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The influence of the martensite α' phase occurring in the structure of cold rolled austenitic Cr-Ni steel on its mechanical properties

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ABSTRACT

Purpose: In this paper the mechanical properties and structure of cold rolled austenitic stainless steel X5CrNi18-8 with a draft of 17%-78% were presented.

Design/methodology/approach: The main methods used for these researches were the static tensile test, microhardness and metallographic observations by optical microscopy. The tested samples have also been analyzed fractographically. The amount of martensite α' in the obtained microstructures was investigated with X-ray diffraction patterns. The scope of this study was to achieve the correlations between the mechanical and structural properties of cold rolled stainless steel.

Findings: Results showed increasing the mechanical properties (R_m, $R_{p0.2}$, HV) and decreasing the plasticity (A) with the increasing degree of draft during cold rolling of investigated austenitic stainless steel.

Research limitations/implications: In future examinations there is a need to broadening the methodology about the magnetic properties investigations which in the more precise way permit to define the quantity of the martensite α' phase in the structure of steel

X5CrNi18-10 and describe its morphology.

Practical implications: A wide range of practical applications of austenitic X5CrNi18-8 steel sheets is warranted by both their high corrosion resistance and high plastic properties, especially in the supersaturated state.

Originality/value: The analytic dependence of the yield point ($R_{p0.2}$) of the investigated steel on the draft degree in cold rolling has been confirmed.

Keywords: Metallic alloys; Austenitic stainless steel; Plastic deformation; Induced martensite; Mechanical properties; Ductile fracture; Cold rolling

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MATERIALS

1. Introduction

Austenitic stainless steels contain about 16÷25%wt. chromium, 0.1%wt. carbon and not less than 7.5%wt. nickel, which is indispensable to obtain the single-phase structure γ [1÷5]. These steels usually exhibit excellent corrosion resistance, toughness, ductility, low thermal and electrical conductivity and good weldability. However, the strength level, particularly the yield strength, is relatively low, about 200 MPa, in the annealed state. In order to increase their strength, austenitic stainless steels are often cold worked after solution annealing. Cold working is a convenient strengthening method since austenitic stainless steels normally have a high strain-hardening coefficient. After thermomechanical treatment a common steel such as X5CrNi18-10 can have its yield strength increased to about 1400 MPa, with an elongation over 10%. During plastic deformation, depending on the steel composition and the cold working variables, stacking faults, two different martensitic phase, ε-martensite (HCP) and α’-martensite (BCC) can be formed [6÷11]. The α’ phase is often called strain-inducted martensite because it is produced by a diffusionless phase transformation. The most probable way of the phase transformation in the 300 series austenitic stainless steels is the: $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ or $\gamma \rightarrow \alpha'$ [12÷15]. These kinds of steels are widely used in chemical, petrochemical, machinery, automobile, nuclear and shipyard industries [16÷20].

The aim of these investigations was to define the influence of the degree of plastic deformation in the cold rolling process on the structure and mechanical properties of austenitic stainless steel type X5CrNi18-8. In particular special attention was put on the amount of martensite α' phase occurring in the structure of tested stainless steels after cold rolling.

2. Experimental procedure

Investigations were carried out on austenitic stainless steel type X5CrNi18-8, resulting from industrial smelting of automotive muffler from the Zakłady Metalowe “Postęp” (Poland). The chemical composition of the investigated steel in delivery condition is to be seen in Table 1. The material for examinations was delivered in the form of sheet-cutting steel with dimensions about 2×100×500mm, subjected to cold rolling ranging from 17%, 35%, 42%, 60%, 72% to 78%, using the sheet mill Quarto type 10502 produced by Skoda. The rolling was conducted at 20°C keeping a constant direction and side of the rolled strip. Additionally, to compare the structure and mechanical properties in different states, the investigated steel was supersaturated for 1 hour at 1100°C, and then cooled down in water. The steel sheets were sampled for research of the mechanical properties, for hardness and microhardness measurements, metallographic observations and the X-ray phase analysis.

The mechanical properties were determined by means of a static tensile test, according to the standard PN-EN 10002-1+AC1:2004 [22] on a testing machine INSTRON 4505 at 20°C with a traverse speed of 20 mm/min and a load ranging to 100kN. The specimens used for measurements of the mechanical properties were cut from the steel sheets parallelly to the rolling direction.

Microscopic examinations of the structure of austenitic X5CrNi18-8 stainless steels were performed on longitudinal polished microsections and chemically etched in the reagent Mi17Fe heated to a temperature of about 40°C, according to standard. Samples for this purpose were cut from the steel sheets in the delivery, supersaturated and deformed state. The times of the etching of individual samples were differentiated. Samples deformed with a larger draft required a longer time of etching. Metallographic observations of the structure and nonmetallic inclusions were performed in a light microscope LEICA 405M, using a magnification from 100 to 1000x. Additionally, the average grain size of specimens was determined using the method of counting the slits grains into the image area, according to standard PN-EN ISO 643:2005 [23]. The quality assessment of nonmetallic inclusions was carried out in accordance with a standard PN-EN 10247:2007 [24].

Hardness and microhardness measurements of the investigated steel X5CrNi18-8 were made by Vickers's method on metallographic samples using the microhardness tester PMT-3 produced by Hauser. Researches were made at room temperature in accordance with the standard PN-EN ISO 6507:2007 [25]. Hardness measurements were carried out with a load of 50N and for the time of about 15s, whereas in microhardness measurements using a load value about 50g and time amounting to 10s were applied. The microhardness measurements were realized on metallographic microsections in bright areas of the austenite grains and grains with small parallel lines characteristic for the martensitic α’ phase.

Table 1.
Chemical composition of the investigated steel

Grade of steel	Kind of analysis	Mass contents in percentage (%)												
		C	N	Mn	Si	P	S	Ni	Cr	V	Cu	W	Ti	Al
X5CrNi18-8	PN-EN*	≤0.05	≤0.11	≤2.0	-	-	-	8.00	18.00	-	-	-	-	-
	check analysis	0.032	0.057	1.32	0.451	0.032	0.0035	7.92	18.43	0.097	1.077	0.064	0.017	0.009

* Standard PN-EN 10088-1:2007

X-ray investigations of cold rolled X5CrNi18-8 austenitic stainless steel were run by means of an X-ray diffractometer type X'PERT PANalytical, applying the filter radiation of an anode λCoK_{α}. The length of radiation (λCoK_{α}) was 1.79021 Å. The data of the diffraction lines were recorded by "step-scanning" method in 2Θ range from 41° to 115° and the 0.05° step, the time of measurements amounting to 10 seconds 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 [26]. In the calculation the respective surfaces of the diffraction lines of the phases γ and α' were measured by means of a planimeter.

The fractographic investigations of the fracture after decohesion of the samples in a tensile test at room temperature were executed in the electron scanning microscope SUPRA^{TM}25 produced by ZEISS with the accelerating voltage 20kV, applying the magnification of 1000÷75000x. Fractures for the fractographic examinations were cleaned ultrasonically in ethanol for 180s.

3. Results and discussion

The metallographic investigations permit to assess the steel structure type X5CrNi18-8 in the delivery and supersaturated state and to define the influence of the degree of plastic deformation on its cold rolled structure with a draft from 17% to 78%. Additionally the metallographic symptom of draft, shape and size of austenite grains were determined. The results of metallographic observations have been presented on microphotos (Figs. 1÷4). It has been found that in the steel structure occurs a small non-metallic inclusions, mainly of the pointwise character, were identified as oxides and copper precipitations about the size 2÷8 μm. Sparse non-metallic inclusions indicate a high metallurgical purity of the examined steel, whereas the occurrence in steel X5CrNi18-8 small precipitations of pure copper proves the incomplete introduction this element to the solution γ. Therefore this element does not hamper on forming the martensitic α' phase in steel X5CrNi18–8 deformed with small drafts degree.

The structure of the investigated corrosion-resistant steel type X5CrNi18-8 in the delivery state characterized austenite grains about 18 μm average a diameter with twins and microhardness about 200 HV05. In the delivery state the steel structure does not show the metallographic symptom of deformation.

After supersaturation in the structure of the examined steel equiaxial austenite grains with twins were observed. The average diameter of the austenite grains in the steel structure after supersaturation in water from the temperature 1100°C amounts to about 73 μm (Fig. 1). In the investigated steel after cold deformation with drafts about 17% a structure of austenite grains with the deformation effect of the inside grains were found (Fig. 2). Deformation with a larger draft causes in the steel structure elongated γ grains in the direction of rolling.

In steel X5CrNi18-8 after cold rolling with a draft of 17% and 33% a few areas of parallel plates characteristic for martensite α' were observed (Fig. 3). These areas are characterized by a hardness of about 251 HV and 353 HV.

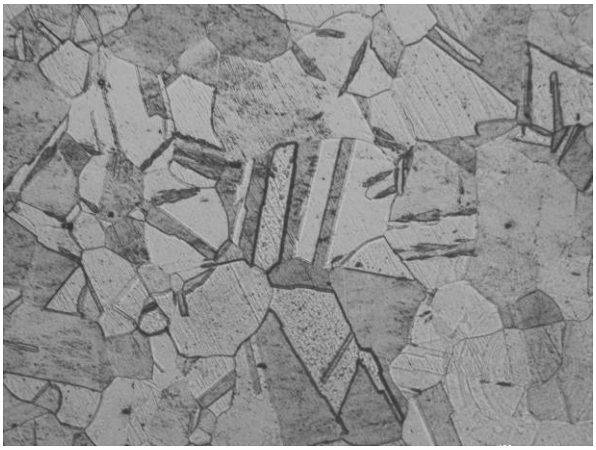


Fig. 1. Structure of X5CrNi18-8 steel after supersaturation at 1100°C; Etching - Mi17Fe; Mag. 200x

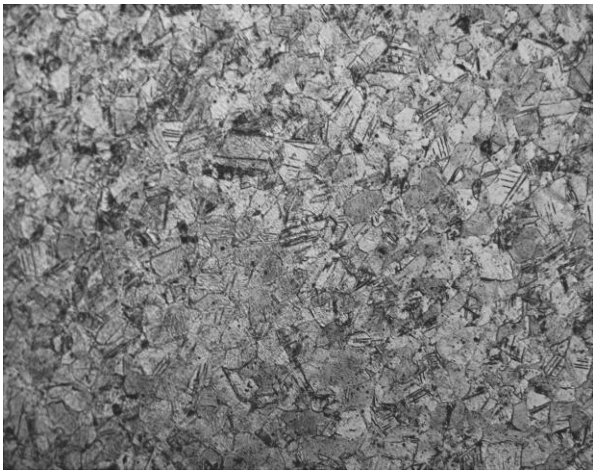


Fig. 2. Structure of the investigated steel after deformation with a draft of 17%; Etching - Mi17Fe; Mag. 200x

Fig. 3. Structure of the investigated steel after deformation with a draft of 33%; Etching - Mi17Fe; Mag. 200x

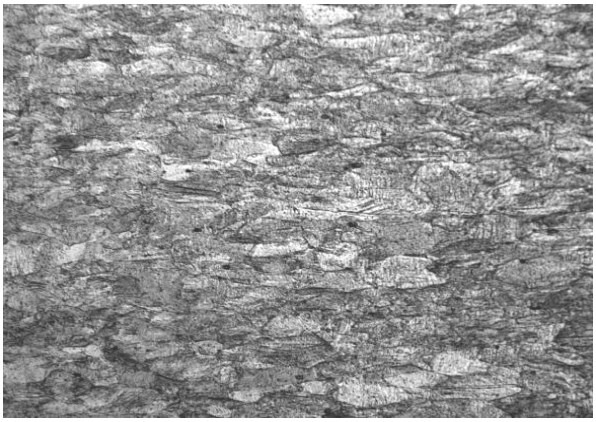


Fig. 4. Structure of the investigated steel after deformation with a draft of 60%; Etching - Mi17Fe; Mag. 200x

Metallographic observations of steel structure deformed with a draft from 60% to 78% show the large areas of elongated austenite with small parallel lines of martensitc α’ phase (Figs. 4 and 5). The hardness in these areas amounts to about 466 HV and 447 HV.

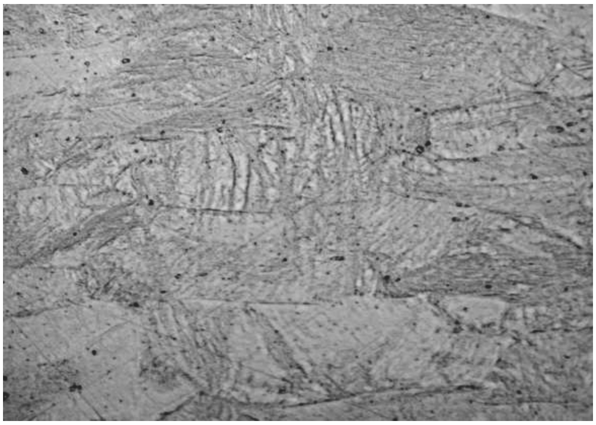


Fig. 5. Structure of the investigated steel after deformation with a draft of 60%; Etching - Mi17Fe; Mag. 1000x

It has been found that during the cold rolling process with an increasing degree of deformation the α’ phase is formed, which causes an essential size reduction of the steel structure and its strain hardening. The occurrence of martensite α’ phase in X5CrNi18-8 steel confirms the results of mechanical investigations.

The results of the mechanical properties were determined by means of a static tensile test. Examples of the tensile curves of the investigated steel type X5CrNi18-8 have been presented in the curves in Fig.6. On the basis of the realized tensile tests the tensile strength R_m and yield point $R_{p0.2}$ were determined. The changes of the samples geometry were used to define the elongation A of the investigated steel. The results of these investigations permit to define the influence of the degree of deformation in the cold rolling of steel on the strength and ductile properties of the examined steel. The results of investigations concerning the mechanical properties have been presented on Figs. 7÷9.

The tensile strength of the investigated steel in the delivery state is about 668 MPa, the yield point about 335 MPa, and the elongation about 51 %. After supersaturation the strength properties of the examined steel decreases while the plasticity increases.

In the supersaturation state the tensile strength of the investigated steel is about 586 MPa, the yield point is about 251 MPa and the elongation about 62 %. After cold rolling steel X5CrNi18-8 displayed high strength properties (R_m, $R_{p0.2}$) and of low plasticity (A). With the increasing deformation within the range of 17% to 78% the tensile strength of the X5CrNi18-8 steel increases from about 955 MPa to about 1550 MPa and the yield point from about 780 MPa to about 1070 MPa.

The results of the influence of the degree of rolling on the values of R_m and $R_{p0.2}$ of the investigated steel were approximated suitably by the function $y = -0.0668x^2 + 16.341x + 676.16$ and $y = -0.2025x^2 + 24.862x + 345.18$. The coefficients of the matching R^2 of the approximate function amounts adequately to 0.999 and 0.9373 which proves good correlation of the approximate function with experimental results (Figs. 7 and 8).

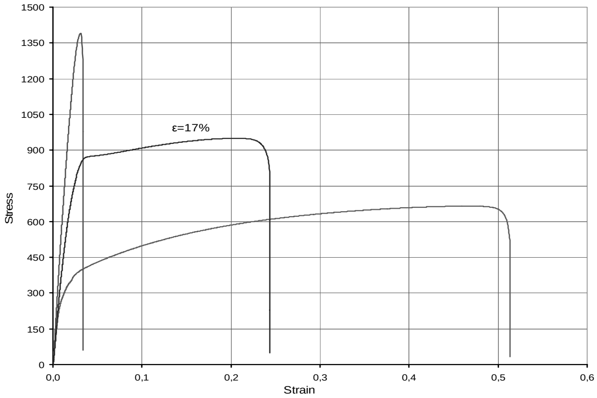


Fig. 6. Examples of the tensile curves of the investigated steel type X5CrNi18-8 in delivery state and after cold rolling with draft 17% and 42%

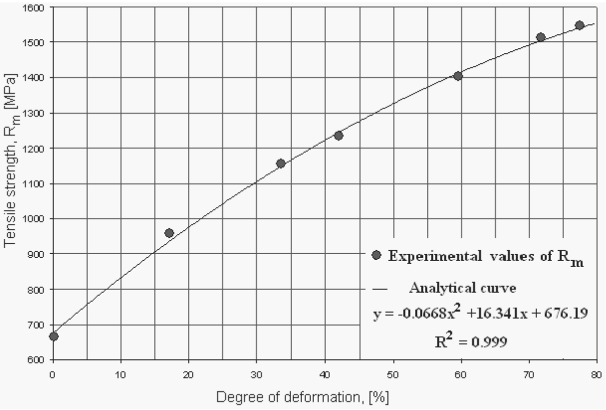


Fig. 7. The influence of the degree of cold deformation on the values of R_m for the investigated steel

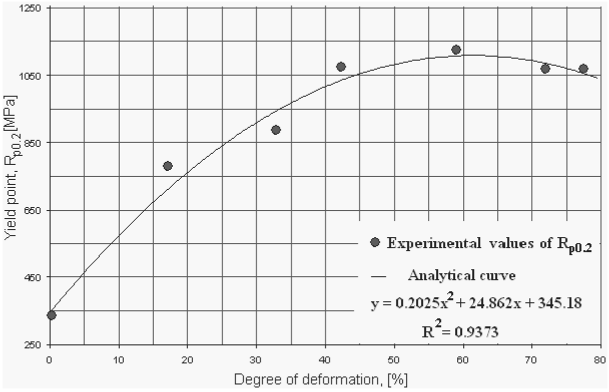


Fig. 8. The influence of the degree of cold deformation on the values of $R_{p0.2}$ for the investigated steel

The dependence of the elongation from the degree of deformation described with the aid of the function $y = -7E\text{-}0.5x^3 + 0,0205x^2 - 1.8355x + 58.653$, whose coefficient of the matching R^2 is about 0.9954 (Fig. 9).

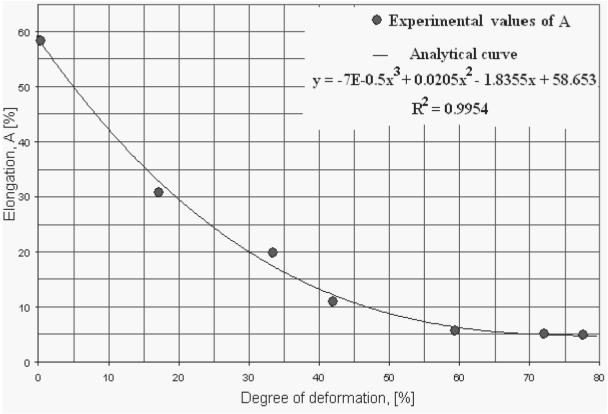


Fig. 9. The influence of the degree of cold deformation on the values of *A* for the investigated steel

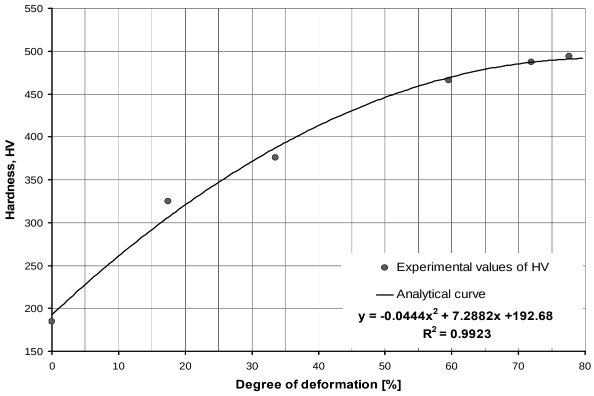


Fig. 10. The influence of the degree of cold deformation on the values of *HV* for the investigated steel

On the basis of the realized hardness measurement the influence of the degree of rolling reduction on the hardness of the investigated steel in the delivery state, supersaturated condition and after deformation have been defined (Fig. 10).

The hardness of the examined X5CrNi18-8 steel in the delivery state amounts to 186 HV and after supersaturation in water from the temperature 1100°C – 146 HV. Cold rolling within the range of 17% ÷ 78% increases the hardness of investigated steel from 325 HV to 494 HV. The dependence of the hardness of the tested steel on the degree of deformation in cold rolling was described by the approximated function: $y = -0.0444x^2 + 7.2882x + 192.68$, whose coefficient of matching R^2 is about 0.9923. The value of the coefficient R^2 of the approximate function is close to unity and proves a good correlation of the analytical curve with experimental ones.

The significant difference was affirmed in the microhardness of austenite γ grain and martensite α’ phase. The values of microhardness show that the hardness of bright grains is characterized by the γ phase and grains with parallel lines – martensite α’ phase. In sample in the supersaturated state the value of microhardness of bright grains of austenite oscillates in the range from 105 HV to 135 HV. In cold rolled samples within the range of 17% ÷ 78% the hardness of austenite grains amounts to 251 HV and martensite α’ phase – to 466 HV. The hardness of austenite grains in the structure of the examined steel in the delivery state is higher than the hardness of the samples in supersaturated state and oscillates in the range from 135 HV to 251 HV. It proves about strain hardening or in some cases a close vicinity of the martensitic phase of measuring area. The hardness of martensite α’ phase amounts from the 329 HV to 466 HV. The lower values of the hardness of this phase result probably from its location among the grains of γ phase.

On the basis of examinations of the mechanical properties it was found that with the increasing deformation of the X5CrNi18-8 steel the strength properties increase, while the plastic properties decrease proportionally to the degree of deformation during the cold rolling.

The X-ray investigation allowed to identify the phases and to define the quantity of the phase composition of steel type X5CrNi18-8 in the delivery state and after cold rolling with a draft of 33%, 60% and 78%. On diffraction patterns of steel type X5CrNi18-8 in the delivered state disclosed diffraction lines coming from planes (111), (002), (220) and (311) austenite phases, that confirmed its homogeneous γ structure (Fig. 11).

After cold rolling of steel with a draft of 33%, 60% and 78% the intensity of austenite peaks gradually decreased and martensite α’ peaks appeared in the spectrums. These spectra show a higher thickness reduction in the case of more numbers and a higher intensity of martensite α’ peaks.

X-ray investigations of steel X5CrNi18-8 deformed with a draft of 60% 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’, (200)α’ and (211)α’ reflection planes, which occurred with matrix lines from (111)γ, (220)γ and (311)γ reflection planes (Fig.12). 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.

For the calculations a fraction of the martensite α’ phase in the structure of examined steel in dependence from the degree of rolling reduction, the 1% of carbides was accepted. The volumetric part of carbides was accepted on the basis of the analysis of X-ray pattern (Figs.11 and 12), on which the lines diffraction coming from carbides were not observed.

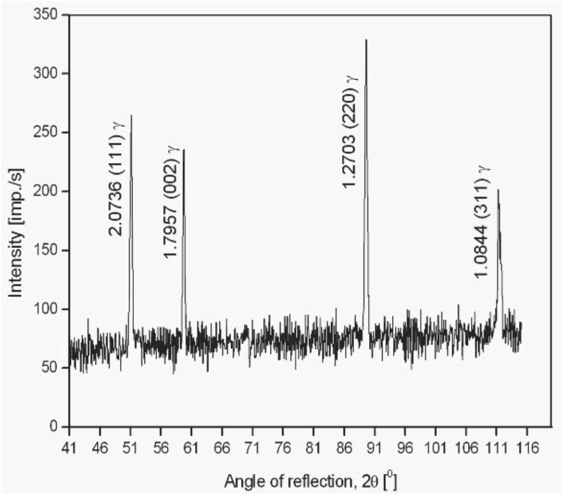


Fig. 11. X-ray diffraction patterns of investigated steel in the delivery state

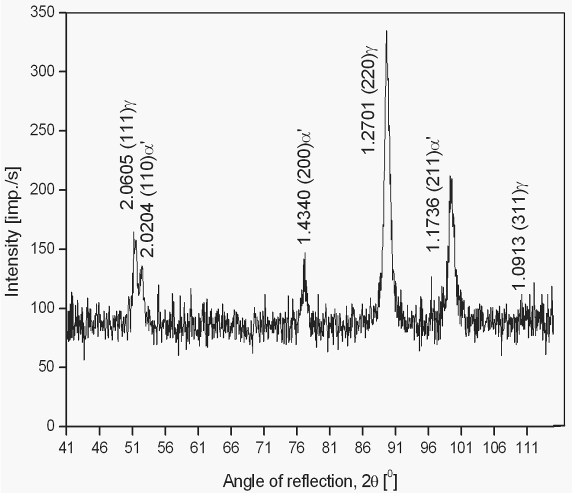
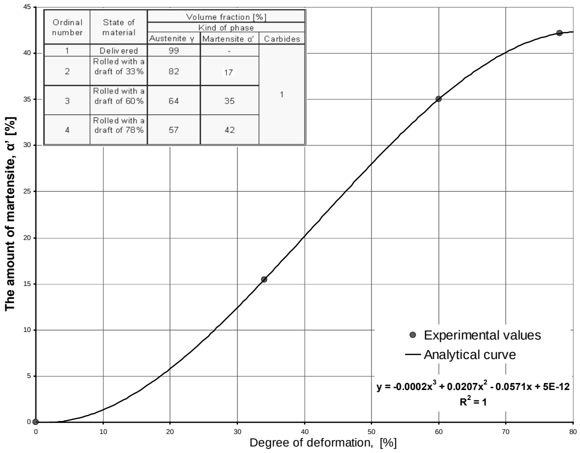


Fig. 12. X-ray diffraction patterns of steel X5CrNi18-8 with a draft of 60%

On the basis of X-ray quantitative phase analysis it was found that the volume of the analyzed α’ phase in the structure of the examined steel increases with the deformation in the cold rolling. In the delivered state of X5CrNi18-8 steel the phase α’ doesn’t occur, but after deformation with a draft of about 33%, 60% and 78% the amount of martensitic α’ phases in its structure is adequately 16%, 35% and 42%.

The dependence of the quantity of martensite α’ phase in the investigated steel structure on the degree of deformation in cold rolling was described by the approximating function: $y = -0.0002x^3 + 0.0207x^2 - 0.0571x + 5E\text{-}12$. The value of the coefficient of matching R^2 of the approximated function amounts to 1 (Fig. 13).



Ordinal number	State of material	Volume fraction [%]		
		Kind of phase		
		Austenite γ	Martensite α'	Carbides
1	Delivered	99	-	1
2	Rolled with a draft of 33%	82	17	
3	Rolled with a draft of 60%	64	35	
4	Rolled with a draft of 78%	57	42	

Fig. 13. The influence of the degree of cold deformation on the formation of martensite α’ in structure of investigated steel

The results of fractographic investigations permitted to determine the influence of the degree of rolling reduction on the character of the fracture of X5CrNi18-8 steel obtained during the decohesion of samples in a tensile test at room temperature. Findings of fractographic observations were introduced on microfractographies (Figs. 14÷18).

In the supersaturated state of steel X5CrNi18-8 the ductile fracture with characteristic smoothing convexities occurred (Fig. 14). After cold rolling with a draft of 17% the investigated steel is characterized by a transcrystalline ductile fracture with large areas of plastic deformation and small areas of brittle cracking (Fig. 15). On plastic deformed surfaces the characteristic craters with diversified size and few small separations have been found.

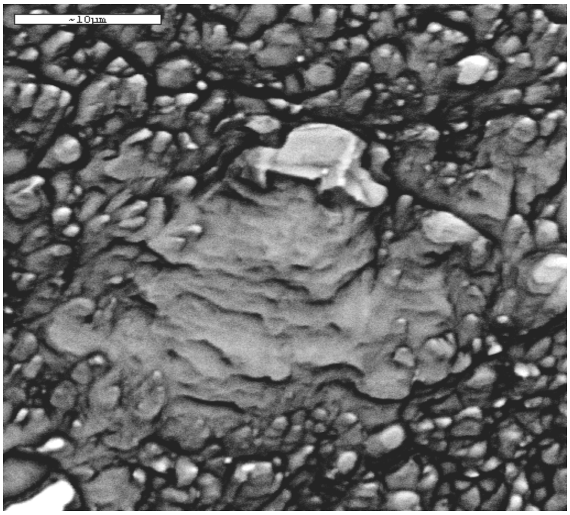


Fig. 14. Ductile fracture of X5CrNi18-8 steel after supersaturation at 1100°C; Mag. 2400x

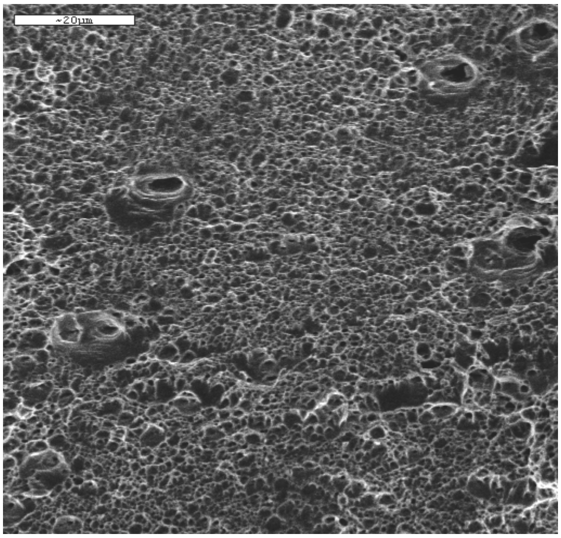


Fig. 15. Transcrystalline ductile fracture of investigated steel X5CrNi18-8 after deformation with a draft of 17%, Mag. 1000x

In areas of brittle cracking probably α' phase occurred. In those places flared flat surfaces were observed with visible lines and ridges (Fig. 16). Cold rolling with a draft of 33% causes, that in X5CrNi18-8 steel fracture areas of plastic deformation occurred and a large quantities of skips on smooth surfaces connected with the presented α' phase. These skips distances are probably the borders of phases γ and α' (Fig. 17). Martensite α' phase existing in X5CrNi18-8 steel structure created on its fractures smooth terraces separated originate from austenite γ phase terraces with surfaces showing plastic deformations (Fig. 18).

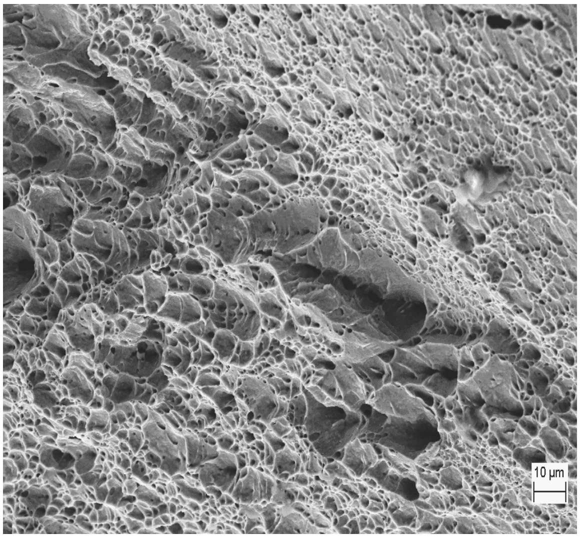


Fig. 16. Transcrystalline ductile fracture of investigated steel after deformation with a draft of 17%, Mag. 2000x

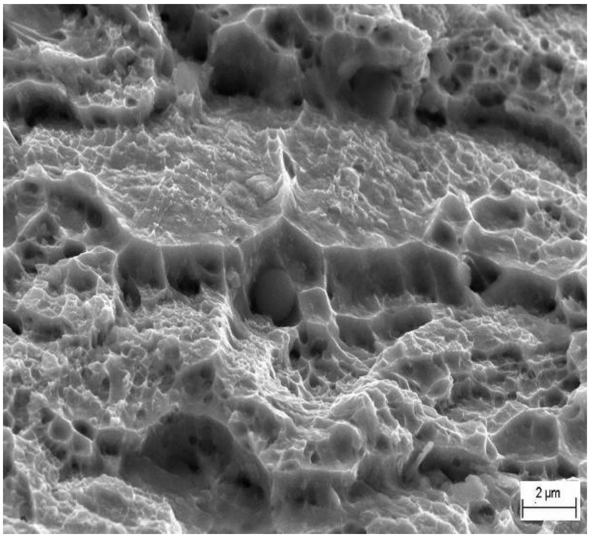


Fig. 17. Terraces on ductile fracture of investigated steel after deformation with a draft of 33%, Mag. 16530x

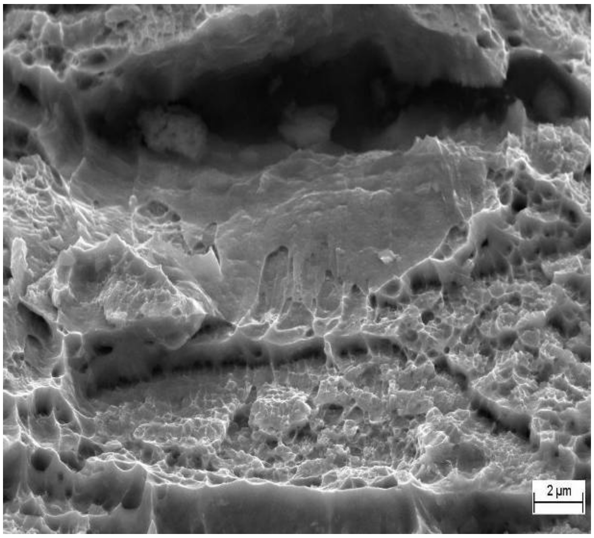


Fig. 18. Terraces on the ductile fracture of investigated steel type X5CrNi18-8 after deformation with a draft of 33%, Mag.17000x

4. Conclusions

The obtained results of investigations lead to the following conclusions:

1. Plastic deformation of steel X5CrNi18-8 in cold rolling with a draft from 17% to 78% causes the increase of the strength properties: R_m from 668 MPa to 1546 MPa, $R_{p0.2}$ from 335 MPa to 1069 MPa and hardness from 186 HV to 494 HV and decreasing the plasticity A from 62% to 3%.

2. The high mechanical properties of the investigated cold rolled steel determined the structure of elongated austenite grains with martensite α’ phase with a microhardness 460HV, resulting from the transformation of the induced plasticity.
3. The fraction of the martensite α’ phase in the structure of X5CrNi18-8 steel depends on the degree of plastic deformation. Deformation within the range from 33% to 78% leads to an increase from 16% to 42% part quantitative martensite α’ phase in structure of the investigated steel.
4. The investigated X5CrNi18-8 steel in the supersaturated state shows ductile fracture, which on draft about 30% changes in the mixed fracture with large areas of brittle cracking and small ductile areas.

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