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MICROSTRUCTURE DEVELOPMENT IN RIDGING AFFECTED FERRITIC STAINLESS STEELS

ROZWÓJ MIKROSTRUKTURY W ODPORNYCH NA KOROZJE STALACH FERRYTYCZNYCH WYKAZUJĄCYCH EFEKT ŻEBROWANIA

The subject of investigation is the ridging phenomenon occuring in ferritic stainless chromium steels. The origin of this undesirable surface phenomenon is connected with the observed strips of texture inhomogeneities showing plastic anisotropy. Basing on measurements of crystallographic orientation topography the texture inhomogeneities together with the ridging effects have been investigated in sheets from earlier stages of the production process. The proposed changes in the traditional technological processing of sheets obtained from this steel type are intended to limit the occurrence of the ridging effect.

Przedmiotem badań jest zjawisko żebrowania występujące w blachach ferrytycznej stali chromowej odpornej na korozję. Przyczyny tego niekorzystnego zjawiska powierzchniowego związane są z występującymi pasmami niejednorodności tekstury wykazującymi anizotropię plastyczną. W oparciu o pomiary topografii orientacji krystalograficznych badano niejednorodności tekstury w powiązaniu z efektami żebrowania we wczesnych stadiach procesu produkcji blach. Zaproponowano zmiany w tradycyjnej technologii produkcji blach w celu ograniczenia występowania efektu żebrowania

1. Introduction

Chromium steels of ferritic structure are an important group of construction materials. Their particular application results from the fact that they remain resistant to a corrosive environment. Such steels passivate under the influence of oxygen present in the air at the

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chromium content higher than 13–14%. However, in widely used industrial applications where corrosion resistance is required, they are often replaced by much more expensive chromium – nickel steels of austenitic structure. This is connected with the occurrence in the ferritic steels of the so-called ridging or roping phenomenon, which to a considerable extent limits their utilization in the processes in which high quality of the surface of the final product is required. This effect consist in that on the smooth surface of cold rolled and recrystalized metal sheet, after tension or deep drawing, there appear ridges and rows "visible with naked eye", lying along the primary direction of rolling. To the ridges on one side of the metal sheet there correspond rows on the other side of the sheet. No changes in the sheet thickness are observed. The distance between the neighbouring ridges vary from 1 to 5 mm, their height being up to 20 μm.

Investigation conducted so far did not explain the cause of the ridging phenomenon. It has been found only that in a material susceptible to ridging there occur some definite, regularly changing inhomogeneities of structure and of the local texture in the form of elongated strips corresponding to the geometry of the observed ridges and rows.

From the analysis of the present state of knowledge and the authors' own observations [1, 2, 3, 9, 10] it follows that the direct cause of the ridging phenomenon in the final product is the plastic anisotropy of strips in the form of chains of grains of a definite crystallographic orientation different from that of the surroundings. The factors which may contribute in an indirect way to the occurrence of the ridging phenomenon are thought to be the effects of segregation of the alloy elements, such as chromium, molybdenum or carbon.

Recent investigations indicate that the primary causes of the ridging phenomenon should be looked for in the first stages of the technological process. It seems essential to trace, at each stage of the technological production process, the changes in the structure and texture of the material, and their inhomogeneities in relation to the phenomenon of segregation of the alloy elements.

Many models have been created aimed at the explanation of the ridging phenomenon as well as presents which allow to minimize it. So far, however, a production technology enabling a complete elimination of this phenomenon in the traditional manufacturing process with hot rolling has not been developed. The subject of the investigations of the present study are the changes in the structure and texture at the initial stages of the manufacturing process of sheets from corrosion resistant ferritic chromium steel. A new direction of changes in the technological process intended to minimize the occurrence of the ridging effect is proposed.

2. Experimental

The investigated material was FeCr17Mo1 steel of chemical composition shown in Table 1. The melt was obtained in a vacuum furnace. The melting point was 1525°C. Mass of the ingot – about 27 kg.

TABLE 1

Chemical composition of the applied steel (wt. %)

C	Cr	Mo	Mn	Ni	Si	Al	N
0.01	17.2	1.14	1.15	0.25	0.3	0.01	0.01

Three types of samples (indicated *A*, *B*, *C*) were prepared by cutting them from appropriate areas (see Fig.1) of the ingot in such a way as to obtain samples in which the main elements of their structure were:

A → columnar grains lying parallel to the assumed hot rolling direction (**RD**),

B → columnar grains situated perpendicular to **RD**,

C → "equiaxed" grains (from the middle part of the ingot).

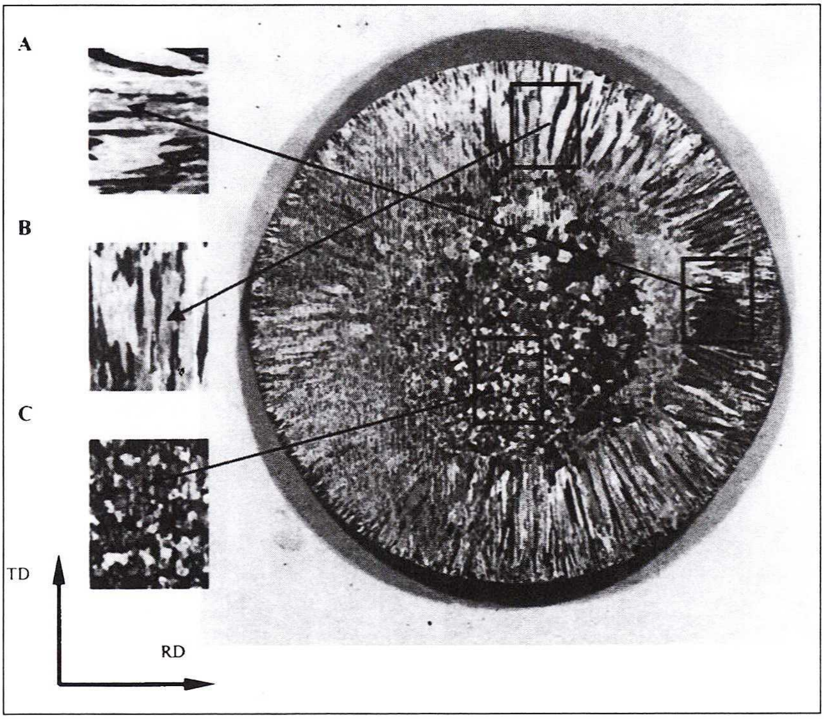

Fig. 1. Types of samples structure

To control the global textures of samples prepared in this way pole figures {200} were measured using the *X*-ray diffraction technique. In the case of large grains (~100 μm) the samples were scanned during the measurement to improve the statistics of the texture data.

The obtained pole figures (Fig. 2a, b) show that the textures of the sample *A* and of the sample *B* can be described by a fibre-type distribution with {100} axes parallel to

TABLE 2

Scheme I, interpass time 10 s.

Pass	Thickness		Reduction [%]	Temperature [°C]
	Start	Finish		
1.	20.0	18.10	9.5	1050
2.	18.10	15.39	15.0	1032
3.	15.39	13.08	15.0	1014
4.	13.08	11.12	15.0	996
5.	11.12	9.45	15.0	978
6.	9.45	8.03	15.0	960
7.	8.03	6.83	15.0	942
8.	6.83	5.80	15.0	924
9.	5.80	4.93	15.0	906
10.	4.93	4.19	15.0	888
11.	4.19	3.56	15.0	870
12.	3.56	3.03	15.0	852
13.	3.03	2.57	15.0	834
14.	2.57	2.2	14.5	816

the **RD** in the case of the sample *A* and parallel to **TD** for the sample *B*. The fibres run from the position of the cubic orientation $\{100\}\langle 001\rangle$ to the Goss position $\{011\}\langle 100\rangle$ for the sample *A*, and from the cubic to the $\{011\}\langle 110\rangle$ position for the sample *B*.

This type of texture results directly from the structure of the samples in which the directions $\langle 100\rangle \|$ **RD** or $\langle 100\rangle \|$**TD** are parallel to the columnar grain axes, whereas the rotation angle around these axes is a free parameter.

The pole figure for the sample *C* (Fig. 2c) shows that the crystallites in the middle part of the ingot are nearly randomly distributed.

Hot rolling of these samples was physically simulated, by means of the thermal – mechanical testing machine Gleeble3500 – according to two schemes: I and II, specified in Table 2 and Table 3, respectively. Scheme I, with the reduction per pass not greater than 15% and the interpass time equal to 10 s, was close to the standard technological conditions. In the deformation according to scheme II the reduction per pass was increased by about 30%, and the interpass time was prolonged to 30s [e.g. 11]. In each case the total reduction was 89%, and pre-heat temperature ~1050°C. During hot rolling the temperature was decreased systematically to stop at ~820°C. After hot rolling, each sample was annealed at 820°C for 10 minutes.

The samples after hot rolling were subjected to ridging tests. To obtain a possibly strong ridging effect the top and bottom surface layers, each of about 20–25% of each

TABLE 3

Scheme II, interpass time 30 s.

Pass	Thickness		Reduction [%]	Temperature [°C]
	Start	Finish		
1.	20.0	17.04	14.8	1050
2.	17.04	12.78	25	1011
3.	12.78	8.95	30	972
4.	8.95	6.26	30	933
5.	6.26	4.38	30	894
6.	4.38	3.07	30	855
7.	3.07	2.2	28.3	816

sample, were removed. The samples (after thinning) were tensioned in the rolling direction by about 10%. Next, on the rolling planes of each sample, the topography of crystallographic orientations was measured. The measurement of single orientations was performed automatically point-by-point with the Tuse of an automatic crystal orientation measurement devise (ACOM) in scanning electron microscope (SEM). Rectangular areas were automatically scanned along the transverse direction at a distance of 50 μm between the measurement points. The local orientation measurements were used to contrast the microstructure (the orientation topography) as well as to calculate the orientation distribution describing the global texture.

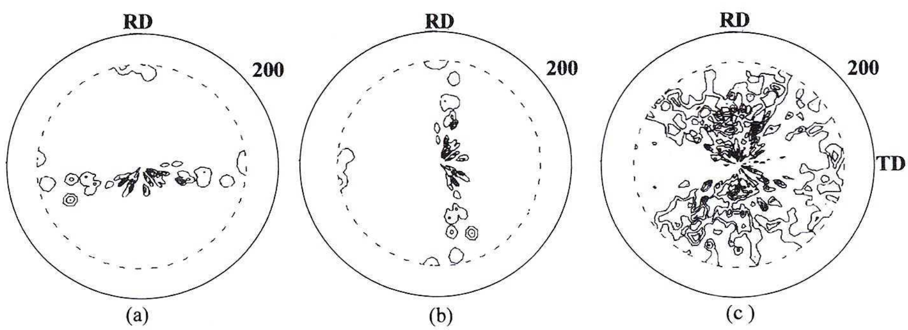

Fig. 2. Pole figures {200} measured in the samples prepared from appropriate areas of the ingot:
a) sample A, dendrities lying parallel to the rolling direction;
b) sample B, dendrities lying perpendicular to the rolling direction;
c) sample C, equiaxed grains from the middle part of the ingot

3. Results

The surface of hot rolled samples after their tension showed deterioration of various degree of intensity. The ridging in the form of quasiperiodic undulations with riges and rows lying nearly parallel to the former hot – rolling direction, occurred only in sample AI, i. e. in a sample, deformed according to scheme I (Table 2), with columnar grains lying parallel to the rolling direction. On the surface of the other samples there appeared the „orange peel'' of various degree of intensity: the weakest being for the samples CII, and the strongest for the samples BI and CI.

Fig. 3 and Fig. 4 show the microstructures (contrasted by topography of orientations) and the corresponding global textures for samples deformed according to scheme I and to scheme II, respectively.

In the case of AI in the orientation topography, we can observe groups of grains in the form of strips extending parallel to the rolling direction (Fig. 4 AI). Colonies of elongated grains correlated clearly with the ridges, which appeared on the surface of AI samples after their tension. Some similarity between the topography of AI and that of CI can be observed, however in CI the arrangement of the strips is not so strongly pronounced; there appear here grains rather strongly elongated in the rolling direction (Fig. 4 CI). To describe the textures of the samples, the densities of orientation distributions have been presented on the section $\varphi_2 = 45°$ of the commonly used space of Euler angles (φ_1, Φ, φ_2). In the orientation distributions of AI and CI samples there can be distinguished components typical for the texture of the final product [6, 9], i.e. sheet metal after hot rolling, annealing, cold rolling and recrystallization.

The texture of the sample AI can be described by a fragment of the α-fibre ($\{001\}\langle110\rangle \div \{114\}\langle110\rangle$), and the position ~$\{111\}\langle112\rangle$ belonging to the γ-fibre.

The orientation density of CI is dispersed along the α-fibre, from $\{001\}\langle110\rangle$ over $\{112\}\langle110\rangle$ to $\{111\}\langle110\rangle$. In AI and CI samples the grains of this orientation form bands lying parallel to the rolling direction. Especially interesting is here the appearance of the component $\{001\}\langle110\rangle$, already at the stage of hot rolling. In BI sample, with the columnar grains perpendicular to the rolling direction, after hot-rolling according to scheme I, there appear diagonally elongated grains. Results on Fig. 3 BI show that rolling of the sample BI leads to the turn of the columnar grains structure by 45° around the normal direction. This is confirmed also by the texture observation where the $(001)[1\bar{1}0]$ orientation moves into the cube position $(001)[0\bar{1}0]$ and the $(111)[1\bar{1}2]$ into the $(111)[1\bar{4}3]$ position (visible with its 3 symmetrically equivalent positions). In the orientation distribution the contribution of the component $\{001\}\langle100\rangle$ is strongly increased.

A change in the deformation scheme, consisting in a significant increase of the reduction per pass and prolongation of the interpass time (see Table 3), produces considerable changes in the texture and in the topography of orientation (Fig 4). In general, the tendency to form banded structures is decreasing. In AII we can observe quasi–equiaxed grains with a tendency to form groups extended along the rolling direction. In CII there appears a structure with equiaxed grains, without showing the direction of forming groups. In AII and CII textures the components of $\langle011\rangle \parallel$ RD type

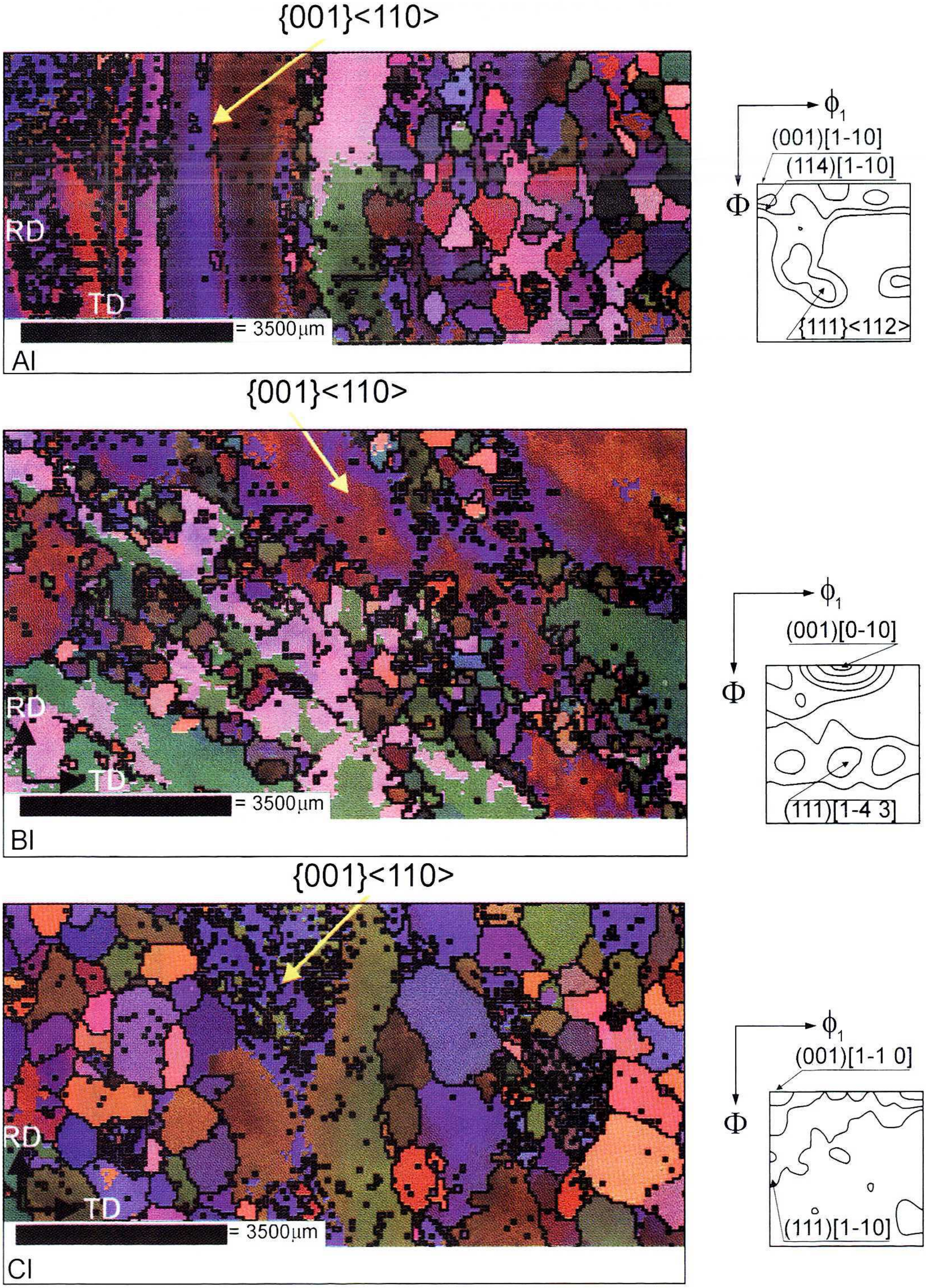

Fig. 3. Orientation topographies and orientation distribution functions, section $\varphi_2 = 45°$, at the 1/4 thickness plane of sheets after hot–rolling according to scheme 1 (the reduction per pass not greater than 15%, the interpass time equal 10 s.), samples A, B and C (black lines in topographies indicate misorientation angles higher than 15°)

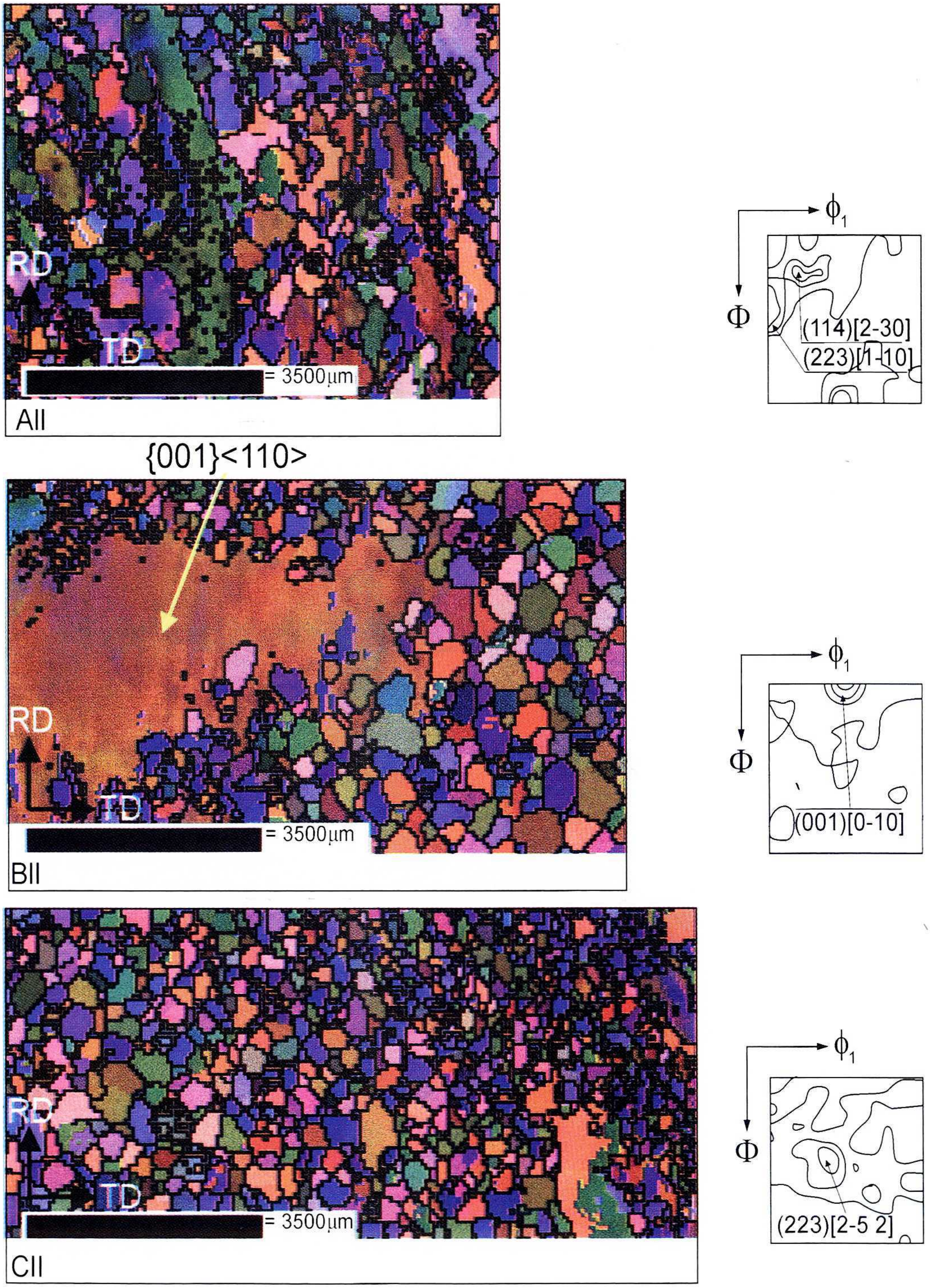

Fig. 4. Orientation topographies and orientation distribution functions, section $\varphi_2 = 45°$, at the 1/4 thickness plane of sheets after hot–rolling according to scheme 2 (the reduction per pass not greater than 15%, the interpass time equal 30 s.), samples A, B and C (black lines in topographies indicate misorientation angles higher than 15°)

remain; in comparison with AI and CI we observe a shift from the positions about {001}⟨110⟩ to the positions ~{223}⟨110⟩ and {114}⟨230⟩ for AII, and to the position {223}⟨252⟩ for CII, the result of which in each case is a strong reduction of the fraction of the unfavourable {001}⟨110⟩ component in the texture. In the microstructure of BII the rotation by 45° around the sheet normal which was observed in the BI case was not clearly visible. Nevertheless, this rotation takes place, which is evidenced by the presence of the cube component in the texture image. In BII samples, besides the equiaxed structure, we observe grains of the orientation {001}⟨100⟩, elongated in the transverse direction. Intensification of deterioration on the sample surface after tension, and the tendency to form the "orange peel" are generally smaller than in the case of deformation according to scheme I. Ridging did not appear in any of the samples. On the surface of CII sample there appeared a very weak "orange peel" (hardly visible with naked eye).

4. Conclusions

In hot rolled sheets of ferritic stainless steels there may develop a specific band structure built of grains strongly elongated in the rolling direction. Appearance of this structure is not necessarily connected with the dendritic structure of the ingot. Under hot rolling conditions, in accordance with the standard technological production conditions (scheme I) (reduction per pass <15%, short time intervals between passes), the quasi – banded structure may also appear in an ingot of equiaxed grains after rolling. From the authors' own investigations, as well as observations of other authors [3] it follows that this specific banded structure may be inherited by the final product. This refers in particular to the inheritance of bands of {001}⟨110⟩ orientation. Bands with this orientation have been observed in the final product [9, 10] and in the present experiments also in sheets after hot rolling.

If a metal sheet with lamellar internal structure has been pulled in tension parallel to the axis of strips, then on its surface a characteristic ridging will appear. In general, this effect is the result of differences in the anisotropy of plastic deformation between the colonies of grains of similar orientation, grouped into strips, and the matrix. On the basis of the authors' earlier investigations of the ridging phenomenon in metal sheets as the final product [9], it could be observed that the positions of the tops of the ridges/bottoms of the rows on the surface of samples tensioned along the primary rolling direction, correspond to the position of strips of {100}⟨011⟩ orientation in middle layers of the samples. It has been found now that a similar correlation appears in samples after hot rolling. Hence it can be assumed that the ridging phenomenon is connected with the difference in the anisotropy of plastic deformation between strips of {100}⟨011⟩ and the matrix, according to the model proposed by Wright [12, 13].

A change in the scheme of hot rolling by increasing the reduction per pass and prolongation of the interpass time interval produces strong changes both in the structure and the texture; the most essential from the point of view of technology is the disappearing tendency to form banded structures and the disappearance of the component {001}⟨110⟩. The consequence of these advantageous changes is the minimization of the ridging effect.

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