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Texture and structure evolution during cold rolling of austenitic stainless steel

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Properties

ABSTRACT

Purpose: The paper analyses the influence of plastic deformation in cold working process on the texture and structure of X5CrNi18-8 austenitic stainless steel.
Design/methodology/approach: The main methods used for these researches were metallographic observations, magnetic investigations as well as X-ray examinations, which were applied for phase analysis and the texture measurements of the rolled strip.
Findings: The deformation texture development in the case of X5CrNi18-8 steel was complex, because during cold rolling three processes were proceeded simultaneously, i.e.: plastic deformation of the austenitic γ-phase, phase transformation γ→α' as well as deformation of the formed α'-martensite. Thus, the resultant deformation texture of the investigated steel is described by the components from the textures of both phases- γ and α'.
Research limitations/implications: The X-ray phase analysis in particular allowed to reveal and identify the phases in the structure of the investigated steel after its deformation within the range 10-70 %. Results of the ferritescope measurements allowed to determine the proportional part of α` phases in the structure of investigated steel in the examined range of cold plastic deformation. The comparison of the martensite orientation distribution functions (ODFs) after deformation with those after (α'→γ) transformation indicates that Kurdjumov-Sachs (K-S) and Nishiyama-Wassermann (N-W) orientation relationships describe well the crystallographic orientation relations between both phases.
Practical implications: The analysis of the obtained results permits to state that the degree of deformation has a significant influence on the structure and texture of the investigated steels.
Originality/value: The character of the texture evolution was analysed during increasing of the plastic deformation, considering the variations of different crystallographic orientations in both phases. The α-phase volume fraction was determined after each rolling pass of strip. This allowed to determine the interdependence between the evolution of texture and phase composition of the investigated steel.
Keywords: Metallic alloys; Austenitic steel; Cold rolling; Deformation texture; Phase transformation; Martensite α'

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1. Introduction

Deformation textures formed by cold rolling in face-cantered cubic (FCC) metals (e.g.: austenitic stainless steel) and alloys can be categorized into two groups: a brass (or alloy) type texture and a copper (or pure metal) type texture. The possible causes for different rolling textures are mainly crystallographic structure, starting texture, chemical composition, grain size and shape, stacking fault energy (SFE) and the forming parameters (rolling degree, rolling temperature and rolling rate) [1-3]. As the SFE increases the texture transition from brass to copper-type takes place. The FCC rolling textures may be described either in terms of ideal orientations or in terms of complete or limited fibre axis. According to the concept of ideal orientations, the copper-type texture is characterized mainly by the orientations {112}<111>, {153}<112> (called S orientation) and {123}<634>, whereas the brass-type texture is described by the orientations {011}<112> and {011}<100> (called the Goss orientation) [4-5]. The transition from copper to brass-type textures is described by the disappearance of {112}<111> component [6].

Austenitic stainless steels are materials widely used because of their excellent corrosion resistance in various aggressive environments, combined with high mechanical and plastic properties. This type of steels, which are produced nowadays, can be divided structurally into: steels with a stable austenitic structure, steels with unstable austenite which can be transformed to the martensite during plastic deformation, steels with an austenitic-ferritic structure [7-10].

Austenitic stainless steels are materials with low and average stacking fault energy. They can undergo deformation in result of slip and mechanical twining, the phase transformations ($\gamma \rightarrow \alpha'$ or $\gamma \rightarrow \varepsilon \rightarrow \alpha'$) also take place. Martensite formation resulting from plastic deformation of metastable austenite is of great interest for producing high strength and ductility in austenitic stainless steels. Substantial strengthening can be obtained in these steels by plastic deformation below M_{d30} temperature (M_{d30} is the temperature at which 50% α' martensite has formed for a true strain of 30%) to produce cubic body cantered α' and hexagonal closed packed ε martensite. The amount of α' and/or ε martensite depends on the alloy composition, stacking fault energy, degree of deformation, temperature etc. [11-15].

The phase transformations as well as the crystallographic relationships between austenite and the products of the transformation – ferrite, bainite or martensite, play an important role in commercial Fe base alloys [16-17].

In the phase transformation which proceeds, according to a special crystallographic orientation relation (OR), a single original orientation changes into a number of final crystallographic orientations depending on the symmetry and initial orientation of the crystal. From the crystallographic point of view, all possible variants resulting from the transformation should appear with the same probability. The crystallographic relationships that are most often observed in steels are Bain, Kurdjumov-Sachs (K-S) and Nishiyama-Wassermann (N-W) [18-21].

The aim of these investigations is to determine the influence of plastic deformation in cold rolling process on the texture and structure forming in the austenitic stainless steel grade X5CrNi18-8.

2. Experimental procedure

Investigations were carried out on austenitic steel grade X5CrNi18-8 [22] with chemical composition given in Table 1. The steel was received in the form of sheet-cutting with dimensions about 2×40×700 mm, subjected to cold rolling process within the range of deformations from 10% to 70%. The rolling was conducted at room temperature keeping a constant direction and side of the rolled strip. Additionally, to compare the structure and texture in different states, the investigated steel was super-saturated for 1 hour at 1100°C, and then cooled down in water.

Table 1.
The chemical composition of investigated steel

Mass contents in percentage, %				
C	Cr	Ni	Mn	Si
0.03	18.07	8.00	1.31	0.39
Mo	P	S	N_2	Fe
0.25	0.03	0.004	0.044	balance

Based on the chemical composition of the investigated steel the values of the following parameters were evaluated, namely: the stacking fault energy of the austenitic γ-phase SFE = 15.76 mJ/m^2 [23], the martensite start temperature M_s = -51.67°C [24] and the temperature of strain induced martensitic transformation M_{d30}= 36.4°C [25].

Metallographic examinations of samples were performed on longitudinal microsections, mechanically ground and chemically etched in the reagent Mi17Fe [26] heated to a temperature of about 40°C. The times of the etching of individual samples were different. Samples deformed with a larger rolling reduction required longer time of etching. The microstructure observations were carried out by means of the optical microscope LEICA MEF4A.

X-ray investigations of X5CrNi18-8 austenitic stainless steel included the phase analysis from the surface and centre layers of the rolled strip and the texture measurements, for the delivery and supersaturation state as well as after selected rolling reductions within the range 10-70%.

X-ray qualitative phase analysis of steel were performed on X-ray diffractometer D500, using monochromatic radiation of the anode CuK_α ($\lambda_{K\alpha}$ = 0.154 nm). The data of the diffraction lines were recorded by "step-scanning" method in 2Θ range from 40° to 92° and the 0.02° step, the time of measurements amounting to 5 s. X-ray quantitative analysis were carried out on samples with dimensions 10×20 mm. Samples for examinations were polished and chemical etched in the reagent Mi17Fe.

Texture measurements were done by means Bruker diffractometer D8 Advance, using CoK_α radiation of $\lambda_{K\alpha}$ = 0.179 nm. Texture analysis was performed on the basis of the orientation distribution functions (ODFs) calculated from the experimental pole figures. The incomplete pole figures were recorded of three planes for each of the component phase, i.e.: the {111}, {200}, {220} planes for austenite and the {110}, {200}, {211} planes for the martensite. The values of the orientation distribution functions f(g) along the typical orientation fibres were examined, i.e.: α =<110>║ND, τ =<110>║PD, β ={110}<112> by {123}<634>

to {112}<111> for the austenite as well as α_1 =<110>‖RD, γ ={111}‖ND and ε =<001>‖ND for the α' martensite. Additionally simulated transformations (α'→γ) of the martensite texture (experimental ODFs) were carried out.

The amount of deformation induced α' martensite was determined by magnetic measurements, using a ferritescope (Helmut Fischer, model FMP30), according to the standard PN-EN ISO 8249:2005 [27]. The device was calibrated with δ-ferrite standard samples and the results were converted to the α'-martensite contents with the correlation factor of 1.7. In measurements, the standard samples sets type M-0620 were used. The effect of sheet thickness on the results was compensated by means of a correction curve provided by the manufacturer of the device. The magnetic measurements with the ferritescope were performed on the metallographic samples, in delivery and supersaturated state as well as after cold rolling. Tests were carried out in 5 point measurements of each specimen.

3. Results and discussion

Within the structure of X5CrNi18-8 steel at the delivery state the equiaxed austenite grains and annealing twins as well as some non-metallic inclusions were observed (Fig. 1). Similar steel structure was observed after supersaturation at 1100°C for 1 hour.

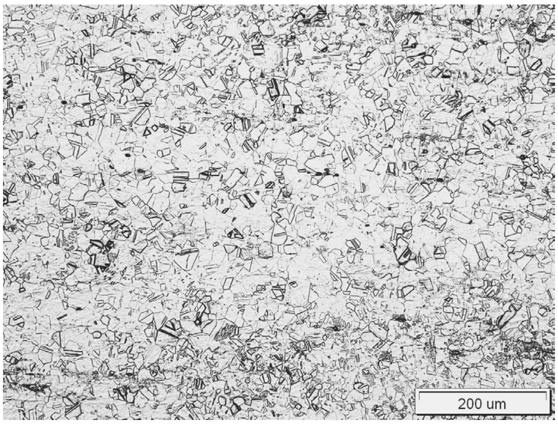

Fig. 1. Structure of X5CrNi18-8 steel at the delivery state; Etching – Mi17Fe

The structure of the studied steel after plastic deformation with rolling reduction from 10 to 20% are characterized by austenite grains with slip bands and deformation twins as well as sparse non-metallic inclusions (Fig. 2a). Deformation with a larger rolling reduction causes in the steel structure elongated γ grains in the rolling direction. After over 30% of rolling reduction in structure of steel elongated austenite grains, slip bands and deformation twins a few areas of parallel plates characteristic for martensite α' were observed (Fig. 2b).

During the plastic deformation in cold working of the X5CrNi18-8 steel with increasing degree of deformation the α' phase is formed. The new formed α' phase divides the elongated grains of austenite, therefore grain size of the steel is significantly reduced and also strain hardened (Fig. 2c).

a)

b)

c)

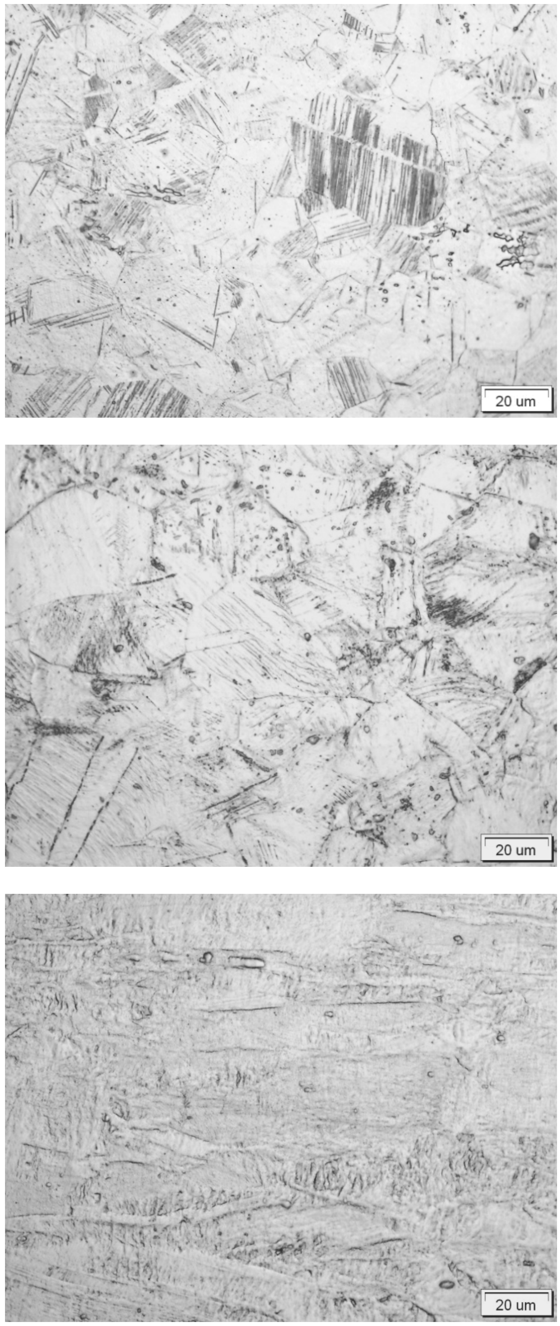

Fig. 2. Structure of X5CrNi18-8 steel after cold rolling with: a) 10%, b) 30%, c) 70% deformation degree; Etching – Mi17Fe

On the basis of metallographic observations it was found that the amount of α' phase in the investigated steel structure increases with increasing deformation degree in the cold rolling process.

The X-ray phase analysis of X5CrNi18-8 steel at delivery state revealed reflection lines coming from both phase γ and α' (Figs. 3a,b). On the diffraction patterns of steel surface at the delivered state, there are appeared four diffraction lines coming from planes (111), (200), (220) and (311) austenite phases and one diffraction line (110) from α' martensite phase (Fig. 3a). Identical diffraction lines occur on diffraction patterns of investigated steel made from the centre layers (Fig. 3b).

On diffraction patterns obtained for surface and centre layers of the strip in a supersaturated state no significant change in the intensity of individual diffraction lines coming from γ and α' phase were observed, in compared to the diffraction patterns of investigated steel in delivery state (Fig. 3a,b).

The occurrence of the α' martensite on diffraction patterns of steel at delivery and supersaturated state proves that phase transformation γ→α' take place. However, α' phase revealed in investigated steel at delivery state could arise at the stage of material pretreatment (i.e.: cutting, machining), while the α' martensite detected in supersaturated samples appeared probably as a result of the samples preparation for subsequent investigations (i.e.: grinding, polishing).

On the diffraction patterns received for steel surface after cold rolling within the range from 10 to 50% decrease in the intensity of the (111)γ, (200)γ and (311)γ picks from austenite and increase in the intensity of the (110)α', (200)α'and (211)α' from martensite was observed (Fig. 3a). In the investigated range of deformation, the intensity of (220)γ diffraction line from austenite was constant. After 70% of rolling reduction, diffraction patterns of the steel didn't disclosed lines coming from the plane {111}γ austenite. However, the (110)α' diffraction line from martensite was observed and its broadening from the side of austenite the {111}γ diffraction line occurrence (Fig. 3a). The picks (200)α' and (211)α' from martensite were disclosed. Diffraction lines coming from the planes {200}γ and {311}γ disappeared, also intensity of the (220)γ plane decrease.

Diffraction investigations of the centre layers of steel deformed with the range from 10 to 40% showed the occurrence of γ phase in its structure, which is displayed by presence of diffraction lines coming from the plane {111}γ, {200}γ, {220}γ and {311}γ austenite as well as {110}α', {200}α' and {211}α' martensite. In the investigated range of deformation, the intensity of diffraction line (110)α' to the line (111)γ increases, which proves the distinct increase of the amount of α' phase in the structure of the investigated steel (Fig. 3b). After 50-70% of rolling reduction the picks from the planes {200}γ and {311}γ were no longer observed on diffraction patterns of the steel. In the investigated range of deformation, the (220)γ pick from austenite was the strongest one. After maximum deformation the strongest diffraction lines from martensite was (211)α'.

On the basis of the realized X-ray diffraction investigations it was found that, the analysed diffraction lines (111)γ, (110)α'; (200)α', (220)γ; (211)α', (311)γ, of the analysed phases of austenite X5CrNi18-8 steel after cold rolling with 40% reduction, shows distinct texturing (Fig. 3a,b). Phase analysis of the deformed steel with deformation from 10 to 70 % didn't disclosed lines coming from the ε phase, what is compatible with a literature [28-30]. It shows that the martensite transformation proceed according to the sequences γ → α'.

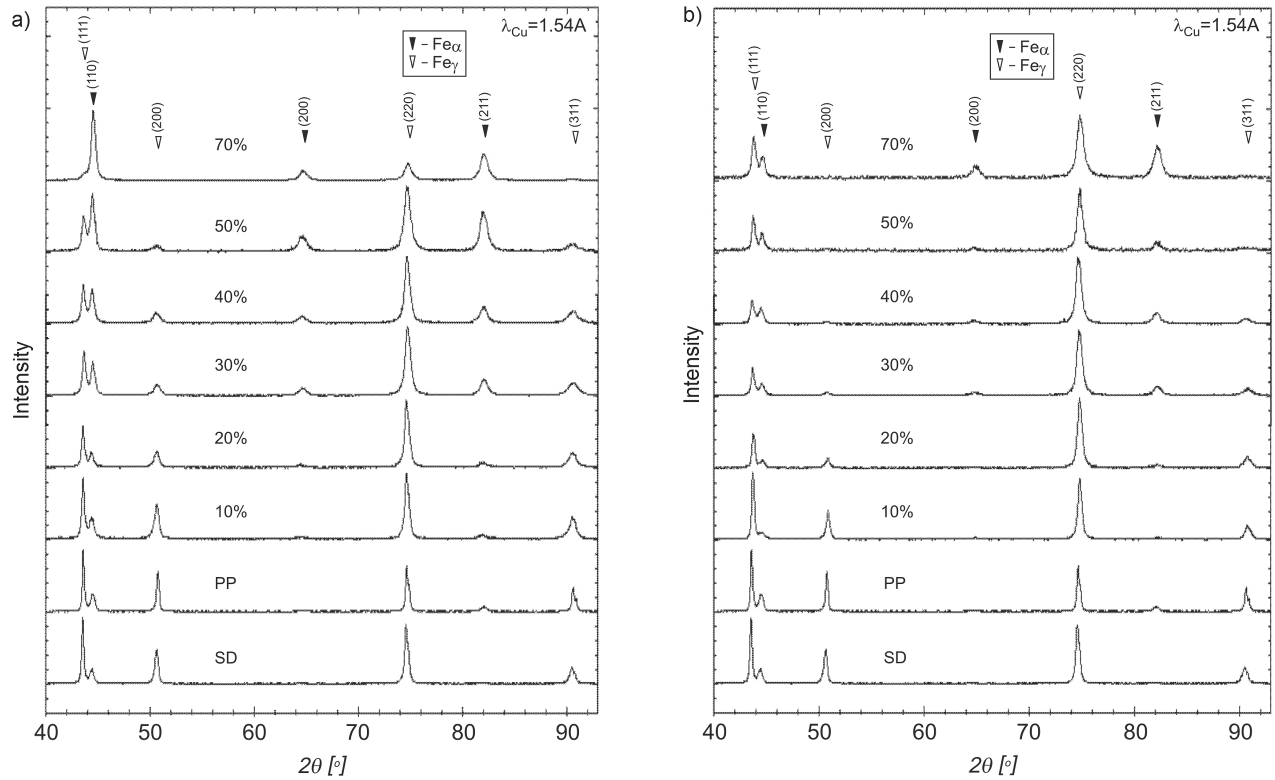

Fig. 3. X-ray diffraction patterns of X5CrNi18-8 steel at delivery state (SD), after supersaturation (PP) and after deformation within the range from 10-70%: a) surface, b) centre layer

The investigated X5CrNi18-8 austenitic steel at the delivery state showed weak texture (Fig. 4). However austenite of the examined steel is the metastable phase and a development of the deformation texture is very complex. During cold rolling the three processes proceeded simultaneously, namely; plastic deformation of the austenitic γ-phase, phase transformation γ→α' as well as deformation of the formed α'-martensite. These processes resulted in the appearance of two phases in the structure of the steel with a definite crystallographic relationship and the orientation changes of both phases with increasing deformation. Thus, the resultant deformation texture of the investigated steel is described by the austenite and martensite texture components (Figs. 4 and 5).

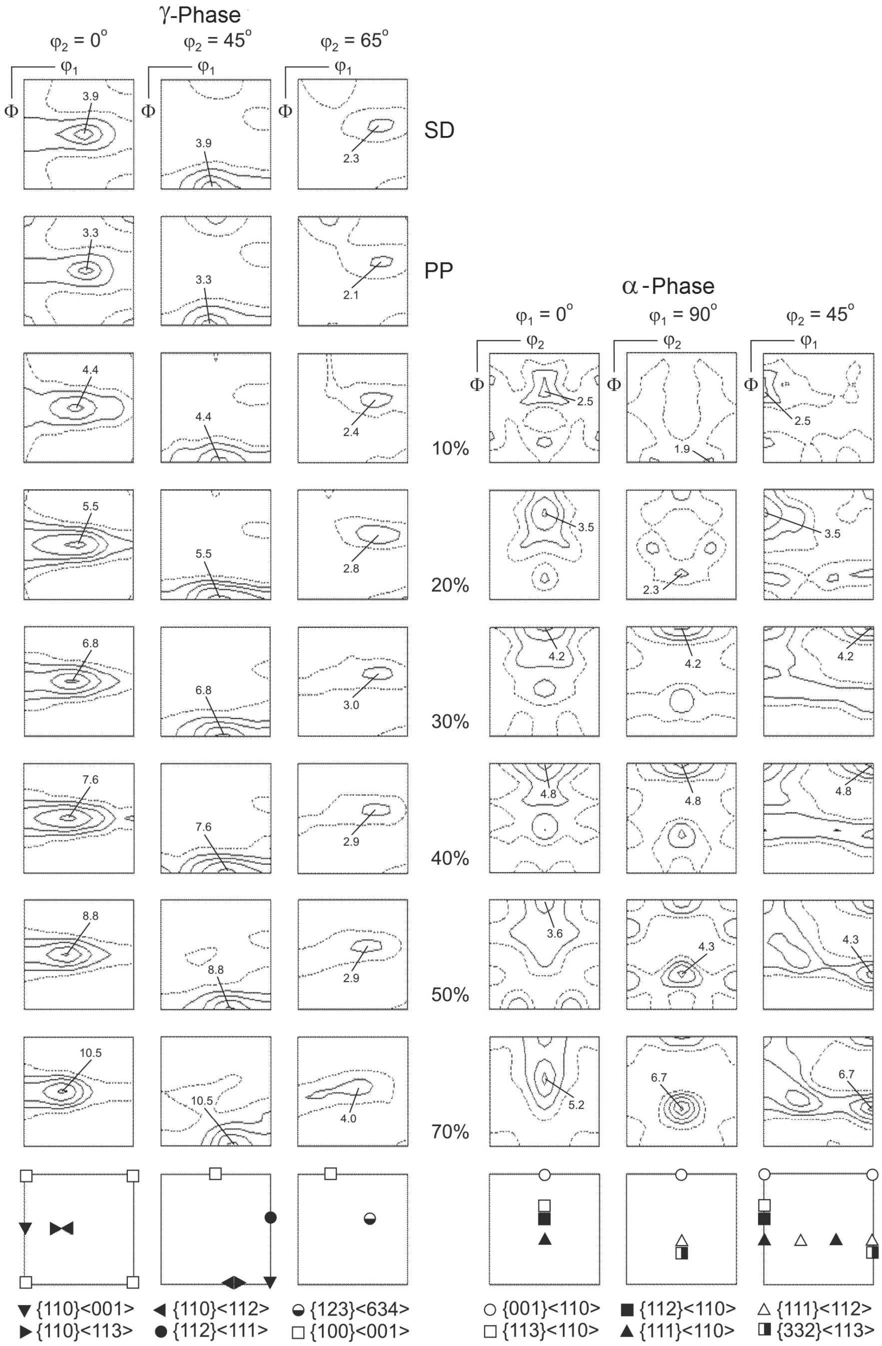

Fig. 4. Orientation distribution functions (ODFs) in sections φ_2=0°, 45°, 65° for austenite and φ_1=0°, 90°, φ_2=45° for martensite for the delivery state (SD) and after supersaturation (PP) as well as after selected rolling reductions

The austenite of investigated steel after supersaturation had a relatively weak texture. The main texture components were the same as for austenite of steel at delivery state, namely; α-fibre (<110>║ND), where the strongest orientation was close to {110}<112> (Fig. 4).

The deformed austenite within the range from 10 to 70% exhibited the fibrous texture, described by following orientation fibres; α =<110>║ND, τ =<110>║PD and β ={110}<112>, which extends from {123}<634> to {112}<111>. With increasing deformation degree the increase of the intensity of austenite texture was observed. The dominating components of the austenite texture occurred the orientations from the α =<110>║ND fibre, mainly {110}<113> orientation, which is close to the {110}<112> alloy-type component. The other component of the austenite texture is the {110}<001> Goss orientation from the τ =<110>║PD fibre (Figs. 4 and 5a). In general the deformation texture of austenite is a typical texture of low and medium stacking fault energy material.

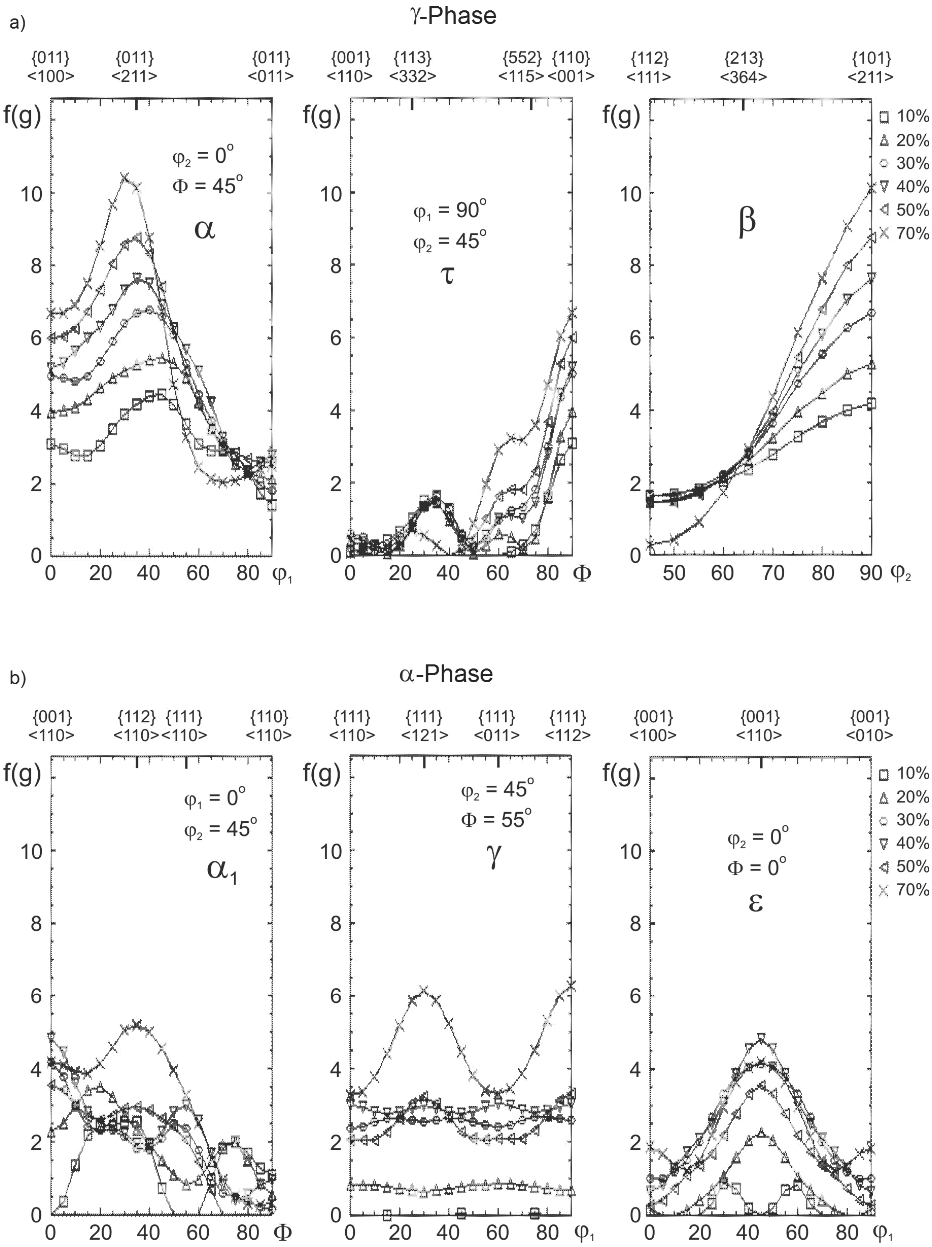

Fig. 5. Values of the orientation distribution functions f(g) along the orientation fibres: α =<110>║ND, τ =<110>║PD, β for the austenite (a) and α_1 =<110>║RD, γ ={111}║ND, ε =<001>║ND for the α' martensite (b) after selected rolling reductions

The martensite texture after cold rolling in the range from 10-70% is described of the orientation fibres: α_1 =<110>║RD, γ ={111}║ND and ε =<001>║ND. The dominating component of the martensite texture is the {111}<112> orientation with γ-fiber (Figs. 4 and 5b). It should be noted that in the case of martensite the texture formation is more complex since it comprises the texture components from the newly formed martensite at a given deformation stage as well as components from previously formed and already deformed martensite.

In order to determine the existing crystallographic orientation relations between the major components of austenite and martensite texture in X5CrNi18-8 steel, the transformations of the experimental orientation distribution functions (ODFs) of martensite according to Kurdjumov-Sachs (K-S) and Nishiyama-Wassermann (N-W) were conduced (Fig. 6). The comparison of the martensite ODFs after deformation with those after ($\alpha' \rightarrow \gamma$) transformation indicates that K-S and N-W orientation relationships describe very well the crystallographic orientation relations between both phases. The transformations were performed without taking into account the variant selection hence the lower maximum values of the resultant ODFs. The increase in the steel deformation degree causes the decrease in the intensity of the orientation {110}<112> austenite, which was related to the course of martensitic transformation ($\gamma \rightarrow \alpha'$) (Fig. 6).

On the basis of the realized magnetic investigations it was found that the amount of the martensite α' phase in the investigated steel structure increases within the increases of the deformation degree in the cold rolling process.

The volume percentage of strain induced α' martensite of cold rolled X5CrNi18-8 steel samples have been presented in Fig. 7.

At the delivery and supersaturation state the X5CrNi18-8 steel characterized the magnetic permeability about 1.05, what allow to classify the studied steel as a paramagnetic material. Perhaps, the presence of α' phase is results of pretreatment of material, which causes the eutectoid changes of γ phase. The α' martensite could also arise during the preparation of samples for testing.

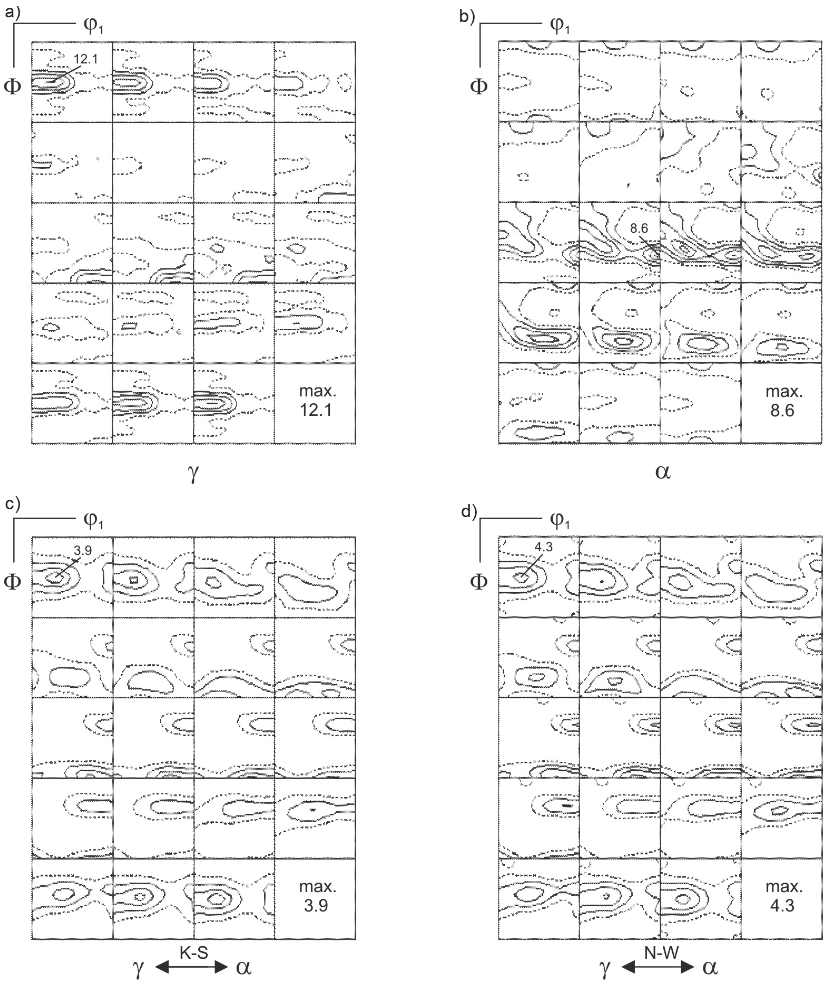

Fig. 6. Experimental ODFs for deformed austenite (a) and martensite (b) as well as simulated transformations ($\alpha' \rightarrow \gamma$) according to K-S (c) and N-W (d) orientation relationships in sections φ_2 = const

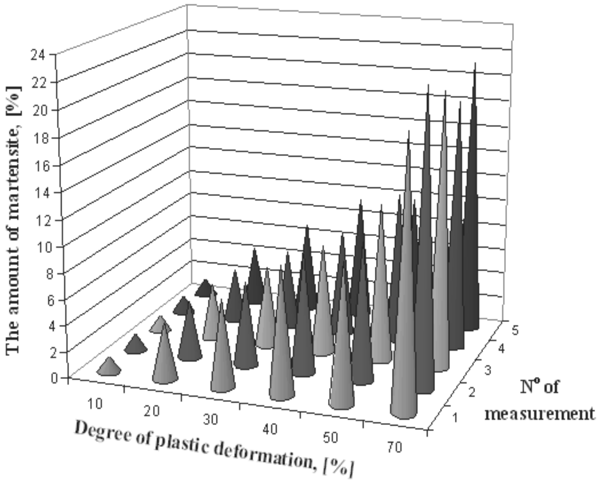

Fig. 7. Changes of martensitic α’ phases as a function of deformation degree in the investigated steel

After that plastic deformation within the range of 10 to 50% the amount of α’ phases in investigated steel structure average from about 1.30 to about 11.10% (Fig. 7), what proves of proceed a martensitic transformation γ→α’. The quantity of formed phases increasing with the degree of deformation and after maximum, 70% of reduction the volume of martensite α’ is equal to 21.0%.

4. Conclusions

Based on microstructure observations, diffraction analysis and magnetic investigations the following conclusions could be formulated:

1. The examined X5CrNi18-8 stainless steel grade is the metastable austenitic steel since plastic deformation induces the phase transformation (γ → α’) within the whole range of applied strains.
2. At the delivery and supersaturated state the steel has equiaxial grains γ with twins and non-metallic inclusions, but after deformation with reduction of about 30% - in a structure with elongated austenite grains with martensite α' phase plates
3. The domination components of the austenite deformation texture are the orientations from the α-fibre, mainly {110}<113> orientation, which is close to the {110}<112> alloy-type texture. However, the main component of the martensite texture is the {111}<112> orientation from γ-fibre.
4. Crystallographic orientation relations between the textures of the γ and α’-phase formed during cold rolling are best described by Kurdjumov-Sachs (K-S) and Nishiyama-Wassermann (N-W) relationships.
5. The amount of α’ phase in X5CrNi18-8 steel depends on the degree of plastic deformation. The increase of the deformation degree of steel in the range from 10 to 70% causes an increase of the volume of α’ phase from 1.30 to about 21%.

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