The scheme of deformation sequences during rolling simulation

Scheme #		1	2	3	4	5	6	7
Pass 1	T_{deform}, °C	850	914	934	982	952	947	912
	ε,–	1.2	0.4	0.3	0.3	0.3	0.3	0.3
Time of break	t_0, s	–	8	8	8	8	8	8
Pass 2	T_{deform}, °C	–	890	914	966	936	931	896
	ε,–	–	0.4	0.3	0.3	0.3	0.3	0.3
Time of break	t_0, s	–	8	8	8	8	8	8
Pass 3	T_{deform}, °C	–	850	890	946	916	911	876
	ε,–	–	0.4	0.3	0.2	0.2	0.2	0.2
Time of break	t_0, s	–	–	8	8	8	8	8
Pass 4	T_{deform}, °C	–	–	850	922	892	887	852
	ε,–	–	–	0.3	0.2	0.2	0.2	0.2
Time of break	t_0, s	–	–	–	8	8	8	8
Pass 5	T_{deform}, °C	–	–	–	890	860	855	820
	ε,–	–	–	–	0.15	0.15	0.15	0.15
Time of break	t_0, s	–	–	–	8	8	8	8
Pass 6	T_{deform}, °C	–	–	–	850	850	815	780
	ε,–	–	–	–	0.05	0.05	0.05	0.05

cooled at the rate of 10°C to the temperature of 300°C and after that cooled to the surrounding temperature on the air. The scheme of temperature change during the simulation is given in Fig. 1.

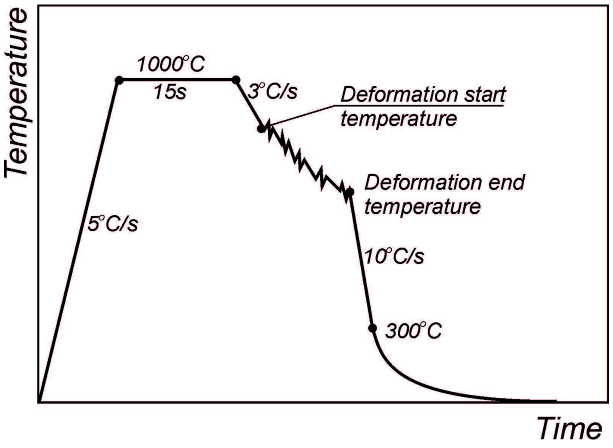

Fig. 1. The scheme of temperature change during rolling simulation

For the analyzed steel in the parallel tests we determined the temperature at which the austenite begins changing into ferrite during the cooling with the rate of 3°C/s. This temperature is about 847°C. When simulating the rolling process, it was accepted that the highest temperature of the end of rolling would be 3°C higher than the determined temperature A_{c3} with the value of 850°C. However, it was supposed that the schemes of rolling would be tested in the range of temperatures when two-phase structure appears in the steel that is austenite and ferrite. Thus, two additional temperatures at the end of rolling were admitted, they were: 815°C and 780°C.

Table 2 shows the schemes of deformations conducted for parallelepiped specimens. The schemes 1-3 do not reflect the real rolling processes of the sheet metal because in the industrial conditions it is not possible to achieve, for example, deformation ε=1.2 in one pass as it exceeds the permitted load of the rolling mill. The simulation of these schemes was done in order to theoretically estimate the influence of large deformation on the steel structure after cooling. However, the schemes of deformation from 4 to 7 reflect the real assembly of presses used in sheet metal rolling mills in the process of six-passes finishing rolling of the sheets. The temperature of the specimens during certain deformations was determined according to the cooling rate of the sheets in the breaks during the following passes of the process of rolling and that this time was constant and equal to 8 s. In scheme 5 it was supposed that the cooling rate would be lower than in scheme 4 and that is why the finishing rolling starts at a lower temperature. However, in schemes 6 and 7 the temperature at the end of rolling would be correspondently lower.

In the second stage of the research the analysis of influence of cooling parameters after the last deformation on the steel structure after cooling to the surrounding temperature was done. For the chosen scheme of deformation reflecting the possible assembly of presses which can be performed in the industrial conditions, the analysis of the influence of the cooling rate, time of break between the final deformation and the beginning of the accelerated cooling and the temperature at the end of accelerated cooling on the steel microstructure was performed. Fig. 2 shows the change in temperature during cooling of the specimens.

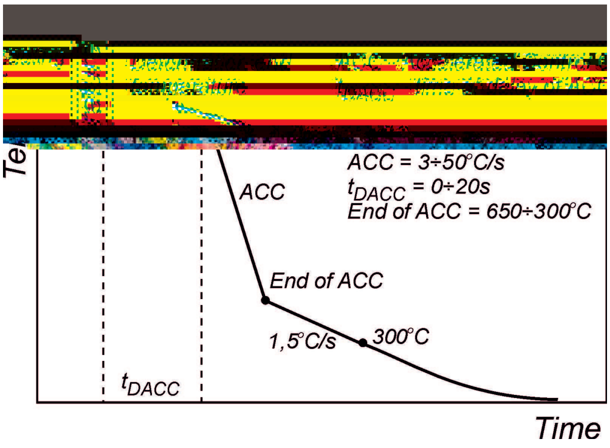

Fig. 2. The scheme of temperature change during the specimens cooling after deformation

The work shows the obtained test results for the cooling rate after deformation which was 3°C/s, 10°C/s, 30°C/s and 50°C/s. Cooling at these rates was analyzed for the specimens deformed according to the assembly of the presses # 7 from Table 2. As a result of the conducted research it was stated that the optimal cooling rate for the chosen conditions of the deformation is 30°C/s and for the same parameters the analysis of the influence of the break between the final deformation and the beginning of the accelerated cooling on the steel structure was conducted. The time within the range of 0÷20 s was tested and on the basis of the obtained results it was stated that the optimal cooling condition for the analyzed steel was accelerated cooling which follows immediately after the final deformation (as short as possible time of the break). For this variant, the analysis of the influence of the temperature at the end of accelerated cooling on the steel structure after cooling to the surrounding temperature was conducted. In this phase of the research the temperature at the end of accelerated cooling was tested and the range of it was 650÷300°C. However, the work shows the chosen results for the temperatures of 600°C, 500°C and 400°C.

3. The results of the tests

Figures 3-9 show the specimens' microstructures after physical simulation of rolling performed in accordance with the schemes from Table 2 and cooling with the rate of 10°C/s to the temperature of 300°C. The use of one large deformation at the temperature of 850°C caused the obtaining of the ferritic structure with the colonies of pearlite after cooling (Fig. 3). The ferrite grain in the structure is refined to the size of about 10÷14 μm. In the specimen deformed according to the scheme two: three presses of the same deformation values ε=0.4, the ferritic-pearlitic structure was obtained with the formation of bainite (Fig. 4). The ferrite grain size was 14÷20 μm. Almost the same structure was obtained in the specimen which was deformed in accordance with scheme 3. Although in this case the refinement of the ferrite grain was larger, and its size was estimated between 12÷17 μm (Fig. 5).

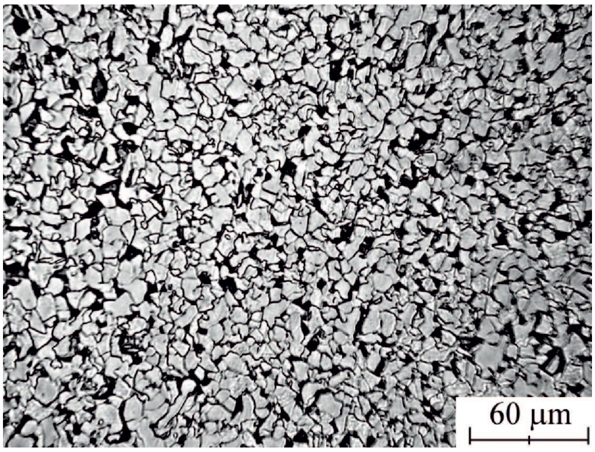

Fig. 3. The microstructure of the specimen after rolling simulation according to scheme 1 from Table 2

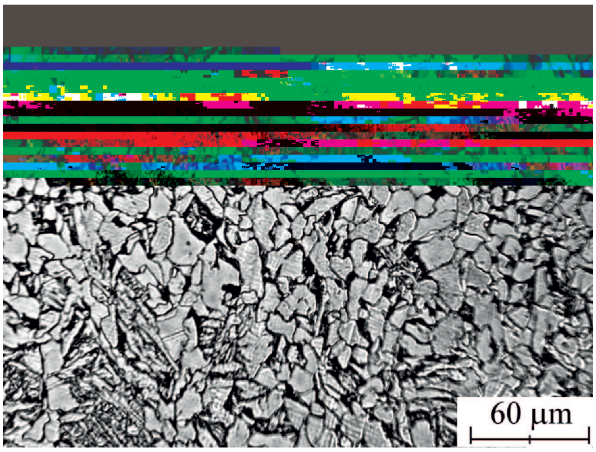

Fig. 4. The microstructure of the specimen after rolling simulation according to scheme 2 from Table 2

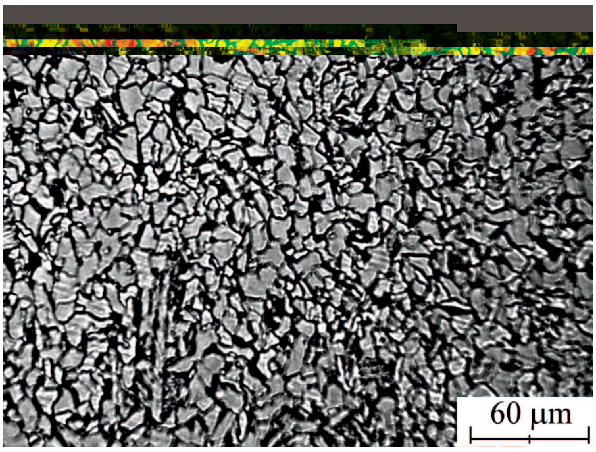

Fig. 5. The microstructure of the specimen after rolling simulation according to scheme 3 from Table 2

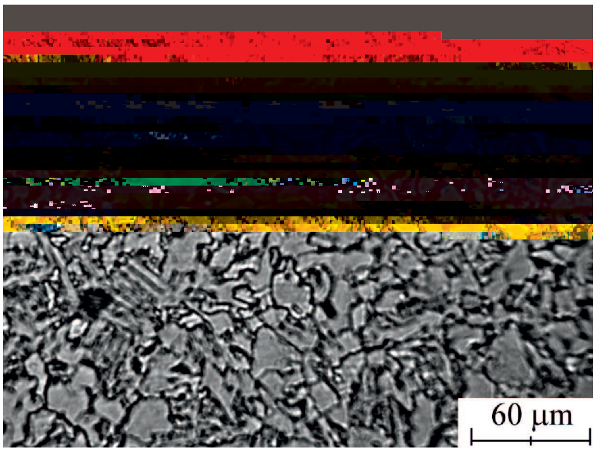

Fig. 6. The microstructure of the specimen after rolling simulation according to scheme 4 from Table 2

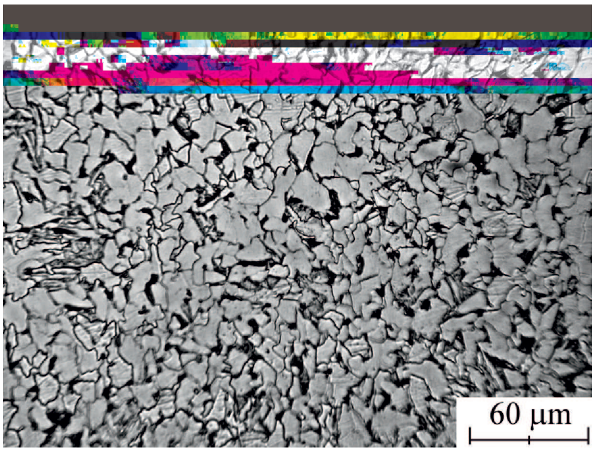

Fig. 7. The microstructure of the specimen after rolling simulation according to scheme 5 from Table 2

After a series of deformations according to scheme 4 the typical multi-phase structure was gained which consisted of ferrite, pearlite and bainite (Fig. 6). In this case the minimal ferrite grain refinement was received, its size within the range of 12÷25 μm. However, reducing the cooling rate of the material between the following deformations according to scheme 5 caused obtaining of the ferritic-pearlitic structure with small bainite formations (Fig. 7). The bigger ferrite grain refinement was also obtained in comparison to scheme 4 of deformations. The ferrite grain was not also homogeneous, but its size is within the range of 7÷24 μm.

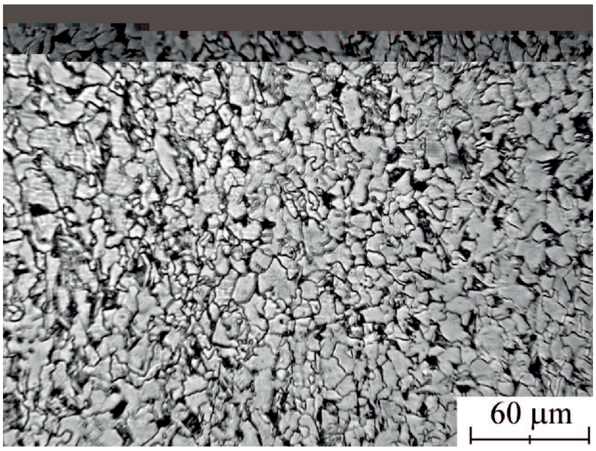

Fig. 8. The microstructure of the specimen after rolling simulation according to scheme 6 from Table 2

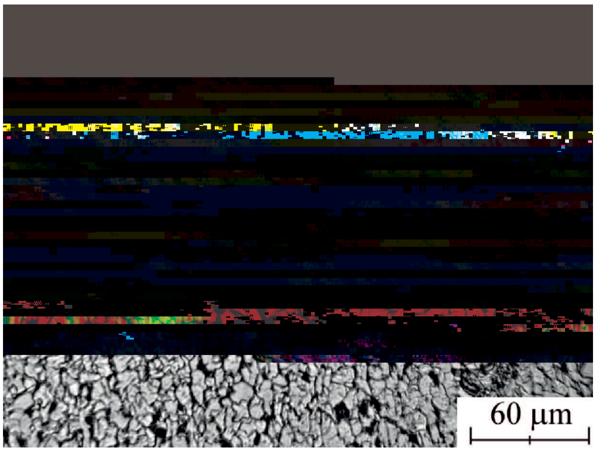

Fig. 9. The microstructure of the specimen after rolling simulation according to scheme 7 from Table 2

The temperature decrease in certain deformations and the end of the cycle with temperature of 815°C caused that the last press was done at the temperature corresponding to the temperature at which two-phase structures appear in the steel. This scheme of deformation resulted in appearance of the ferritic-pearlitic structure with the average ferrite grain size of 6.5 μm (Fig. 8). However, further decrease in deformation temperature lead to getting ferritic-pearlitic structure in the steel with the average grain size of 5.5 μm (Fig. 6). These parameters were received at the scheme of deformation ending with the temperature of 780°C, whereas the last two presses were made in the conditions when the two-phase structure appeared in the steel.

Cooling of the steel under analysis immediately after deformation at the rate corresponding to the atmospheric cooling (about 3°C/s) resulted in appearance of the ferritic-pearlitic structure with the ferrite grain size of about 6 μm (Fig. 10a). The increase in the cooling rate immediately after the final deformation to 30°C/s caused higher ferrite grain refinement whose average size in the ferritic-pearlitic structure was about 5 μm (Fig. 10b). However, cooling at the rate of 50°C/s immediately after the last deformation resulted in the ferritic-pearlitic structure with the average ferrite grain size of 4.5 μm (Fig. 10c). At the same time, it is not practically possible to obtain high cooling rates in the conditions of the industrial rolling, that is why the optimal cooling rate after rolling is accepted to be 30°C/s.

Fig. 11 shows the microstructure of the specimens deformed according to scheme # 7 from Table 2, and then cooled at the rate of 30°C/s taking into account the time of break between the last deformation and the beginning of accelerated cooling. When cooling starts after 4 s from the last deformation, it results in the ferritic-pearlitic structure with a lot of needle-like ferrite (Fig. 11a).

The average ferrite grain size in this structure is less than 4 μm; however, the result can contain a significant mistake regarding the kind of microstructure (the presence of needle-like ferrite). The increase in the time between the last deformation and the beginning of cooling causes a significant increase of the obtained ferrite grain whose size can be about 8.5 μm in the steel which was cooled with 12 s delay and about 10 μm in the steel cooled with 20 s delay (Fig. 11b and 11c). The conducted analysis thus shows that the optimal way of cooling is its immediate start after deformation.

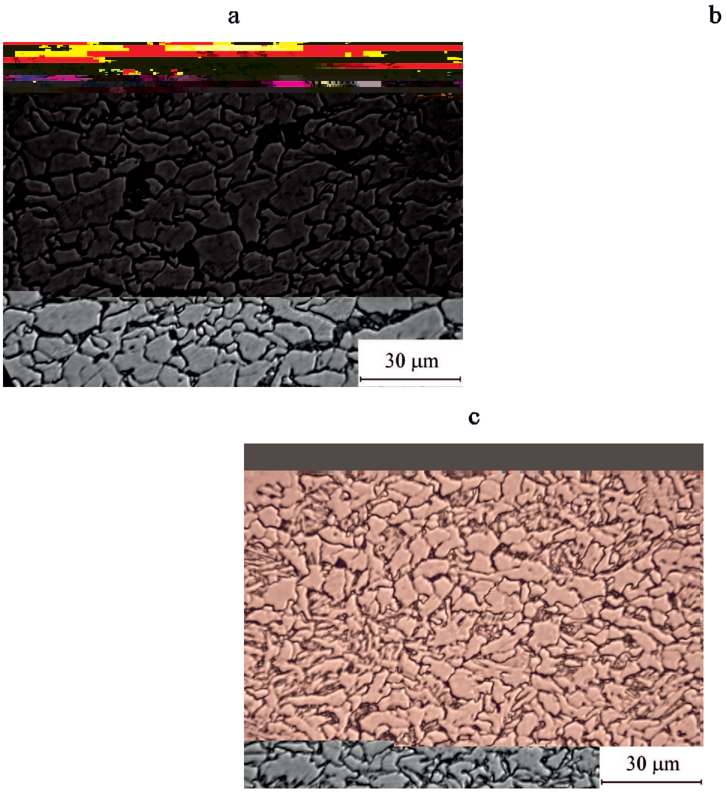

Fig. 10. The microstructure of the specimens after rolling simulation according to scheme 7 from Table 2 cooled after deformation at different rates: a – 3°C/s, b – 30°C/s, c – 50°C/s

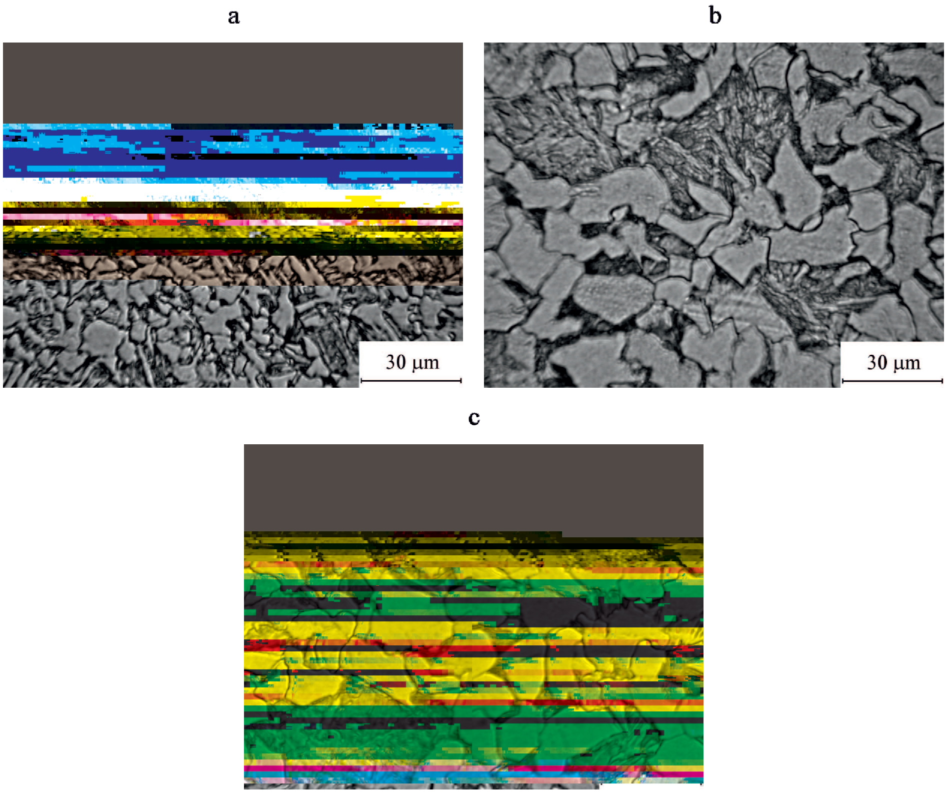

Fig. 11. The microstructure of the specimens after rolling simulation according to scheme 7 from Table 2 cooled after the deformation at the rate of 30°c/s with different time of delay: a – 4 s, b – 12 s, c – 20 s

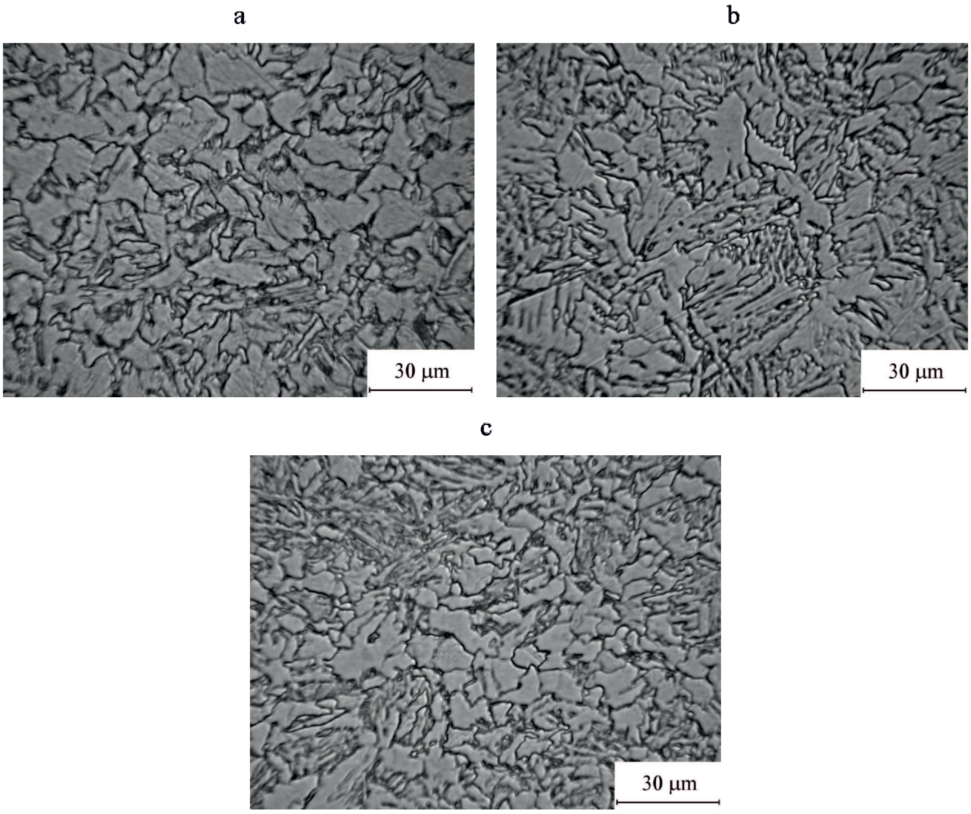

Fig. 12. The microstructure of the specimens after rolling simulation according to scheme 7 from Table 2 cooled immediately after deformation at the rate of 30°C/s to the temperature: a – 600°C, b – 500°C, c – 400°C, and then to the surrounding temperature at the rate of 1.5°C/s

The microstructures of the specimens obtained in the conditions of controlled accelerated cooling to the certain temperature presented in Fig. 12 show that for the tested steel it is even better to conduct accelerated cooling even to the surrounding temperature. If the process of steel cooling at the temperature 600°C is slowed down, it results in the ferritic-pearlitic structure with the ferrite grain size of about 6.5 μm (Fig. 12a), although in case of accelerated cooling to the temperature of 500°C and 400°C and then its slowing down results in the structure with a lot of needle-like ferrite formations (Fig. 12b and 12c).

4. Summary

The analysis of different deformation schemes shows that the end of rolling at the temperature of 850°C and cooling the material at the rate of 10°C/s to the temperature of 300°C lets achieving fine-grain ferritic-pearlitic structure with the ferrite grain size of about 7.5 μm. A decrease in the temperature at the end of rolling to 815°C and then to 780°C causes an increase in the ferrite grain refinement, and its average size is correspondently 6 μm for the temperature at the end of rolling 815°C and about 5.5 μm for the temperature of 780°C. A decrease in the end rolling temperature influences, however, the increase of the banding of the structure. Analyzing the course of the strain-stress curves registered during rolling simulation, it was stated that in all cases the structure rearrangement takes place after each deformation which neutralizes the results of mechanical hardening. In each next press the stress in the function of strain increases the same as in case of the first deformation. Thus, the reason for the lack of a higher grain refinement in the following deformations is that the breaks between the next deformations are too long, and the deformation rate in the next presses is too low.

Analyzing the received results of the influence of the cooling rate after the final deformation on the properties of the tested steel structure, it is possible to say that the change in the cooling rate does not have much influence on the ferrite size; however, has a lot of influence on the structure kind. As the cooling rate increases the morphology of the steel structure after the deformation changes from ferritic through ferritic-pearlitic to ferritic-bainitic. Obtaining the ferritic-bainitic structures or ferritic-pearlitic with the bainite formations in which ferrite grain is very small, significantly increases the lasting qualities of the steel, it also can cause the decrease in its plasticity.

From the results of the further test it is possible to state that for the analyzed steel disregarding the scheme of deformation the introducing of the break between the beginning of accelerated cooling results in the ferrite grain of the larger diameter. This size increases with the increase of the time of the break. The conducted analysis of the influence of the temperature at the end of accelerated cooling on the properties of the material structure after rolling showed that in case of the sheet metal rolling process the stop of accelerated cooling within the temperature range of 400÷600°C and slowing it down to the rate of 1.5°C/s causes appearance of the ferritic-pearlitic structure in the steel with a lot of formation of the needle-like ferrite. These structures are undesirable regarding their high anisotropy of mechanical properties as well as decrease in their lasting qualities.

Acknowledgements

This publication in developed on the bases of the work done in the research project # N R07 0008 04 entitled "Developing the bases of the industrial technology of structure shaping and properties of the metal and alloy items using the physical and numeric simulation" sponsored by the State Center of Research and Development, conducted by the Institute for Ferrous Metallurgy named after Stanislaw Staszic in Gliwice (supervisor), AGH University of Science and Technology, Czestochowa University of Technology, Silesian University of Technology and Warsaw University of Technology.

Received: 10 January 2011.

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