# The influence of chemical composition on structure and mechanical properties of austenitic Cr-Ni steels

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**Materials**

## ABSTRACT

**Purpose:** The aim of the paper is to investigated the influence of the chemical composition on the structure and mechanical properties of austenitic Cr-Ni steels. Special attention was put on the effect of solution heat treatment on mechanical properties of examined steels.

**Design/methodology/approach:** The examinations of static tensile tests were conducted on ZWICK 100N5A. Hardness measurements were made by Vickers method. The X-ray analyzes were realized with the use of Dron 2.0 diffractometer equipped with the lamp of the cobalt anode. The metallographic observations were carried out on LEICA MEF 4A light microscope.

**Findings:** Results shown that after solution heat treatment the values of strength properties (UTS, YS0.2) and hardness (HV) of both investigated steels decrease and their elongation (EL) increases. The X5CrNi18-8 steel in delivery state shown austenitic microstructure with twins and numerous non-metallic inclusions, while in steel X10CrNi18-8 revealed a austenitic microstructure with numerous slip bands in areas with deformation martensite α'. The examined steels after solution heat treatment followed by water-cooling has the structure of austenite.

**Research limitations/implications:** To investigate in more detail the influence of chemical composition on structure and mechanical properties the examinations of substructure by TEM should be conducted.

**Originality/value:** The relationship between the solution heat treatment, structure and mechanical properties of investigated steels was specified.

**Keywords:** Austenitic steel; Chemical composition; Mechanical properties; Static tensile test; X-ray analysis

## 1. Introduction

Austenitic Cr-Ni stainless steels possess many favorable mechanical properties, including high strength, good ductility, excellent corrosion resistance and a reasonable weldability. Consequently, these materials have found widespread application under both low and high loading rate conditions in a diverse range of Fields [1-3].

Austenitic steels have a large application in production of tank containers, pressure pipes for liquid and gaseous nitrogen, and also for high strength and ductile fine wires.

Their continuing development has resulted in complex steel compositions with substantial amounts of alloying elements. These alloying elements are of course introduced in the steel for one or more reasons but the final aim is mainly to obtain better mechanical properties (especially high creep strength and high creep-rupture ductility) and/or higher corrosion resistance (especially oxidation resistance in the case of high temperature application) [4-6].

Alloying elements can be found in the free state; as intermetallic compound with iron or with each other; as oxides, sulfides, and other nonmetal inclusions; in the form of carbides; or as a solution in iron As to the character of their distribution in steel, alloying elements may be divided into two groups:

- Elements that do not form carbides in steel (e.g. Ni, Si, Co, Al, Cu and N)
- Elements that form stable carbides in steel (e.g. Cr, Mn, Mo, W, V, Ti, Zr, and Nb).

Chromium (16-28%wt) is the most important alloying element in Cr-Ni stainless steels. It is this element that gives their basic corrosion resistance. The corrosion resistance increases with increasing chromium content. It also increases the resistance to oxidation at high temperatures [3].

The main reason for the Ni addition (3,5-32%wt.) is to promote an austenitic structure. Nickel generally increases ductility and toughness. It also reduces the corrosion rate and is thus advantageous in acid environments [7-9].

The Mn addition (2-6%wt.), near to the small contents of carbon (usually below 0.1%wt.), allow for obtaining the stable austenitic structure at the room temperature.

Moreover these steel can contain such elements as molybdenum (2-6%wt.), which substantially increases the resistance to both general and localized corrosion. It reduces the intensity of the oxidizing effect required to insule passivity and decrease the tendency of previously formed passive films to break down.

In austenitic Cr-Ni steels the important addition is titanium, because of increasing the resistance to intergranular corrosion. It also increases the mechanical properties at high temperatures [10].

Nitrogen is a very strong austenite former and strongly promotes an austenitic structure. It also substantially increases the mechanical strength. Nitrogen affect on the resistance to localized corrosion, especially in combination with molybdenum [8].

In investigated steels, the strengthening mechanisms are based on the precipitation of fine dispersed carbide (NbC). In this steels, as far as corrosion resistance is concerned, it is well known that stabilising the grade by Nb additions prevents the risk of intergranual corrosion in heat affected zones. To prevent this the niobium is added in sufficient amounts, depending on the carbon and nitrogen levels [5-9].

Mechanical properties of Cr-Ni austenitic steel strongly depend of their microstructure which is controlled by phase transformation, precipitation or recrystallization. The yield strength of austenitic stainless steels can be increased by cold working. The microstructure of the austenitic stainless steels consists of metastable austenite phase, which may be transformed to strain-induced martensite phase during deformation of the steel. Two types of martensite phases can be formed: $\varepsilon$-martensite (hexagonal close-paced, paramagnetic phase) or $\alpha'$-martensite (body-centered tetragonal, ferromagnetic phase). The amount of $\alpha'$ and $\varepsilon$ martensite is controlled by following parameters:

temperatures - $M_s$ and $M_{d30}$ and stacking fault energy (SFE) of the steel [11-12].

Several empirical equations have been determined to calculate the values of $M_s$ and $M_{d30}$ and SFE. The Equation 1 formulated by Eichelman and Hull [13] gives an approximation the temperature of $\alpha'$ martensite formation ($M_s$). This temperature is strongly connected with the chemical composition of the alloy and for all 300 austenitic stainless steels, it can be calculated by the formula:

$$M_s \ (°C) = 502 - 810(\% \ C) - 1230(\% \ N) - 13(\% \ Mn) - 30(\% \ Ni) - 12(\% \ Cr) - 54(\% \ Cu) - 6(\% \ Mo) \tag{1}$$

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

The dependence of temperature $M_{d30}$ with a composition of cold rolled 18-8, 18-12 and 18-12-Ti austenitic grades formulated by Angel [14] (eq.2):

$$M_{d30}(°C) = 497 - 462(\% \ [C + N]) - 9.2(\% \ Si) - 8.1(\% \ Mn) - 13.7(\% \ Cr) - 20(\% \ Ni) - 18.5(\% \ Mo) \tag{2}$$

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 [15,16] such as (eq.3):

$$SFE \ (mJ/m^2) = -53 + 6.2(\% Ni) + 0.7(\% Cr) + 3.2(\% Mn) + 9.3 \ (\% Mo) \tag{3}$$

The aim of these investigations is to determine the influence of the chemical composition on the structure and mechanical properties of austenitic Cr-Ni steels.

## 2. Experimental procedure

The investigation were carried out on two industrially manufactured austenitic steel grade X5CrNi18-8 and X10CrNi18-8, with a chemical composition given in Table 1. The materials used for the investigations was delivered in the form of 2-mm thick sheet and was solution heat treated at the temperature 1100°C for 1 hour and then cooled down in water. Heat treatment was realized in an electric furnace chamber, which was equipped in temperature regulator with an accuracy of ±2°C. After heat treatment the sheets were sampled for research of the mechanical properties, for microhardness measurements, metallographic observations and the X-ray phase analysis.

Based on the chemical composition of the investigated steels the value of the stacking fault energy of the austenitic $\gamma$-phase SFE were calculated. The SFE of steel X5CrNi18-8 is about 15.82 $(mJ/m^2)$ and the steel X10CrNi18-8 is on the level 14.33 $(mJ/m^2)$.

The mechanical properties of investigated steels were determined applying static tensile test and measurements of the hardness.

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 according to EN ISO 6892-1: 2009 [17]. The dimension and shape of the samples used in tensile test is presented in Fig. 1.

Table 1.
Chemical composition of the investigated steels

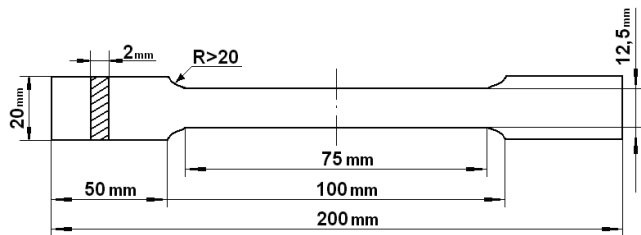| Grade of steel | Kind of analysis | Mass contents in percentage (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Mn | Si | P | S | Cr | Ni | N | Mo |
| X5CrNi18-8 | ladle analysis | 0.047 | 1.120 | 0.42 | 0.028 | 0.006 | 18.35 | 8.06 | 0.06 | 0.28 |
| X10CrNi18-8 | | 0.810 | 0.919 | 0.39 | 0.042 | 0.006 | 18.21 | 8.33 | - | - |

Fig. 1. The dimension and shape samples used in tensile tests [17]

The hardness measurements of the analyzed steels were carried out by a hardness tester PMT-3 produced by Hauser, according to the standard PN-EN ISO 6507-1:2007 [18]. Researches were made by Vickers's method on metallographic samples with a load of 50g.

Microstructure observations of the specimens etched in Adler reagent [19] were carried out on LEICA MEF 4A light microscope, with magnifications 200x.

The X-ray tests were realized with the use of Dron 2.0 diffractometer equipped with the lamp of the cobalt anode ($\lambda CoK_{\alpha}$ = 0.17889 nm) of 40 kV voltage and 20 mA filament current was used. Diffraction tests were carried out in the $2\Theta$ angle range from 20 to 90° (measurement step 0.05°). Pulse counting time was 4s. The obtained diffractions patterns were analyzed applying the PCPDFWIN program.

# 3. Results and discussion

The metallographic investigations permit to assess the steel structure of two austenitic steels grade X5CrNi18-8 and X10CrNi18-8 in the delivery and supersaturation state. The results of metallographic observations have been presented on microphotos (Figs. 2-3).

The structure of the investigated X5CrNi18-8 steel in the delivery state characterized austenite grains with annealing twins and some non-metallic inclusions (Fig. 2a). In the delivery state the structure of X5CrNi18-8 steel does not show the metallographic symptom of deformation. However, in X10CrNi18-8 steel in delivery state besides the austenite grains, twins and numerous slip band inside the grains of γ phase, the areas of α' martensite were observed. Austenite grains characterized with some deformation (Fig. 2b).

After solution heat treatment at 1100°C the examined steels has the austenitic single-phase structure (Fig. 3a,b).

The results of the mechanical properties of investigated steels in delivery and solution heat treatment state are presented in the Tables 2 and 3. On the basis of the realized tensile tests the tensile strength UTS and yield point $YS_{0.2}$ were determined, additionally the measurements of the hardness were carried out.

Steel X10CrNi18-8 in the delivery state is characterized by high value of strength properties (UTS, $YS_{0.2}$) and hardness as well as very low elongation (EL), in comparison to steel X5CrNi18-8 in the same condition.
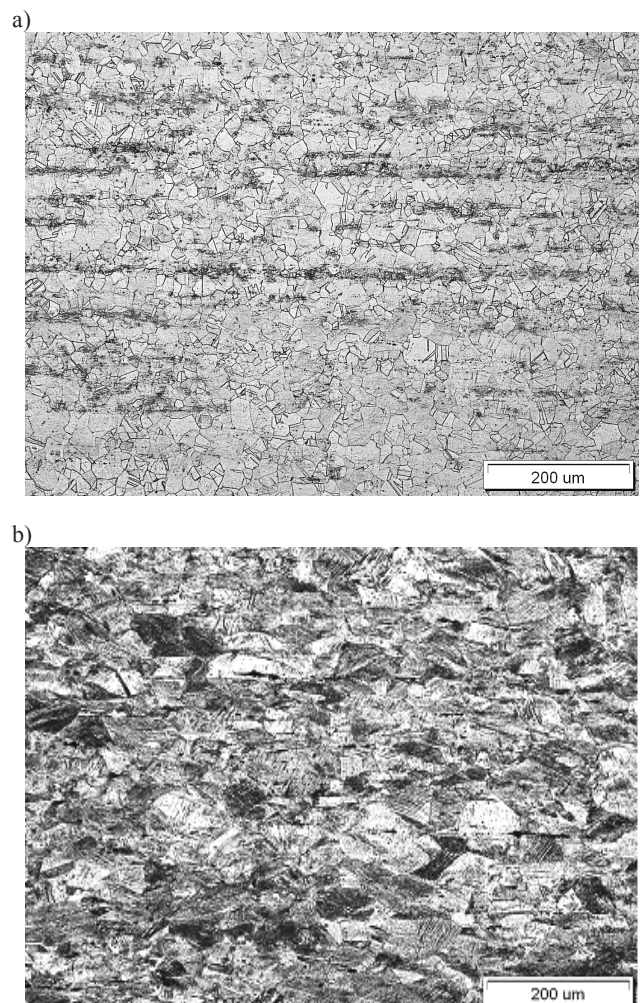
a)



b)



Fig. 2. Structure of the investigated steels in the delivery state: a) Steel X5CrNi18-8, b) Steel X10CrNi-18-8, Etching- Adler
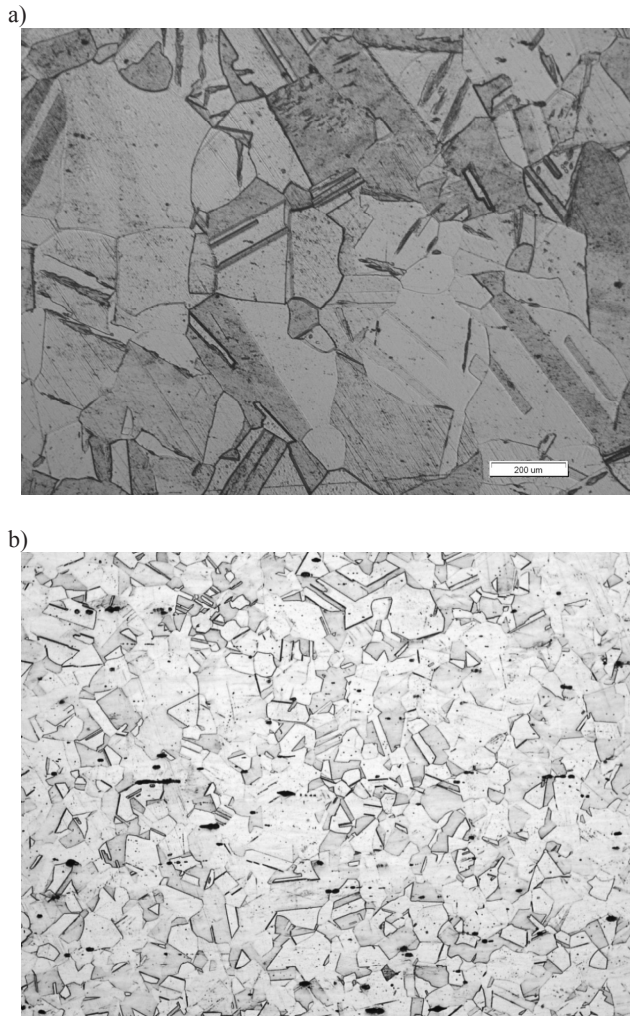
a)



b)



Fig. 3. Structure of the investigated steels after solutioning heat treatment at 1100°C: a) Steel X5CrNi18-8, b) Steel X10CrNi-18-8, Etching- Adler
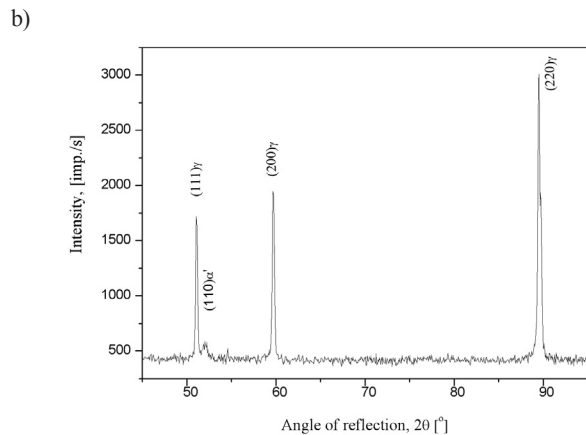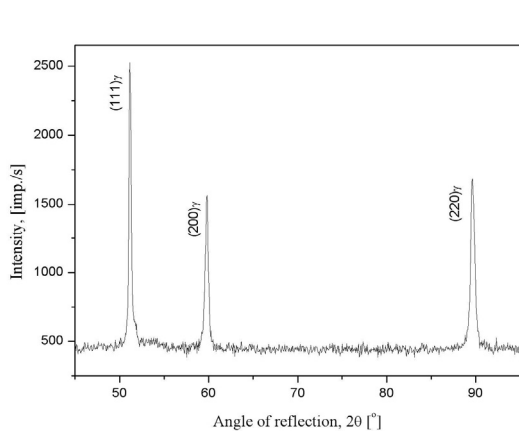
The tensile strength of X10CrNi18-8 steel in the delivery state is about 1327 MPa, the yield point is about 1287 MPa, the Vickers hardness is about 392 HV and the elongation is only 1.48% (Table 2). However, steel X5CrNi18-8 in the same state shows lower values of UTS = 630 MPa, $YS_{0.2}$ = 302 MPa, HV = 160 MPa and higher value of EL = 53% (Table 2).

In the samples of both steels after solution heat treatment at 1100°C no significant difference was stated in the value of mechanical properties and hardness, but it should be note that steel X10CrNi18-8 show much lower values of elongation in opposite to steel X5CrNi18-8 (Table 3). Solution heat treatment removes the strain hardening of the material in delivery state and provides single-phase austenitic structure, so the strength properties of investigated steels were decreased.

On the basis of examinations of the mechanical properties it was found that in the delivery state the X10CrNi18-8 steel is strengthened, possibly by the presence of martensite α' phase in its structure.

Table 2.
Mechanical properties and microhardness of investigated steels in delivery state

| Grade of steel | Mechanical properties | | | |
|---|---|---|---|---|
| | $\overline{UTS}$ MPa | $\overline{YS_{0.2}}$ MPa | $\overline{EL}$ % | $\overline{HV}$ |
| X5CrNi18-8 | 630 | 302 | 53 | 160 |
| X10CrNi18-8 | 1327 | 1287 | 1.48 | 392 |

Table 3.
Mechanical properties and microhardness of investigated steels after solution heat treatment at 1100°C

| Grade of steel | Mechanical properties | | | |
|---|---|---|---|---|
| | $\overline{UTS}$ MPa | $\overline{YS_{0.2}}$ MPa | $\overline{EL}$ % | $\overline{HV}$ |
| X5CrNi18-8 | 510 | 250 | 61 | 145 |
| X10CrNi18-8 | 670 | 360 | 23 | 203 |

a)



b)



Fig. 4. X-ray diffraction patterns of investigated steels in the delivery state: a) steel X5CrNi18-8, b) steel X10CrNi18-8

Table 4.
Results of the X-ray phase analysis of the analysed steels in delivery state

| Grade of steel | N° | Experimental | | | Identification (ICDD) | | | |
|---|---|---|---|---|---|---|---|---|
| | | Angle of reflection [°2Θ] | Interplanar distance d [Å] | Intensity $I/I_{max}$ [%] | Interplanar distance $d_{hkl}$ [Å] | Intensity [%] | (hkl) | Phase |
| X5CrNi18-8 | 1 | 51.1621 | 2.0716 | 100 | 2.0750 | 100 | 111 | γ |
| | 2 | 59.8128 | 1.7940 | 62 | 1.7961 | 45 | 200 | γ |
| | 3 | 89.5896 | 1.2695 | 66 | 1.2697 | 26 | 220 | γ |
| X10CrNi18-8 | 1 | 51.1681 | 2.0715 | 57 | 2.0750 | 100 | 111 | γ |
| | 2 | 52.0086 | 2.0403 | 19 | 2.0268 | 100 | 110 | α' |
| | 3 | 59.5851 | 1.8003 | 65 | 1.7961 | 45 | 200 | γ |
| | 4 | 89.4978 | 1.2705 | 100 | 1.2697 | 26 | 220 | γ |

The X-ray investigation allowed to identify the phase composition of analysed steels in the delivery state and after solution heat treatment. The results obtained for samples in the delivery state are presented in Fig. 4 a,b and Table 4.

The results of diffraction patterns of phase analysis of steel X5CrNi18-8 revealed the presence only of austenite (γ-phase), while in the steel X10CrNi18-8 the α'-martensite too occur. On diffraction patterns of X10CrNi18-8 steel in the delivered state disclosed diffraction lines coming from planes (111), (200), (220) austenite phase and (110) α'-martensite phase (Fig. 4b).

Diffraction lines (111)γ, (110)α' analysis phases of the X10CrNi18-8 steel in delivery state shows distinct texturing. Perhaps, the presence of α' phase in delivery state of X10CrNi18-8 steel results from the pretreatment of material, which causes eutectoid changes of the γ phase.

Investigated steels after solution heat treatment at 1100°C exhibits pure austenitic structure

## 4. Conclusions

The analysis of the obtained results of investigated austenitic Cr-Ni steel allowed to formulate the following statements:

- In the delivery state the X5CrNi18-8 steel structure disclose a typical grains of γ solution with twins and non-metallic inclusions, ensuring the following mechanical properties: tensile strength UTS about 630 MPa, yield strength $YS_{0.2}$ about 302 MPa and hardness about 160.
- The high strength properties of the X10CrNi18-8 steel in delivery state determined the structure of slightly elongated austenite grains with martensite α' phase and numerous slip band inside the grains of γ phase. The tensile strength is about 1327 MPa, the yield strength is about 1287 MPa and hardness is about 392.
- The solution heat treatment at 1100°C of investigated steel causes significant decrease of strength properties and meaningful increase of plasticity.
- X-ray investigations of X10CrNi18-8 steel in delivery state confirmed the occurrence of α' martensite in the steel structure. α' phases were detected on diffraction patterns on the basis of the diffraction lines according to identifications

from (110)α' reflection planes, which occurred with matrix lines γ from (111)γ, (200)γ and (220)γ reflection planes.
- Phase analysis of the X5CrNi18-8 steel in delivery state didn't disclose the diffraction lines coming from the α' martensite phase. Perhaps, the presence of α' phase in delivery state of X10CrNi18-8 steel results from the pretreatment of material, which causes eutectoid changes of the γ phase.

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