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The effect of ($\gamma \rightarrow \alpha'$) phase transformation on microstructure and properties of austenitic Cr-Ni steels

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ABSTRACT

Purpose: The paper presents the results of the investigations concerning the effect of ($\gamma \rightarrow \alpha'$) phase transformation on microstructure, magnetic and mechanical properties of austenitic stainless steel grade X5CrNi18-10.

Design/methodology/approach: Light microscope examinations, microhardness measurements and static tensile tests were performed in order to reveal microstructure and changes in mechanical properties. The magnetic properties: relative magnetic permeability μ (Maxwell-Wien bridge) and coercive force H_c (permalloy probe) were measured at room temperature. The analysis of the phase composition was carried out on the basis of X-ray investigations. In the qualitative X-ray analysis the comparative method was applied.

Findings: It was found that the plastic deformation in cold rolling within the range 10-70% of investigated austenitic Cr-Ni steel induced in its structure a phase transformation of paramagnetic austenite into ferromagnetic martensite.

Research limitations/implications: The results of the X-ray quantitative analysis allowed to determine the proportional part of martensite phases α' in the structure of investigated steel in the examined range of cold plastic deformation.

Practical implications: A wide range of practical applications of austenitic X5CrNi18-10 steel sheets is warranted by both their high corrosion resistance and high plastic properties, especially in the supersaturated state. Besides, a strong correlation was found between the magnetic properties and the ($\gamma \rightarrow \alpha'$) phase transformation.

Originality/value: In the course of deformation, the volume fraction of martensite increased at the expense of the amount of austenite resulting in the hardening of the material. In general, a gradual increase of the yield strength results from the strain hardening of the austenite structure and formation of strain-induced martensite.

Keywords: Austenitic Cr-Ni steel; Plastic deformation; Induced martensite; Structural and mechanical behaviour; Magnetic measurements

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PROPERTIES

1. Introduction

Metals and their alloys, mainly steels, belong to the most ecological and future constructional materials. The large demand for steel products is especially distinct in various industrial branches. The increase of raw steel production in the last 20 years in the world was about 60%, besides products from austenitic stainless steel constitute over 2% of the production [1-3]. The austenitic grades usually contain a maximum of about 0.1% carbon, a minimum of 16% chromium and sufficient amount of nickel and/or manganese to retain an austenitic structure in the whole temperature range (from the temperature of solidus to the room temperature). However, the structure of the 300 series of austenitic stainless steels changes during deformation in dependence on its chemical composition, stacking fault energy (SFE), thermodynamical stability of its constituent phases as well as deformation conditions, like temperature and strain. These steels usually exhibit excellent corrosion resistance, toughness, ductility, low thermal and electrical conductivity and good weldability. Equipments made of these materials are indicated for many applications in the chemical, petrochemical, machinery, automobile, nuclear and shipyard industries [4, 5].

Annealed austenitic stainless steels have low yield strength $R_{p0.2}$ about 200-250 MPa, which is similar to the yield strength of carbon steels. Their tensile strength lies within the range of 520 to 760 MPa. The increase of the yield strength of these steels can be attained by cold deformation. Particularly extremely high yield strength of 1200 MPa or even higher can be obtained in cold drawn wires [6, 7].

The plastic deformation of 18%Cr- and 8%Ni- containing austenitic stainless steels during cold working results in three main products: the appearance of ϵ - phase and α' -phase and increased dislocation densities within the base material [8].

Two types of martensite phases can be formed by cooling (thermally) or cold working (mechanically) in austenitic stainless steel. These are body-centred-cubic α' -martensite and hexagonal closed-packed ϵ -martensite. The formation of ϵ -martensite in austenitic stainless steels takes place at small strain and it transforms almost completely to α' -martensite when deformation increases. The α' phase is often called strain-induced martensite because it is produced by a diffusionless phase transformation [9-11].

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_d temperature (i.e. temperature at which at 30% deformation, 50% of its structure transforms into martensite). The amount of α' and ϵ martensite depends on the alloy composition, stacking fault energy (SFE), strain rate, stress state, deformation temperature, etc. The most probable way of the phase transformation in the 300 series austenitic stainless steels is the: $\gamma \rightarrow \epsilon$, $\gamma \rightarrow \alpha'$ or $\gamma \rightarrow \epsilon \rightarrow \alpha'$ [12-14].

Austenitic stainless steels are effectively paramagnetic in the annealed condition but due to cold working or welding some ferromagnetism may be noticed. Plastic deformation of these steels leads to a phase transformation from paramagnetic austenite into ferromagnetic martensite [15].

The objective of this investigation was to define the influence of cold rolling process on the structure, mechanical and magnetic properties. Special attention was drawn to the phase transformation of metastable austenite into martensite in investigated cold-rolled sheet of corrosion resistant steel type X5CrNi18-10 with different contents of nickel.

2. Experimental procedure

Investigations were conducted on three melts from metastable austenitic stainless steel type X5CrNi18-10 according to PN-EN 10088:2007 [16], as a result of industrial smelting from the UGINE&ALZ (Poland). The material for examinations was delivered in the form of sheet steel with dimension about 40×2×700 mm, subjected to cold rolling process within the range of deformations from 10 to 70%. This sheet was sampled for research of the magnetic and mechanical properties, for microhardness measurements, metallographic observations and the X-ray phase analysis. The chemical composition of the tested steel is presented in Table 1.

Based on the chemical composition of three grades of X5CrNi18-10 steel, the values of the following parameters were evaluated, namely: the temperature of strain induced martensitic transformation M_{d30} [17-18] and the stacking fault energy (SFE) of the austenitic γ -phase [19].

Metallographic examinations of samples were performed on longitudinal microsections, mechanically ground and chemically etched in the reagent Mi17Fe heated to a temperature of about 40°C, according to the standard PN-61/H-04503 [20]. The etching was carried out to disclose the steel structure in the delivery state, to detect the non-metallic inclusions and to define the influence of the degree of plastic deformation on its cold rolled structure with a draft from 10 to 70%. Additionally, in order to distinguish martensite from austenite and to confirm the occurrence of martensite α' in deformed steel, the metallographic specimens were etched in the Baraha's reagent [21]. The times of the etching of individual samples were differentiated. Samples deformed with a larger draft required longer time of etching. Metallographic observations of the investigated steel structure were made on LEICA MEF4A optical microscope, equipped with Leica Qwin image analyzer. The microstructure was studied at magnification of 200, 500, and 1000x. Additionally, the average grain size of specimens was determined using the method of counting the slits grains into the image area.

The mechanical properties were determined by means of a static tensile test on the universal testing machine ZWICK 100N5A. The specimens used for mechanical properties measurements were determined on the basis of standard PN-EN 10002-1+AC1:2004 [22] and cut from the steel sheet along to the rolling direction. Tensile tests were performed at room temperature.

Microhardness measurements of the investigated steel X5CrNi18-10 were made by Vickers' method on metallographic samples with a load of 50g, using the microhardness tester PMT-3 produced by Hauser. Investigations were made at room temperature in accordance with a PN-EN ISO 6507-1:2007 [23] standard.

Table 1.
Chemical composition of the investigated steels

Steel heat	Type of analysis	Chemical composition in mass %										
		C	Mn	Si	P	S	Cr	Ni	N	Mo	Cu	Fe
X5CrNi18-10	Ladle analysis	0.03	1.31	0.39	0.030	0.004	18.07	8.00	0.044	0.25	-	Bal
A		0.033	1.32	0.41	0.026	0.002	18.08	9.03	0.026	0.23	-	Bal
B		0.047	1.12	0.42	0.028	0.006	18.35	8.06	0.060	0.28	0.36	Bal
C	by PN-EN 10088:2007	Chemical composition in mass %, according to standard										
Standard steel grade		≤ 0.07	≤ 2.0	≤ 1.0	≤ 0.045	≤ 0.015	17-19	8-11	≤ 0.11	-	-	Bal
X5CrNi18-10												

In order to study the structural changes taking place during cold plastic deformation on X5CrNi18-10 steel, X-ray phase analysis has been used applying the filter radiation of an anode λCoK_α .

X-ray phase analysis was run by means of an X'PERT PANalytical diffractometer at accelerating voltage of 45 kV and current intensity of 40 mA. The data of diffraction lines were recorded by "step-scanning" method in 2θ range from 40° to 115° and the 0.05° step and time of measurements amounting to 10 seconds. The obtained diffraction patterns were analyzed applying the program PCPDFWIN.

X-ray diffraction was also used to determine the relative amounts of different phases formed after cold rolling.

The amount of martensite α' phase was quantitatively measured by the Averbach Cohen method [24]. In the calculation, the respective surfaces of the diffraction lines of the phases γ and α' was measured by means of a planimeter.

The relative magnetic permeability μ were measured by Maxwell-Wien bridge at frequency about 1030 Hz and magnetic field value of 0.5 A/m; open coil, demagnetization factor was numerically and experimentally determined. The coercive force H_c was measured by coercimeter with permalloy probe [25]. The specimens used for magnetic measurements were cut into size of 12×100 mm in the rolling direction of different reduction in thickness. Both, the relative magnetic permeability μ and the coercive force H_c were carried out at room temperature.

3. Results and discussion

The metallographic investigations permit to define the metallographic symptom of draft, shape and size of austenite grains. On the basis of metallographic observations it was found that three steel grades A, B and C in their delivery state possess a homogeneous austenite structure with many annealed twins and some non-metallic inclusions, which were identified as carbonitrides, oxides, globular silicates, sulfides, with medium standard indices.

The quality assessment of non-metallic inclusions was carried out in accordance with a standard PN-EN 10247:2007 [26]. Additionally, in steel C the agglomerations of copper precipitations were affirmed. The occurrence of copper precipitations proves about incomplete introduction this element to the γ solution. Therefore, this element does not hamper on forming the martensitic α' phase in steel X5CrNi18-10 deformed with small drafts degree.

The average diameter of the equiaxial austenite grains in the structure is about: 21 μm for steel A, 22 μm for steel B and 20 μm for steel C. Measurements of grain sizes were made according to the standard PN-EN ISO 643:2005 [27]. It was found that with increased deformation the number of grains with etched internal structure increased.

In the investigated steels A, B and C after cold deformation, a structure of elongated austenite grains with slip bands, deformation twins and sparse non-metallic inclusions were found. Metallographic observations of the structure of all grades of X5CrNi18-10 steel type deformed at degree from about 40% to about 70% show that in elongated γ grains there are areas of parallel plates characteristic for martensite α' (Fig. 1). Additionally, the occurrence of martensite α' in deformed steel structure confirms the etching in Beraha's reagent. The dark phase in the structure is strain-induced martensite and the light area is the austenite matrix (Fig. 2). The volumetric part of the dark α' martensite phase in investigated A, B, C steel structure deformed (with a draft of 40% is on the same level). The results of the X-ray quantitative phase analyses confirm the occurrence of martensite α' .

Elongated austenite grains are characterized by the deformed state of steel, whereas the austenite grains undergo elongation in the rolling direction. During the plastic deformation in cold working of the Fe-Cr-Ni steel with an increasing degree of deformation the α' phase is formed, which causes an essential size reduction of its structure and its strain hardening. The occurrence of martensite α' in deformed steel structure is confirmed by the results of mechanical investigations.

On the basis of the mechanical properties results it was found that in the delivery state steel A characterized by the highest yield point $R_{p0.2}$ displays about 330 MPa, while steel C shows $R_{p0.2}$ about 302 MPa and steel B only 300 MPa (Fig. 3). Similarly, in the case of tensile strength R_m (Fig. 4), the highest strength has steel A - 647 MPa, steel C - 630 MPa and the lowest tensile strength has steel B - 624 MPa. The elongation A (Fig. 5) is almost at the same level for these three steels and amounts to about 53 %. Steel A, B and C have a considerable different reduction of area Z (Fig. 6). Steel C is distinguished by the highest value of Z about 66 %, followed by steel B with Z about 54 % and steel A with the lowest reduction of area amounting to about 48%. Fig. 7 shows that in the delivery state steel B shows the largest micro-hardness 183 $\text{HV}_{0.05}$ and steel C the lowest, about 155 $\text{HV}_{0.05}$. While steel A displays an average value of the micro-hardness amounting to about 162 $\text{HV}_{0.05}$.

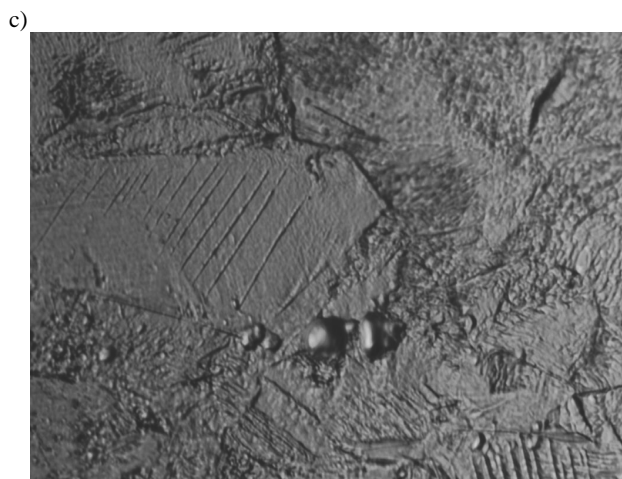
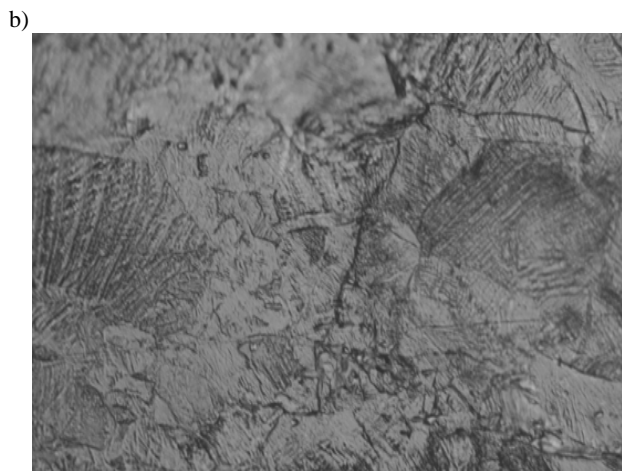


Fig. 1. Structure of the investigated X5CrNi18-10 steel type after deformation with a draft of 40%; a-c melts of these steel; Etching - Mi17Fe; Mag. 500x



Fig. 2. Structure of the investigated steel type X5CrNi18-10 after deformation with a draft of 40%; a-c melts of these steel; Etching - Beraha's reagent, Mag. 1000x

With the increasing deformation within the range of 10-50%, the yield point of steel A increases from about 586 MPa to about 969 MPa, the tensile strength from about 784 MPa to about 1257 MPa, the micro-hardness from about 227 HV_{0.05} to 357 HV_{0.05}, while the elongation decreases from about 32 % to about 1 % and the reduction of area from about 45 % to 15 %. In these same conditions steel B is characterized by similar mechanical and plastic indices. Its $R_{p0.2}$ increases from about 542 MPa to about 1059 MPa, the R_m from about 783 MPa to about 1228 MPa, the micro-hardness from about 279 HV_{0.05} to 445 HV_{0.05}, while the A decreases from about 35 % to about 2 % and the Z from about 50 % to about 13 %. Deformation with a draft from 10 to 50 % of steel C causes increasing its yield point from 535 MPa to 1198 MPa, the tensile strength from 763 MPa to 1295 MPa, the micro-hardness from 234 HV_{0.05} to 351 HV_{0.05}, while the decreasing of elongation from about 37 % to about 2 % and the reduction of area from 58 % to 29 %.

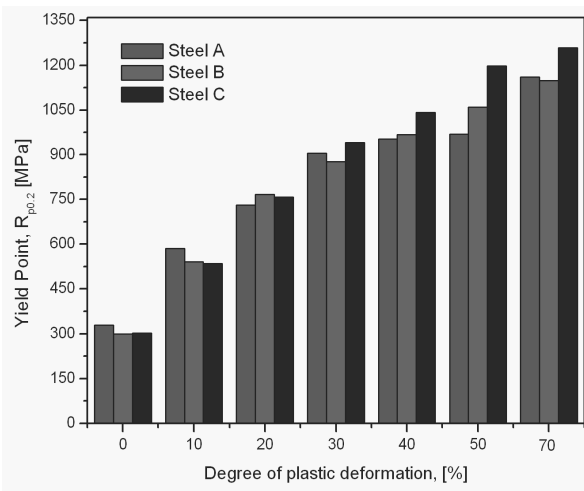


Fig. 3. Changes of the yield point for cold rolled steels A, B and C, depending on degree of deformation

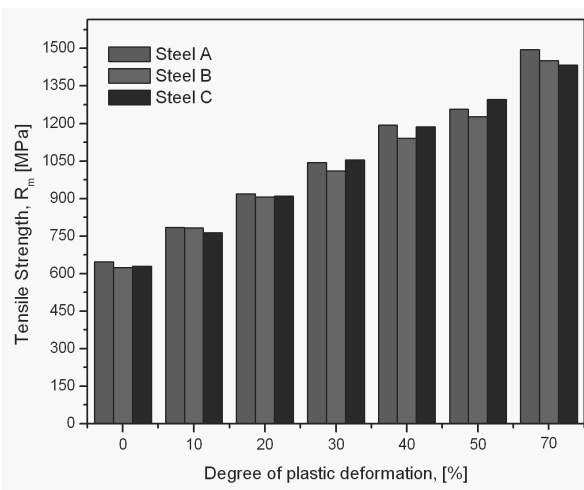


Fig. 4. Changes of the tensile strength for cold rolled steels A, B and C, depending on a degree of plastic deformation

At the 70 % of deformation, steel C demonstrates the highest values of $R_{p0.2}$, about 1259 MPa. This is possible related to the higher nitrogen content present in this steel [28]. Steel A and B show a little lower value of $R_{p0.2}$, 1161 MPa and 1148 MPa, respectively (Fig. 3).

Fig. 4 shows the values of tensile strength (R_m) of the investigated steel samples, deformed with a draft of 70 %. The highest values of tensile strength, about 1496 MPa demonstrates steel A. Steels B and C exhibit a little lower value of R_m , amounts about 1452 MPa (steel B) and about 1433 MPa (steel C).

The elongation is on the same level for deformed steels B and C with the 70% draft, amount about 1 %. Steel A shows a little lower elongation, about 0.68 % (Fig. 5).

It was affirmed that after maximum deformation the C steel is characterized by values of the reduction of area Z by about 23 %, while steel A shows about 11 % and steel B only 10 % (Fig. 6).

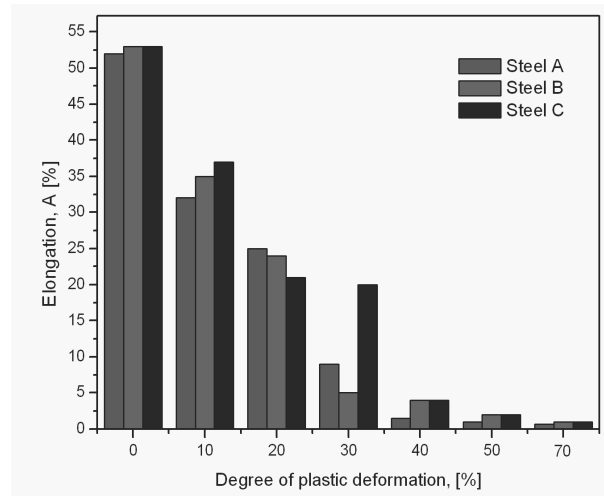


Fig. 5. Changes of the elongation for cold rolled steels A, B and C, depending on a degree of deformation

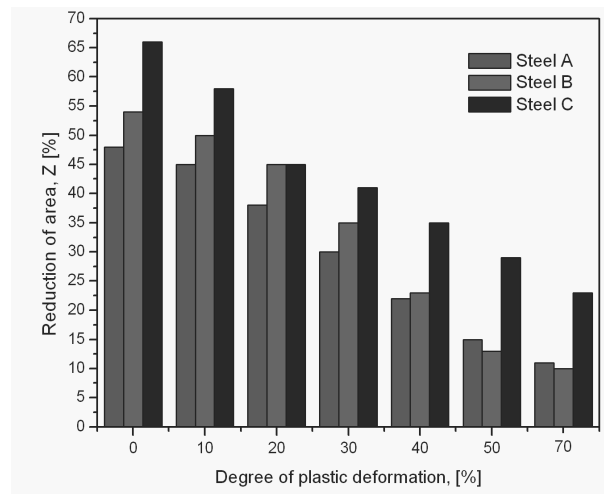


Fig. 6. Changes of the reduction of area in the investigated cold rolled steels A, B and C, depending on a degree of deformation

In the investigated steels A, B and C after cold deformation with draft of about 70 % the increase of hardness value was found (Fig. 7). Steel B demonstrates the highest values of micro-hardness, about 554 HV_{0.05}, while steels A and C show similar values of micro-hardness, about 400 HV_{0.05} and about 415 HV_{0.05}, respectively.

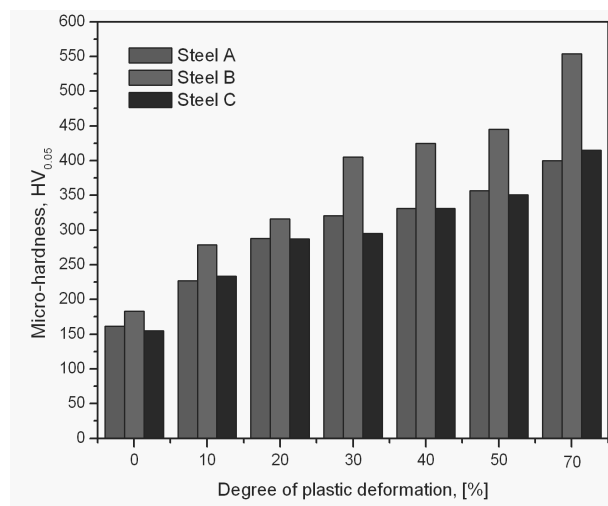


Fig. 7. Changes of the micro-hardness for cold rolled steels A, B and C, depending on degree of plastic deformation

Realized investigations permit to affirm that in all investigated types of steel at increase degree of a draft during cold rolling, the mechanical properties (R_m , $R_{p0.2}$, $HV_{0.05}$) increase, while the plasticity (A , Z) decreases.

The susceptibility to martensite-induced transformation of austenitic stainless steel is generally related to the stacking fault energy (SFE), which is also a composition-sensitive parameter. Using the equation proposed by Shramm and Reed [19] the value of SFE_{γ} for the investigated steel A is about 15.8 mJ/m², steel B is about 22 mJ/m² and steel C is at the level 15.5 mJ/m². Steel B is characterized by the highest values of the SFE_{γ} , while steel A and C show a similar value of stacking fault energy of austenitic γ -phase. Nickel tends to raise the stacking fault energy, thereby influencing dislocation cross slip, while chromium, manganese and silicon tend to decrease the stacking fault energy of the austenite. Steel B contains much more nickel than steel A and C, what explains the highest values of the SFE_{γ} . On the basis of the values of SFE_{γ} it was affirmed that in steel A and C (with much lower SFE_{γ}) the kinetics of the $\gamma \rightarrow \alpha'$ transformation proceed faster, what is compatible with literature [29-31].

Steel A have the highest value of M_{d30} , about 36.3°C. Steel B demonstrates a little lower values of M_{d30} , amount about 22.7°C, while steel C shows the lowest value of M_{d30} about 16.8°C. Steels with a higher M_{d30} values are more susceptible to the formation of strain-induced martensite during deformation at room temperature.

The volume percentage of strain induced α' martensite of cold rolled samples of three melts of X5CrNi18-10 steel is determined by X-ray quantitative phase analysis and gathered in Table 2 and in Fig. 8.

In the delivered condition of steels, the martensite α' phase does not occur. With the increasing deformation within the range

of 10-50 % the amount of martensitic α' phases in steel A increases from about 9 % to about 40 %, in steel B from about 11% to about 37 %, and in steel C from about 10 % to about 34% (Fig. 8). It was observed that the amount of martensite increases with the increase in deformation. At deformations of greater than ten percent, the amount of martensite increases rapidly in all investigated steel melts. The largest amount of martensite (up to 50%) is observed in steel A deformed to 70 %, while the amount of martensite formed in steels B and C show similar values, about 42 % and 41%, respectively (Table 2).

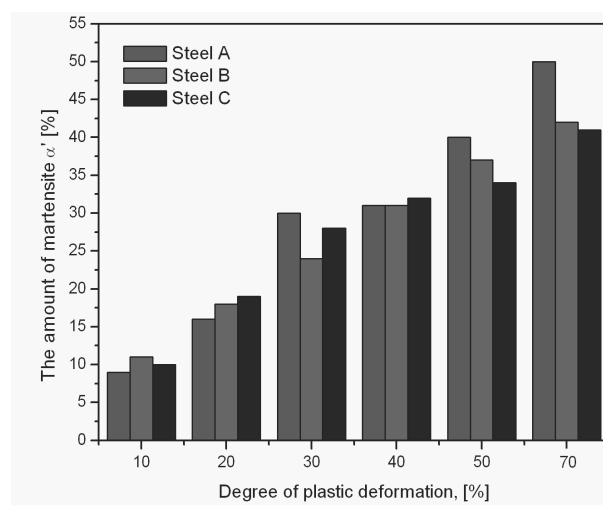


Fig. 8. Dependence of the volume fraction of α' - phase on degree of plastic deformation of investigated steel

Table 2. Volume percentage of martensite in various deformed specimens of X5CrNi18-10 steel

Steel heat X5CrNi18-10	Cold work level [%]	Volume of α' martensite, %
A	0	-
	10	9
	20	16
	30	29
	40	31
	50	40
	70	50
B	0	-
	10	11
	20	18
	30	24
	40	31
	50	37
	70	42
C	0	-
	10	10
	20	19
	30	28
	40	32
	50	34
	70	41

The X-ray phase analysis, the microstructure observations and the magnetic investigations revealed that the initial structure of X5CrNi18-10 steel (that is in as delivered condition), is purely austenitic. Therefore, in the delivered state of the investigated materials the diffractive phase analysis disclosed peaks coming only from the austenite with the strongest one coming from plane (111) γ for steel C and (220) γ both, A and B steel. The picks from the α' martensite started to appear on diffraction patterns from the beginning of deformation process. X-ray investigations of three grades deformed with draft from 10 to 50 % confirmed the occurrence of α' martensite in its structure. α' phases were detected on diffraction patterns on the basis of the diffraction lines according to identifications from (110) α' and (211) α' reflection planes, which occurred with matrix lines for γ phase from (111) γ , (200) γ , (220) γ and (311) γ reflection planes. It was also found that with the increase of deformation the share of the reflection lines (110) α' in the dual line with the reflection lines (111) γ increases, too. It proves a distinct increase of α' phase in the structure of the investigated steel. The results of the X-ray phase analysis are presented in Fig. 9.

After maximum degree of deformation (about 70%) in all investigated steels, the occurred peaks coming from the α' martensite (110) α' , (200) α' , (211) α' with peaks (111) γ and (220) γ coming from the austenite, but about different intensity.

Diffraction lines (111) γ , (220) γ and (110) α' , (200) α' , (211) α' of the analysed phases of the cold rolled X5CrNi18-10 steel show distinct texturing.

Phase analysis of deformed steel with draft from 10 to 70 % did not disclose lines coming from the ϵ phase, what is compatible with literature [32-33]. It shows that the martensite transformation proceeds according to the sequence $\gamma \rightarrow \alpha'$.

The investigations of magnetic properties allowed to determine the changes of the relative magnetic permeability (μ) and coercive force (H_c) of investigated steel. The results of the magnetic properties are presented in Figs. 10 and 11. On the basis of the realized investigations of magnetic properties it was found that in all investigated types of X5CrNi18-10 steel with the deformation increasing, the relative magnetic permeability μ increases (Fig. 10), while the coercive force H_c decreases (Fig. 11).

In delivery state steel C characterized by the lowest value of relative magnetic permeability μ displays about 1.05, while steel B shows μ about 1.18 and steel C till 1.41. The magnetic permeability levels 1, what indicates on the paramagnetic character of investigated steel C melt in delivery condition. In case of the A and B steel melts, which relative magnetic permeability μ in their delivery state are higher than the unity it was found at the presence of the ferromagnetic martensite α' phase. The occurrences of α' phase in A and B steel structure is a consequence of pre-treatment of material (cutting, roughing, machining), which causes the eutectoid changes of austenite.

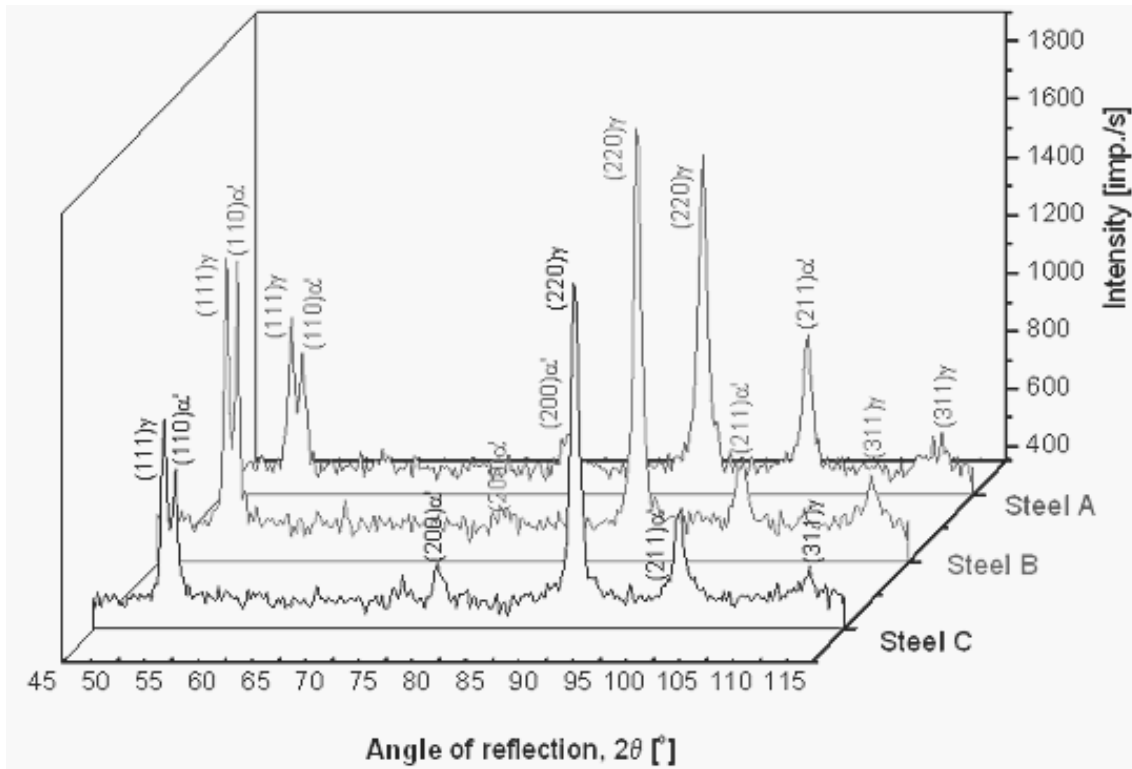


Fig. 9. X-ray diffraction patterns of steel grades A, B and C with a draft of 50%

After the plastic deformation within the range of 10-50% the relative magnetic permeability of steel A increases from about 1.42 to about 10.35, in steel B from about 1.28 to about 5.28 and for steel C from about 1.36 to about 7.60 (Fig. 10). The increase of the magnetic permeability during deformation testified about formed the α' phase and induces in its structure a martensitic transformation $\gamma \rightarrow \alpha'$. The volume percent of formed martensite α' phase increases with the degree of deformation, while the volume percent of γ austenite matrix decreases.

After the maximum degree of deformation (about 70%), steel A show the highest values of magnetic permeability, about 19.64. While steels B and C characterized a similar value of μ , namely; steel B, about 13.25 and steel C, about 13.21 (Fig. 10).

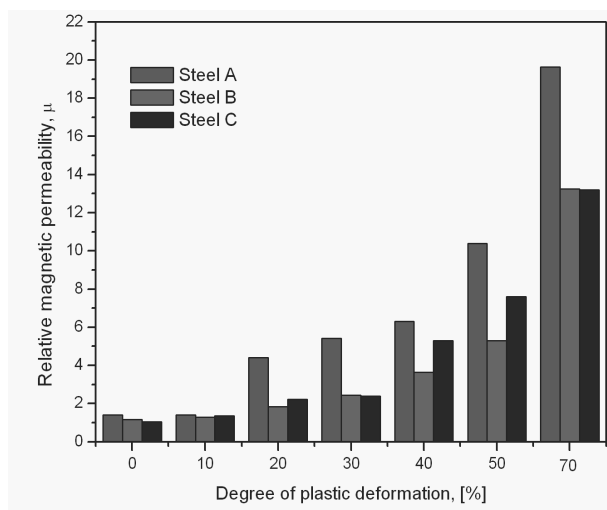


Fig. 10. Changes of the relative magnetic permeability in the investigated cold rolled steels A, B and C, depending on degree of deformation

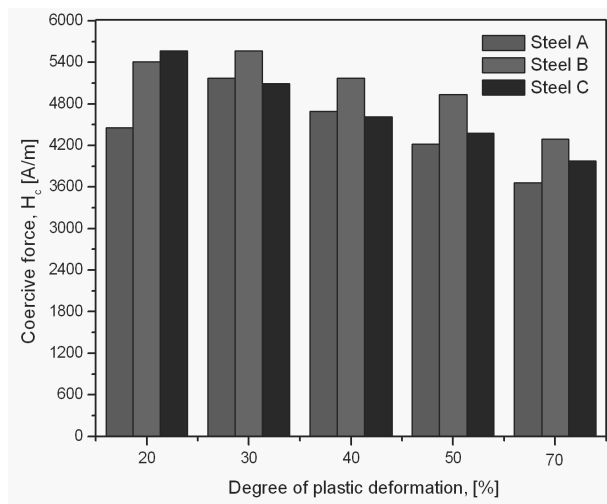


Fig. 11. Changes of the coercive force in the investigated cold rolled steels A, B and C, depending on degree of deformation

The change in magnetic response is due to atomic lattice straining and formation of martensite. In general, the higher the nickel to chromium ratio, Ni/Cr [34] the more stable is the austenitic structure and the less magnetic response will be induced by cold working. Steel A has the lowest value of Ni/Cr ratio, about 0.57%. The Ni/Cr ratio for steel B and steel C is almost in the same level and amounts to about 0.61% and about 0.62%, respectively. The lower value of Ni/Cr for both steels B and C is evidence of their greater metastability with respect to the martensite transformation.

It was found that intensity of coercive force H_c for X5CrNi18-10 steel deformed with draft from 20 to 50% decreases from 5200 A/m to about 4200 A/m (steel A), from 5400 A/m to about 4900 A/m (steel B) and from about 5600 A/m to 4400 A/m (steel C), which is presented in Fig. 11.

Steel B distinguished by the highest coercive force (H_c) of all investigated steels, and after maximum cold reduction it is characterized by about 4300 A/m. Steels A and C show similar values of H_c , about 3700 A/m and about 4000 A/m, respectively.

Fig. 11 shows the coercive force measurement result in the specimens only after 20-70% reduction, while in fact, the steels start deformed with a draft of 10%. It happens because the coercive force (H_c) strongly correlates with steel microstructure. These changes induce also the point defects, dislocations and precipitations with magnetic properties (i.e. carbides). Furthermore, the coercive force depends also on the shape, distribution and volume percent of martensite phase.

The coercive force tends to decrease with the amount of deformation and, consequently, with an increase in martensite volume fraction. The increase of the quantity of α' martensite, or the decrease of the quantity of paramagnetic γ austenite, is accompanied by a decrease of the coercive field. It could be due to the decrease of the α'/γ interfaces and also to mechanical stress. The increase of deformation degree causes an increase of magnetic permeability as soon as the decrease of coercive force.

4. Conclusions

The analysis of the obtained results of investigated stainless steel type X5CrNi18-8 in the delivery state and after cold rolling allowed to formulate the following statements:

1. The examined X5CrNi18-10 stainless steel grade is the metastable austenitic steel since plastic deformation induces the martensitic transformation ($\gamma \rightarrow \alpha'$) within the whole range of applied strains.
2. In the delivery condition, the steel has a single-phase austenite structure with grain sizes of about: 21 μm for steel A; 22 μm for steel B; 20 μm for steel C, twins and non-metallic inclusions.
3. The amount of α' phase in X5CrNi18-10 steel depends on the draft degree and after the maximum deformation (about 70%), α' content increasing from 9 % to about 50 % (Steel A), from about 11 % to about 42 % (Steel B) and from about 10 % to about 41 % (Steel C).

4. When deformed, both phases (austenite and martensite) became textured, what was observed on diffraction lines (111) γ , (220) γ and (110) α' , (200) α' , (211) α' .
5. After plastic deformation of steel X5CrNi18-10 in cold rolling a good correlation was found between changes of the structure and the effects of investigations of mechanical properties, connected with the appearance of martensitic α' phases.
6. With the increasing deformation within the range of 10-70 % the mechanical properties (R_m , $R_{p0.2}$, $HV_{0.05}$) of steels A, B and C increase, while the plasticity (A , Z) decreases.
7. Increase of deformation degree within the range 20-70% essentially influence on changes its magnetic properties causes increase magnetic permeability μ from 4.42 to 19.64 (Steel A); from 1.85 to 13.25 (Steel B); from 2.23 to 13.21 (Steel C) and decrease coercive force H_c from 5200 A/m to 3700 A/m (Steel A); from 5400 A/m to 4300 A/m (Steel B) and from 5600 A/m to 4000 A/m (steel C).
8. Changes of the magnetic properties of metastable austenitic stainless steel are closely connected with the occurrence of ferromagnetic martensite α' phase in structure during cold rolling.

References

- [1] H. Abreu, S. Carvalho, P. Neto, R. Santos, Deformation induced martensite in an AISI 301LN stainless steels, *Materials Research* 10 (2007) 359-366.
- [2] U. Krupp, C. West, H.-J. Christ, Deformation-induced martensite formation during cyclic deformation of metastable austenitic steel: Influence of temperature and carbon content, *Materials Science and Engineering A* 481-482 (2008) 713-717.
- [3] B. Surowska, A. Weroński, Cold work effect of pitting corrosion of some biomaterials, *Proceedings of the 14th International Scientific Conference "Advanced Materials and Technologies"*, Gliwice – Zakopane, 1995, 425-428.
- [4] S. Tavares, D. Gunderov, V. Stolyarov, Phase transformation induced by severe plastic deformation in the AISI 304L stainless steel, *Materials Science and Engineering A* 358 (2003) 32-36.
- [5] V. Toshkov, R. Russev, T. Madjarov, On low temperature ion nitriding of austenitic stainless steel AISI 316, *Journal of Achievements in Materials and Manufacturing Engineering* 25/1 (2007) 71-74.
- [6] D. Jandova, J. Rehor, Z. Novy, Deformation processes in austenitic stainless steel, *Proceedings of the 9th International Scientific Conference "Achievements Mechanical and Materials Engineering" AMME'2000*, Gliwice – Gdańsk – Sopot, 2000, 254-258.
- [7] F. Ciura, A. Kruk, G. Michta, W. Osuch, Influence of temperature and degree deformation on structure and mechanical properties during the phase transformation in Fe-30%Ni alloy, *Proceedings of the 10th International Scientific Conference "Achievements Mechanical and Materials Engineering" AMME'2001*, Gliwice – Zakopane, 2001, 69-74.
- [8] A. Kurc, Z. Stokłosa, Some mechanical and magnetic properties of cold rolled X5CrNi18-8 stainless steel, *Archives of Materials Science and Engineering* 34/2 (2008) 89-94.
- [9] A. Baron, Influence of electrolytic polishing on electrochemical behaviour of austenitic steel, *Journal of Achievements in Materials and Manufacturing Engineering* 18 (2006) 55-58.
- [10] K. Pałka, A. Weroński, K. Zalewski, Mechanical properties and corrosion resistance of burnished X5CrNi18-9 stainless steel, *Journal of Achievements in Materials and Manufacturing Engineering* 16 (2006) 57-62.
- [11] M. Ahlers, The Martensitic Transformation, *Revista Materia* 9 (2004) 169-183.
- [12] W. Ozigowicz, E. Kalinowska-Ozigowicz, A. Kurc, Influence of plastic deformation on structure and mechanical properties of stainless steel type X5CrNi18-10, *Archives of Materials Science and Engineering* 32/1 (2008) 37-40.
- [13] W. Zieliński, A. Abduluyahed, K. Kurzydłowski, TEM investigations of the surface influence on mechanical properties of austenitic stainless steel, *Materials Engineering* 3 (1998) 331-334.
- [14] H. Fujita, S. Ueda, Stacking faults F.C.C. (γ) \rightarrow H.C.P. (ϵ) transformation in 18/8-type stainless steel, *Acta Metallurgica* 20 (1972) 759-767.
- [15] E. Perdahcioglu, H. Geijselaers, Influence of plastic strain on deformation-induced martensitic transformations, *Scripta Materialia* 58 (2008) 947-950.
- [16] Standard PN-EN 10088:2007, Steels resistance on corrosion (in Polish).
- [17] P. Lacombe, B. Baroux, G. Beranger, *Stainless Steels*, Published by Les Editions De Physique Les Ulis, 1993.
- [18] T. Angel, Formation of martensite in austenitic stainless steels: Effects of deformation, temperature and composition, *Journal of The Iron and Steel Institute*, 1954, 165-174.
- [19] R.E. Shramm, R.P. Reed, Stracking fault energies of austenitic stainless steels, *Metallurgical and Materials Transactions A* 6/7 (1975) 1345-1351.
- [20] Standard PN-61/H-04503, Reagents for microstructure tests of iron alloys (in Polish).
- [21] G.F. Vander Voort, *Metallography: Principles and Practice*, ASM International, Materials Park, Ohio, 1999.
- [22] Standard PN-EN 10002-1+AC1:2004, Metals. Tensile tests, Method of investigation in the ambient temperature (in Polish).
- [23] Standard PN-EN ISO 6507-1:2007, Metals. Hardness measurements made by Vickers's method (in Polish).
- [24] B. Cullity, *Elements of X-ray Diffraction*, Addison-Wesley Series in Metallurgy and Materials, 1967 (in Polish).
- [25] R. Nowosielski, R. Babilas, P. Ochinn, Z. Stokłosa, Thermal and magnetic properties of selected Fe-based metallic glasses, *Archives of Materials Science and Engineering* 30/1 (2008) 13-16.
- [26] Standard PN-EN 10247:2007, Micrographic examination of the non-metallic inclusion content of steels using standard pictures (in Polish).
- [27] Standard PN-EN ISO 643:2005, Steel. Standard Test Method for Determining Average Grain Size.

- [28] D. Peckner, I.M. Bernstein, Handbook of Stainless Steels, MacGraw-Hill, 1977, 20-39.
- [29] S. Sagar, B. Kumar, G. Dobmann, D. Bhattachatya, Magnetic characterization of cold rolled and aged AISI 304 stainless steel, NDT & E International 38 (2005) 674-681.
- [30] S.S.M. Tavares, J.M. Neto, M.R. da Silva, H.F.G. de Abreu, Magnetic properties and α' martensite quantification in an AISI 301LN stainless steel deformed by cold rolling, Materials Characterization 59 (2008) 901-904.
- [31] K. Mumatz, S. Takahashi, J. Echigoya, Magnetic measurements of martensitic transformation in austenitic stainless steel after room temperature rolling, Journal of Materials Science 39 (2004) 85-97.
- [32] J. Barcik, The kinetics of sigma-phase precipitation in AISI-310 and AISI-316 steels, Metallurgical and Materials Transactions 14 A (1983) 635-641.
- [33] M. Blicharski, S. Gorczyca, Structural inhomogeneity of deformed austenitic stainless steel, Metal Science 12 (1978) 303-312.
- [34] M. Blicharski, Material engineering - Steel, WNT, Warsaw, 2004.