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The effect of the cold rolling on the structure and mechanical properties in austenitic stainless steels type 18-8

W. Ozgowicz, A. Kurc*
Division of Constructional and Special Materials Engineering,
Institute of Engineering Materials and Biomaterials,
Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding author: E-mail address: agnieszka.kurc@polsl.pl

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ABSTRACT

Purpose: In this paper the effect of the cold rolling on the transformation of austenitic stainless steel type X5CrNi18-10 to martensite was studied as a function of rolling reduction.

Design/methodology/approach: The investigations included observations of the structure on a light microscope, researches of mechanical properties in a static tensile test and microhardness measurements made by Vickers's method. The analysis of the phase composition was carried out on the basis of X-ray researches. In the qualitative X-ray analysis the comparative method was applied, whereas X-ray quantitative phase analysis was carried out by the Averbach Cohen method.

Findings: Plastic deformation in a cold rolling of investigated austenitic stainless steel induced in its structure martensitic transformation $\gamma \rightarrow \alpha'$.

Research limitations/implications: The X-ray phase analysis in particular permitted to disclose and identify the main phases on the structure of the investigated steel after its deformation within the range 10%÷70%. Moreover, 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: The analysis of the obtained results permits to state that the degree of deformation has a significant influence on the structure and mechanical properties of the investigated steels. Besides, a good correlation was found between changes of the structure and the effects of investigations of the mechanical properties.

Originality/value: Revealing the analytic dependence of the yield point of the Cr-Ni steel on the degree of deformation in cold working has essential practical importance for the technology of sheetmetal forming of the analyzed steel.

Keywords: Metallic alloys; Austenitic stainless chromium-nickel steel; Plastic deformation; Inducted martensite; Structural and mechanical behaviour; Cold rolling

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MATERIALS

1. Introduction

Austenitic stainless steels are the most popular type of stainless steel because of their excellent formability, corrosion resistance in various aggressive environments and weldability. The presence of chromium (16-28%wt.) and nickel (3.5-32%wt.) near to the small contents of the carbon (usually below 0.1%wt.) assures a stable austenitic structure in the whole range of the temperature (from the temperature of solidus to the room temperature). Moreover can contain such elements as molybdenum (2-6%wt.), titanium and niobium. After supersaturation in water from 1100°C steel a single-phase austenitic structure with high corrosion resistance and without carbides extractions was obtained. In the supersaturated state austenitic stainless steels are characterized by high plasticity and relatively low strength (R_m about 550 MPa; $R_{p0.2}$ about 200-250 MPa). They are widely used in chemical, petrochemical, machinery, automobile, nuclear and shipyard industries [1-5].

One of the possible mechanisms of the plastic deformation in steels type 18-8 is strain-induced martensitic transformation leading to the transition of paramagnetic austenite into ferromagnetic martensite. Austenite has a FCC crystal structure, while martensite at low carbon concentration crystallizes in BCC structure. Martensite is harder and stronger than austenite. Some alloying components are inhibitors of martensitic transformation in austenitic stainless steels. It is well known that N, Mn, and Cu are such inhibitors, because they broaden the area of the occurrence of the γ phase. However in such elements as: Mo, W, Si, Ti, Nb, V are putt into steel in order to increase the strength properties and corrosion resistance contribute to restricting the range of the occurrence γ (increasing susceptibility to precipitation of the σ, χ phases) [6-10].

The mechanical behaviour and evolution of phases in metastable materials, particularly Fe-Cr-Ni steels, have been the subject of experimental and theoretical studies for a long time. The reason is that these materials are quite often used in modern engineering. However, their mechanical properties are not fully investigated, because the character and the intensity of phase transformations depend on many factors, such as strain rate and strain level, stress state and regime of mechanical loading, and temperature [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 (M_d is the temperature at which 50% α' martensite has formed for a true strain of 30%) to produce cubic body centered α' and hexagonal closed packed ε martensite. The amount of α' and ε martensite depends on the alloy composition, stacking fault energy, degree of deformation, temperature etc. In metastable austenitic stainless steels different transformations take place, such as: $\gamma \rightarrow \varepsilon$, $\gamma \rightarrow \alpha'$ or $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ [12-13].

The Equation 1 formulated by Eichelman and Hull [14] gives an approximation the temperature of α' martensite formation (M_s). This temperature is strongly connected with the chemical composition of the alloy and for all AISI 300 series austenitic stainless steels, it can be calculated by the formula:

$$M_s\,(^\circ C) = 502 - 810(\%\,C) - 1230(\%\,N) - 13(\%\,Mn) - 30(\%\,Ni) - 12(\%\,Cr) - 54(\%\,Cu) - 6(\%\,Mo)$$

All alloying elements, except cobalt, dissolved in austenite affect the temperature M_s.

The dependence of temperature M_{d30} with a composition cold rolled 18-8, 18-12 and 18-12-Ti austenitic grades formulated by Angel [15] (eq.2):

$$M_{d30}(^\circ C) = 497 - 462(\%\,[C + N]) - 9.2(\%\,Si) - 8.1(\%\,Mn) - 13.7(\%\,Cr) - 20(\%\,Ni) - 18.5(\%\,Mo)$$

The stacking fault energy (SFE) plays an essential role in the strain-induced martensite transformations. It can be estimated as a function of the chemical composition from empirical relation given by Schramm and Reed [16] such as (eq.3):

$$SFE\ (mJ/m^2) = 25.7 + 2(\%Ni) + 410(\%C) - 0.9(\%Cr) - 77(\%N) - 13(\%Si) - 1.2(\%Mn)$$

The metastability of austenite stainless steels increases with the decrease of SFE. Austenitic stainless steels are materials with low and average stacking fault energy. They can undergo deformation in result of slide, as well as the mechanical twinning proceed.

The aim of these investigations is to determine the influence of plastic deformation in cold rolling process on the structure, mechanical properties and phase transformation metastable austenite into martensite in investigated cold-rolled sheet of stainless 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 10088-1:2007 [17], as a result of industrial smelting from the UGINE&ALZ (Poland). The material for examinations was delivered in the form of sheet-cutting steel with dimension about 40×2×700mm, was subjected cold rolling process within the range of deformations from 10% to 70%. This sheet was sampled for research of the 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.

In order to determine the influence of cold plastic treatment on the mechanical properties, structure and phase composition, particularly on the quantity of martensite α' in the structure of the investigated corrosion resistant stainless steels type X5CrNi18-10, metallographic investigation have been carried out on an optical microscope, as well as a qualitative X-ray phase analysis, static tensile test and measurements of microhardness.

Static tensile tests were carried out at room temperature 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 [18] and cut from the steel sheet along to the direction of rolling.

Table 1.
Chemical composition of the investigated steel

Melt of steel X5CrNi18-10	Kind of analysis	Chemical composition in mass %									
		C	Mn	Si	P	S	Cr	Ni	N	Mo	Cu
A	ladle analysis	0.03	1.31	0.39	0.03	0.004	18.07	8.004	0.044	0.25	-
B		0.033	1.32	0.41	0.026	0.002	18.08	9.03	0.026	0.23	-
C		0.047	1.12	0.42	0.028	0.006	18.35	8.06	0.06	0.28	0.36
Standard grade of steel X5CrNi18-10	by PN-EN 10088-1:2007	Chemical composition in mass % according to standard									
		≤0.07	≤2.0	≤1.0	≤0.045	≤0.015	17-19	8-11	≤0.11	-	-

Microscopic examinations of the structure of austenitic X5CrNi18-10 stainless steels were performed on longitudinal polished microsections and chemically etched in the reagent Mi17Fe heated to a temperature of about 40°C. Metallographic observations of the structure and nonmetallic inclusions were performed in a light microscope LEICA MEF4A, equipped with a Leica Qwin image analyzer with a magnification of 100-1000x. Additionally the average grain size of specimens was determined using the method of counting the slits grains into the image area, according to the standard PN-EN ISO 643:2003 [19].

Microhardness measurements of the investigated steel X5CrNi18-10 were made by Vickers's method on metallographic samples with a load of 50g, using the microhardness tester PMT-3 produced by Hauser. Researches were made at room temperature in accordance with a standard PN-EN ISO 6507-1:2007 [20]. Time of microhardness measurements amounting to 15s.

X-ray investigations of cold rolled X5CrNi18-10 austenitic stainless steel were run by means of an X-ray diffractometer type X'PERT PANalytical, applying the radiation of an anode λCoK_{α} and a Fe filter. Phase analysis was supplied by a current intensity of 40 mA and the accelerating voltage of 45 kV.

The length of radiation (λCoK_{α}) was 1.79021 Å. The data of diffraction lines were recorded by "step-scanning" in the 2Θ range from 40° to 115°. Step-scanning method was used at a step value $0.1^{o}2\Theta$ and a time of measurements amounting 2 second in one measurement position. The obtained diffraction patterns were analyzed applying the program Diffract AT Search/Match.

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

The amount of martensite α' phase was quantitatively measured by the Averbach Cohen method [21]. In the calculation the respective surfaces of the diffraction lines of the phases γ and α' were measured by means of a planimeter.

3. Results and discussion

The structures of the investigated steel type X5CrNi18-10 in their delivery state have been presented on a micro-photograph (Fig.1). On the basis of metallographic observations it was found that three steel grades A, B and C exhibit 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. Additionally, in steel C the agglomerations of copper precipitations were affirmed. A kind of non-metallic inclusions occurring in steel X5CrNi18-10 are presented in many literature positions [22-24].

The average diameter of the equiaxial austenite grains in the structure of investigated steel A, B and C carried out about 21 µm. Measurements of grain sizes were made according to the standard PN-EN ISO 643:2005 [25]. It was found that with increased deformation the number of grains with etched internal structure increased.

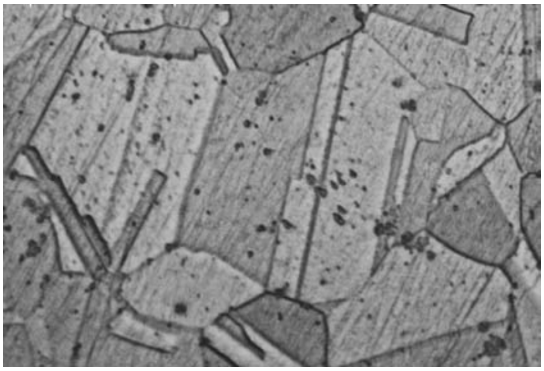
In the investigated steels A, B and C after cold deformation a structure of elongated austenite grains with slip bands, deformation twins and sparse non-metallic inclusions were found. Metallographic observations of the structure of all grades of steel type X5CrNi18-10 deformed with a degree from about 40% to about 70% show that in elongated γ grains there are areas of parallel plates characteristic for martensite α' (Fig.2).

Elongated austenite grains are characterized by the deformed state of steel, whereby the austenite grains undergo elongation in the rolling direction. The steel structure shows a much more fine-grained character; the observed process has an influence on its strain hardening. The result is α' phase forming and increased its amount during the cold rolling process. The occurrence of martensite α' in X5CrNi18-10 steel confirms the results of mechanical investigations.

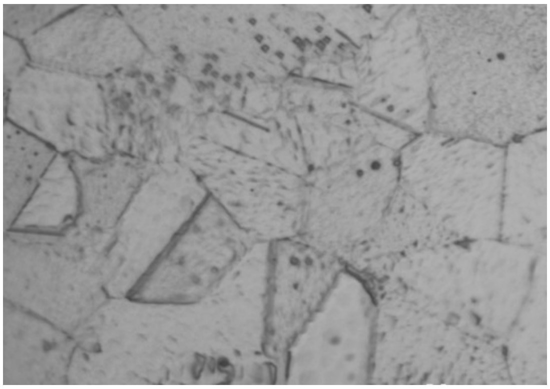
The results of researches of the microhardness measurements and mechanical properties of the investigated steel have been gathered in Table 2 and in Figs. 3-7.

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. Similarly in the case of tensile strength R_m, the highest strength has steel A about 647 MPa, steel C about 630 MPa and the lowest tensile strength has steel B, about 624 MPa. The elongation A is almost on 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. 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 %. It was affirmed that in the delivery state steel B shows the largest micro-hardness 183 $HV_{0.05}$ and steel C the lowest, about 155 $HV_{0.05}$. While steel A displays an average value of the micro-hardness amounting to about 162 $HV_{0.05}$.

a)



b)



c)

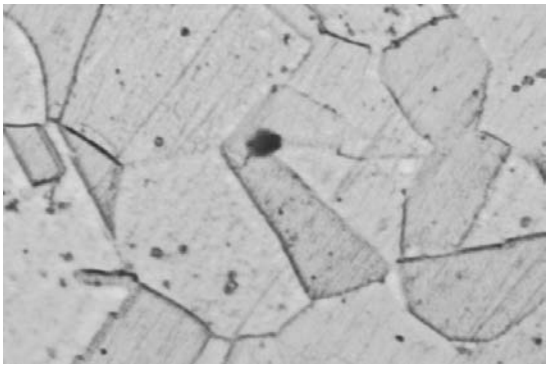
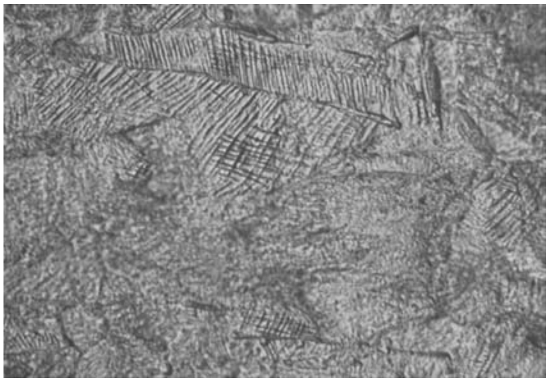


Fig. 1. Structure of the investigated steel type X5CrNi18-10 in the delivery state; a-c melts of these steel; Etching-Mi17Fe; Mag. 1000x

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 about 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 draft from 10 % to 50 % of steel C causes increasing its yield point from about 535 MPa to about 1198 MPa, the tensile strength from about 763 MPa to about 1295 MPa, the micro-hardness from about 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 about 58 % to about 29 %.

At the 70 % of deformation, steel C demonstrates the highest values of $R_{p0.2}$ values about 1259 MPa, while steel A and B show a little lower value of $R_{p0.2}$, 1161 MPa and 1148 MPa respectively (Fig. 3).

a)



b)

c)

Fig. 2. Structure of the investigated steel type X5CrNi18-10 after deformation with a rolling reduction of 50%; a-c melts of these steel; Etching - Mi17Fe; Mag. 500x

Table 2.
Micro-hardness and mechanical properties of investigated steel in delivery state and at different cold reduction levels

Melt of steel X5CrNi18-10	Draft [%]	R_m MPa	$R_{p0.2}$ MPa	A %	Z %	$HV_{0.05}$
		Mechanical properties				
A	-	647	330	52	48	162
	10	784	586	32	45	227
	20	918	732	25	38	288
	30	1044	905	9	30	321
	40	1194	953	1.5	22	331
	50	1257	969	1	15	357
	70	1496	1161	0.68	11	400
B	-	624	300	53	54	183
	10	783	542	35	50	279
	20	906	767	24	45	316
	30	1010	877	5	35	405
	40	1141	967	4	23	425
	50	1228	1059	2	13	445
	70	1452	1148	1	10	554
C	-	630	302	53	66	155
	10	763	535	37	58	234
	20	909	758	21	45	287
	30	1053	941	20	41	295
	40	1187	1041	4	35	331
	50	1295	1198	2	29	351
	70	1433	1259	1	23	415

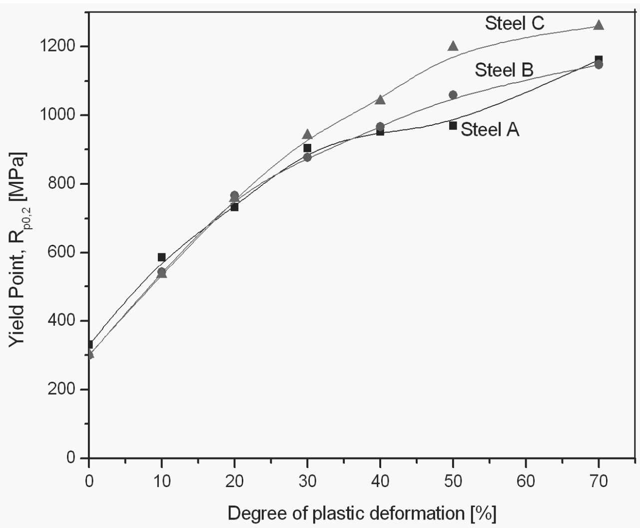


Fig. 3. Changes of the yield point investigated cold rolled steel A, B and C depending on degree of deformation

After the maximum degree of deformation, about 70% steel A show the highest values of tensile strength, about 1496 MPa. While steels B and C characterized a similar value of R_m; steel B, about 1452 MPa and steel C, about 1433 MPa (Fig.4).

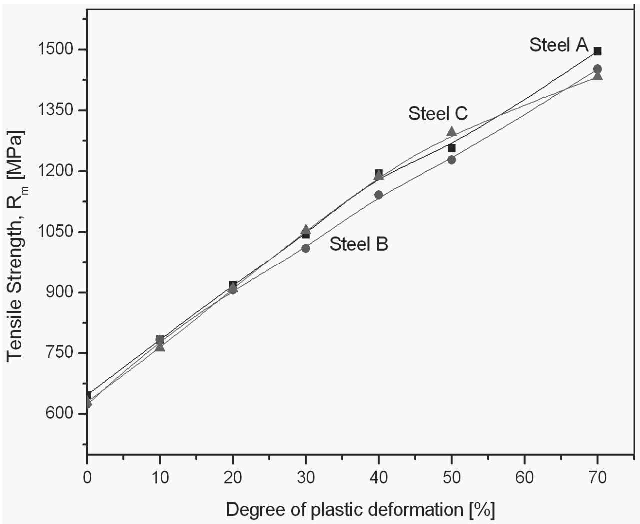


Fig. 4. Changes of the tensile strength investigated cold rolled steel A, B and C depending on degree of plastic deformation

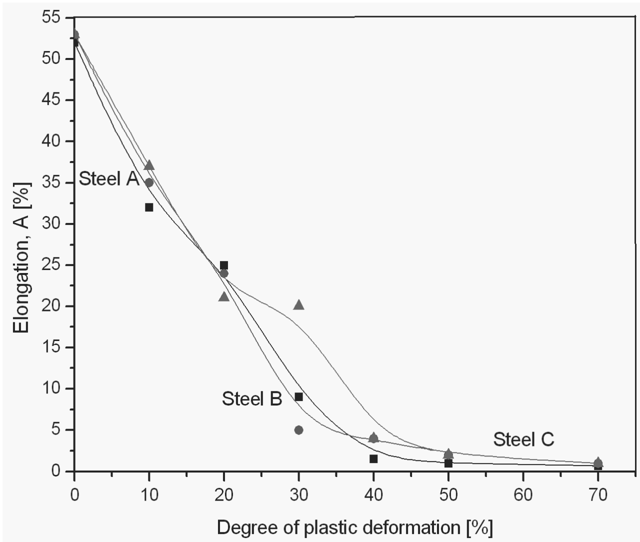


Fig. 5. Changes of the elongation investigated cold rolled steel A, B and C depending on degree of deformation

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

It was affirmed that after maximum deformation steel C 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).

Steel B is the hardest of all investigated steels, and after maximum cold reduction it is characterized by about 554 $HV_{0.05}$. Steels A and C show similar values of micro-hardness, about 400 $HV_{0.05}$ (steel A) and about 415 $HV_{0.05}$ (steel C), which is presented in Fig.7.

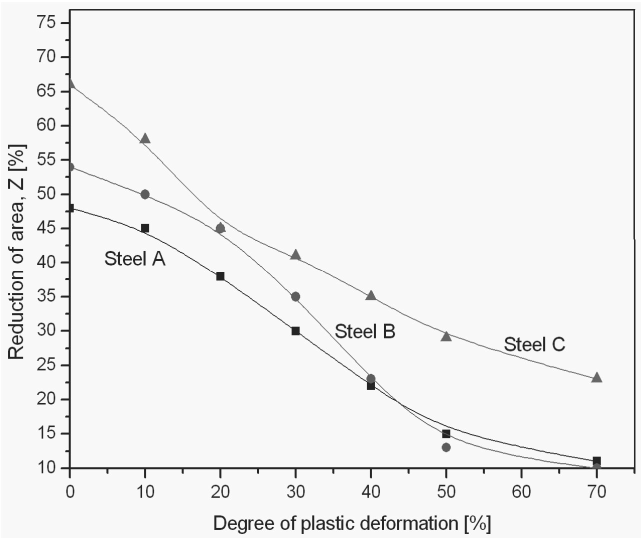


Fig. 6. Changes of the reduction of area in the investigated cold rolled steel A, B and C depending on the degree of deformation

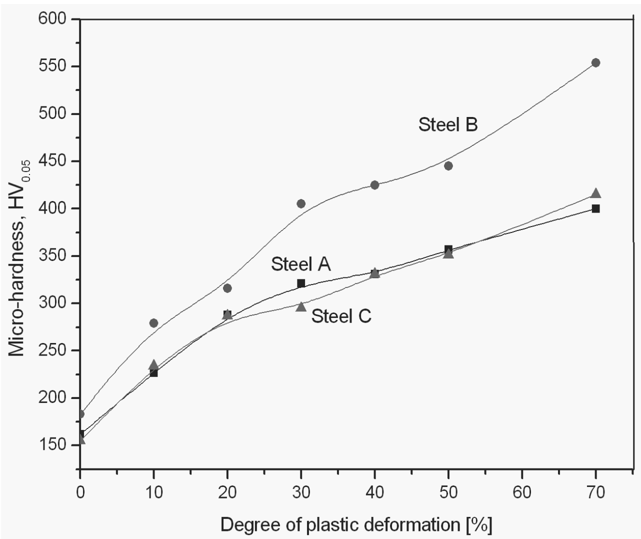


Fig. 7. Changes of the micro-hardness investigated cold rolled steel A, B and C depending on degree of plastic deformation

Table 3.
Values of Martensite Transformation Temperatures and Stacking Fault Energy for investigated steels

Grade of steel	Transformation Temperatures (°C)		
	M_s (°C)	M_{d30} (°C)	SFE (mJ/m^2)
A	-51.9	36.3	27.7
B	-63.1	22.7	32.1
C	-107.5	16.8	33.1

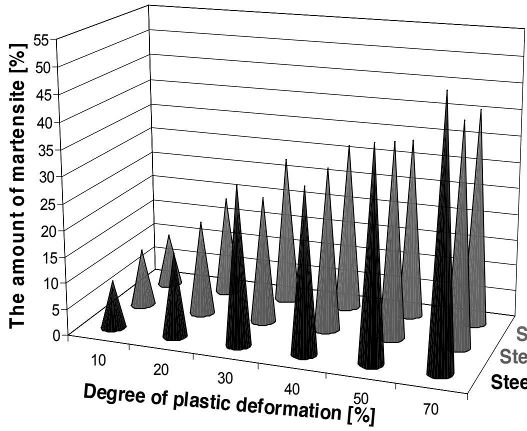


Fig. 8. Dependence of the volume fraction of α'- phase on degree of plastic deformation investigated steel

On the basis of the carried out examinations it has been found that in all investigated kinds of steel the value of the yield point $R_{p0.2}$, tensile strength R_m and micro-hardness $HV_{0.05}$ increase with the degree of deformation, but the value of necking Z and elongation A decreases.

Table 3 compares values of M_s, M_{d30} and SFE of three grades of X5CrNi18-10, medium stacking fault energy steel. The values were calculated with Equations 1, 2 and 3. All three values for M_s are in the sub-zero scale. M_{d30} values, temperature that 50 % of austenite is transformed to martensite with 30 % of deformation, suggest that the formation of martensite at room temperature for these steels will be progress relatively easy. Steel A have the lowest value of SFE, which maybe causes a weak stability of austenite phase in this steel. Addition of Cu in steel C causes increasing the value of SFE. On the basis of the SFE value it have been found that in investigated case only the martensite α' phase is formed.

On the basis of X-ray quantitative phase analysis it was found that the volume fraction of martensite α' phase increases with the increasing cold reduction in all three grades of X5CrNi18-10 steel. In the undeformed state of steels the martensite α' phase does not occur. With the increasing deformation within the range of 10 % - 70 % the amount of martensitic α' phases in steel A increases from about 9 % to about 50 %, in steel B from about 11 % to about 42 %, and in steel C from about 10 % to about 41 % (Fig.8). After maximum deformation, about 70% steel A shows the highest amount of martensitic α'.

In the undeformed 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.

X-ray investigations of three grades steel type X5CrNi18-10 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 γ phase from (111)γ, (200)γ,

Table 4.
Results of the X-ray phase analysis of the investigated grades of steel with a draft of 70%

Melt of steel	Ordinal number	Experimental			Identification (ICDD)			
		Angle of reflection [º2Θ]	Interplanar distance d [Å]	Intensity I/I_{max} [%]	Interplanar distance d_{hkl} [Å]	Intensity [%]	(hkl)	Phase
A	1	51.225	2.0694	57	2.0750	100	111	γ
	2	52.175	2.0346	53	2.0268	100	110	α’
	3	76.975	1.3921	51	1.4332	20	200	α’
	4	89.575	1.2698	100	1.2697	26	220	γ
	5	99.425	1.1726	94	1.1702	30	211	α’
B	1	51.177	2.0724	100	2.0750	100	111	γ
	2	52.121	2.0374	47	2.0268	100	110	α’
	3	77.043	1.4372	37	1.4332	20	200	α’
	4	89.580	1.2705	96	1.2697	26	220	γ
	5	99.360	1.1739	55	1.1702	30	211	α’
C	1	51.2161	2.0695	100	2.075	100	111	γ
	2	52.1815	2.0339	55	2.0268	100	110	α’
	3	77.2432	1.4331	40	1.4332	45	200	α’
	4	89.6302	1.2691	96	1.2697	26	220	γ
	5	99.4494	1.1724	60	1.1702	30	211	α’

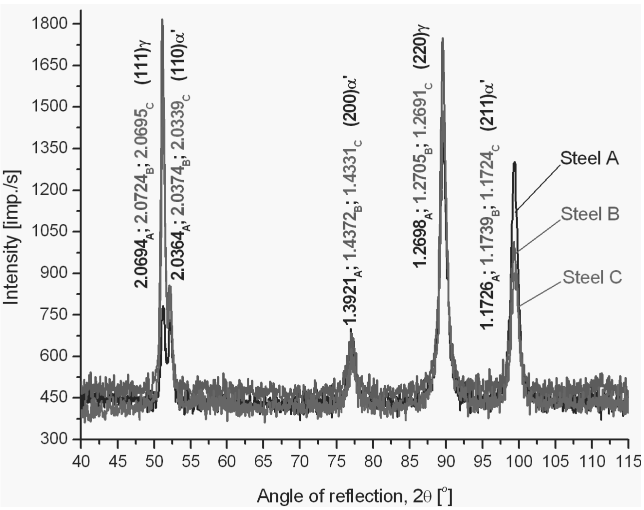


Fig. 9. X-ray diffraction patterns of steel grades A, B and C with a draft of 70%

(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 have been gathered in Table 4 and Fig 9.

After maximum degree of deformation, about 70% in all investigated steels 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 (Fig.9).

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

Phase analysis of deformed steel type X5CrNi18-10 with draft from 10 % to 70 % didn’t disclosed lines coming from the ε phase, what is compatible with literature [26-28]. It shows that the martensite transformation proceed according to the sequence γ → α’.

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. It has been found that an increase of the mechanical properties during cold rolling on the investigated steel type X5CrNi18-10, results from the strain hardening and martensite transformation.
2. In the delivery state steel has a single-phase austenite structure with grains about 20 µm average a diameter, twins and non-metallic inclusions.
3. The amount of α’phase in X5CrNi18-10 steel depends on the degree of plastic deformation. The increasing deformation within the range of 10 % - 70 % induces in its structure a martensitic transformation γ → α’, increasing part of the α’phase 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. Diffraction lines (111)γ, (220)γ and (110)α’, (200)α’,(211)α’ of the analysed phases of cold rolled the X5CrNi18-10 steel show distinct texturing.
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 the mechanical properties, connected with the appearance of martensitic α’ phases.

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