ANALYSIS OF THE AUSTENITIC STAINLESS STEEL'S r-VALUE BEHAVIOR AT ELEVATED TEMPERATURES

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Resume

An analysis of the anisotropy properties of austenitic steel AISI 304 (X5CrNi18-10) at elevated temperatures is presented in this paper. Considerations of the anisotropy problems are presented in the theoretical part of the paper, as well as the procedure for determination of the normal anisotropy coefficient. The experimental part of the paper describes the plan, methodology and equipment for testing of material's normal anisotropy and mechanical characteristics. The objective of conducting the experiments was to investigate influence of temperature on normal anisotropy, as well as on the mechanical properties of the considered material. The normal anisotropy was monitored by the coefficient – the so-called "r-value". Besides that, the tensile strength, yield stress and elongation at break were monitored, also. The tests were done on the 0.7 mm thick sheet metal within the temperature range 20 to 700 °C.

Available online: http://fstroj.uniza.sk/journal-mi/PDF/2015/08-2015.pdf

1. Introduction

The subject of this work is experimental investigation of the normal anisotropy coefficient of austenitic steel AISI 304 at elevated temperatures. Taking into account that the stainless steels are characterized by relatively high value of strength, subsequently the large deformation force is necessary for piece forming; those steels must be heated to reduce their deformation resistance. The aim of investigations conducted in this paper was to study the change of the mechanical properties, especially the normal anisotropy coefficient of the AISI 304 steel, at elevated temperatures.

The normal anisotropy represents unevenness of material properties over its thickness with respect to properties within the thin sheet plane. It is expressed by the coefficient of the normal anisotropy – or the r-value, which shows the resistance of the thin sheet at gainst thinning. The value of this coefficient is influenced by the in-plane anisotropy, as well. Thus, some materials exhibit the best characteristics in the direction of the thin sheet rolling (0°), some in the direction perpendicular to the rolling direction (90°) and some even in the direction at certain angle to the rolling direction (45°) [1, 2]. Therefore, the low-carbon steel's thin sheet DC 04 has higher values of the r-value in directions at 0° and 90°. On the contrary, the aluminum alloy AlMg4.5Mn0.7 and austenitic and ferritic stainless steels AISI 304 and AISI 430, exhibit maximum of the r-value in the direction of 45° with respect to the rolling direction. Obtained results are presented in Fig. 1.
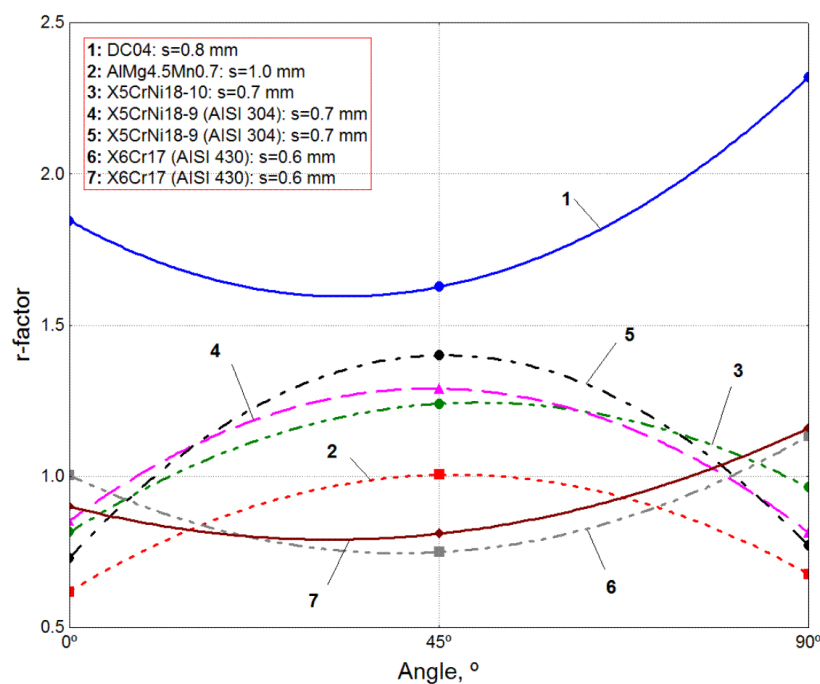
Fig. 1. Variation of the r-value in terms of the in-plane angle for several materials.
(full colour version available online)

The normal anisotropy coefficient is significant, especially in thin sheets aimed for plastic forming. Though the r-value was previously mainly investigated for steels, today other materials are also tested. Thus, authors of paper [2] were dealing with investigation of the anisotropy properties in aluminum alloys, while authors of the works [3, 4] were investigating influence of thin sheet manufacturing on change of the anisotropy properties of magnesium alloys, both at room and elevated temperatures. Properties of anisotropy of molybdenum thin sheets were investigated as well in [5], i.e., the influence of temperature on change of mechanical properties and anisotropy. Conclusions of all those authors were that temperature does not impose strong influence on the r-value, but that it does strongly affect tensile strength and the yield stress. In addition, authors [6 - 8] were dealing with investigation of the normal anisotropy coefficient of thin sheets used in the automobile industry. For the r-value determination, they applied corresponding software and presented influence of the anisotropy variation on formability of the tested materials.

As it was already mentioned earlier, unlike the majority of steels, where $r_{max} = r_0$, for brass and aluminum, the maximum value of the r-value is achieved at an angle of 45° ($r_{max} = r_{45}$). In Fig. 1 are shown curves that illustrate the mentioned difference in the r-value depending on material and angle at which the samples are cut-out. The presented diagram of the r-value, in terms of the samples' in-plane cutting out direction (0º, 45º, 90º), was obtained based on experimental investigations of other authors [1]. The diagram confirms the fact that the low carbon steel thin sheet is the optimal material for plastic forming, where the best characteristics of the r-value are exhibited in the rolling direction and in direction perpendicular to it (90°). Results obtained for testing of the ferrite stainless steel [6, 7] show that those thin sheets behave in the same way as the low carbon sheets, but with significantly lower r-values. It was also confirmed that the non-ferrous (colored) metals (e.g. Al) and austenitic stainless steels behave similarly. They reach the maximum of the r-value at an angle of 45º with respect to the sheet's rolling direction. Stainless steels [3 - 5] have exhibited somewhat better properties with respect to the Al alloy [2].

2. Theoretical considerations – determination of the r-value for different materials

It is known that anisotropy can be defined as unevenness, namely diversity over the volume, of material properties and characteristics depending on direction. This means that properties and characteristics of material defined for one or several directions are significantly different from the same characteristics for other directions. In real conditions, it is very difficult to eliminate anisotropy, it is always present to the lesser or greater extent. Anisotropy of thin sheets can be generally considered in two ways: as anisotropy within the thin sheet's plane (planar), which refers to change in properties and characteristics depending on directions in-plane and as the normal anisotropy, which refers to changes of properties over the thickness, with respect to the in-plane properties.

One of the most used indicators of the thin sheet's anisotropy is the so-called coefficient of the normal anisotropy – the r-value. Determination of the anisotropy characteristics is of practical importance when material is tested by the uniaxial tensile test of samples cut out from the thin sheet's plane in directions at certain angle with respect to the rolling direction. If the assumption was adopted that the x-axis coincides with the sheet's rolling direction, the y-axis is perpendicular to that direction within the sheet's plane, while the z-axis is perpendicular to the sheet's plane, then those axes are the anisotropy axes and simultaneously the principal axes (Fig. 2) [2].

Definition of the normal anisotropy coefficient (the r-value) for determination by uniaxial tension is given as [1, 9, 12]:

$$r = \frac{\phi_b}{\phi_s} = \frac{\int_{b_0}^{b}\frac{db}{b}}{\int_{s_0}^{s}\frac{ds}{s}} = \frac{\ln\frac{b}{b_0}}{\ln\frac{s}{s_0}} = \frac{\ln\frac{b_0}{b}}{\ln\frac{s_0}{s}} = \frac{\log\frac{b_0}{b}}{\log\frac{s_0}{s}} \quad (1)$$

where: ϕ_b – natural (logarithmic) deformation over the thin sheet sample's width (b), ϕ_s – natural deformation over the thin sheet sample's thickness (s). By introducing the hypothesis of the volume constancy ($l_0 \cdot b_0 \cdot s_0 = l \cdot b \cdot s = const.$), expression (1) can be transformed into the more convenient form, which will be used in the experimental part of the work:

$$r = \frac{\ln\frac{b}{b_0}}{\ln\frac{l_0 b_0}{lb}} = \frac{\log\frac{b}{b_0}}{\log\frac{l_0 b_0}{lb}} = \frac{\ln\frac{b_0}{b}}{\ln\frac{lb}{l_0 b_0}} \quad (2)$$

where: b_0 and b – is the sample's width before and after tension, respectively; l_0 and l – is the sample's initial and final length, respectively.
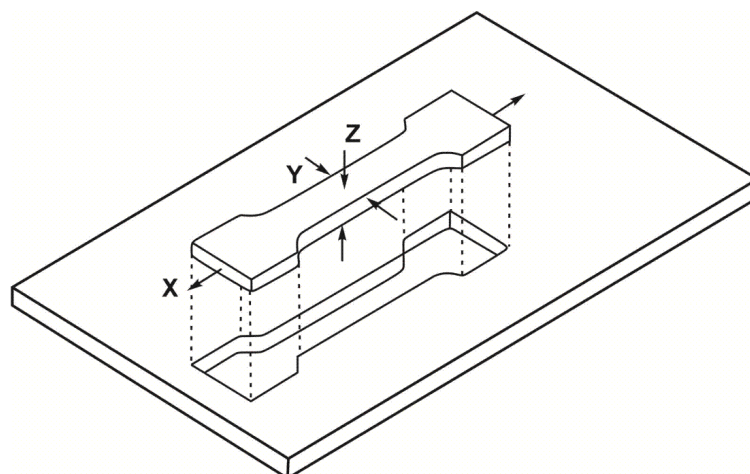

Fig. 2. Cutting out the sample in the thin sheet's rolling direction (x).

Table 1

Review of the r-value values.

r = 0.5 – 1 (r < 1)	very poor machinability
r = 1 – 1.2	poor machinability
r = 1.2 – 1.5	good (medium) machinability
r = 1.5 – 1.8	very good machinability
r > 1.8	exceptionally good machinability

Table 2

Chemical composition of AISI 304 (X5CrNi18-10) steel.

Alloying element	C	Si	Mn	P	S	Cr	N	Ni
Content (%)	0.07	1.00	2.00	0.045	0.030	17 - 19.5	0.110	8 - 10.5

Considering the accuracy in determination of the r-value, it is preferable that the final deformations of length and width be as large as possible. The sample's tension is stopped within the area of homogeneous deformation, somewhat prior to reaching the maximum force (usually denoted as point M at the tension diagram). That is usually 1 to 3 % less than the expected percentage elongation at point M. Elongation value at maximum tensile force for majority of low carbon steel thin sheets for car's body amounts to 20 % [1], while for the other thin sheets those values could be significantly higher. In Table 1 are presented values of the r-value and expected materials' machinability corresponding to those values or range of values of the r-value, obtained in previous investigations [1].

3. Experimental investigations. Equipment, experiment plan, samples

Determination of the normal anisotropy coefficient at room and elevated temperatures for thin sheets made of austenitic stainless steel AISI 304 (X5CrNi18-10) with thickness 0.7 mm was the objective of the experiment. That steel belongs into a group of highly alloyed steels that contain over 17 % of Cr and 8 % of Ni (Table 2). It is the standard austenitic stainless steel, which is widely applied in different branches of industry, due to its favorable properties and other advantages. It is also characterized by good corrosion resistance, favorable machinability by plastic forming and nice surface appearance.

Influence of elevated temperatures on mechanical properties of this material is known. Results of some of the previous investigations are given in Table 3. Optimal characteristics of the AISI 304 steel are achieved after quenching from the austenitic region, in water or in the strong air stream, with temperatures 1000 to 1120 °C. There, the special attention should be paid to time for which it is kept within the temperature range 450 to 850 °C, since this steel is prone to forming the special chromium carbides.

Experimental plan (Fig. 3) predicted that the samples testing should be done at room and elevated temperatures. The standard samples were tested (Fig. 4); the temperature range was 20 to 700 °C; the planned number of samples was 18. Testing was done on the computer-controlled machine for mechanical testing ZWICK/Roell Z 100. A special chamber, which is mounted to the machine, was used for samples heating (Fig. 5a). Samples were cut out from thin sheets in the rolling direction (0°), Fig. 2.

It is useful to present the mounting system for sample clamping in the machine's jaws (Fig. 5b). Since, it is not possible to perform the pneumatic clamping over the flat surfaces at elevated temperatures; it had to be done in a special way. Considering the strength of the tested material and the limited space in the heating chamber, there was a problem

of sample clamping due to sliding in the jaws.

The problem was resolved by an original design solution presented in Fig. 5b. In that way the larger values of the clamping force were ensured and the more reliable mounting of the sample was enabled.

Mechanical characteristics of the AISI 304 steel at lower and elevated temperatures [10, 11, 13].

Temperature (°C)	Tensile strength R_m (MPa)	Yield stress $R_{p0.2}$ (MPa)	Elongation A (%)
-196	1620	386	40
-62	1110	345	57
-40	1000	331	60
0	841	296	65
21 (room)	**586**	**241**	**55**
204	496	159	51
316	469	134	45
427	441	114	40
538	386	97	36
649	303	88	34
760	200	76	36
871	110	-	40
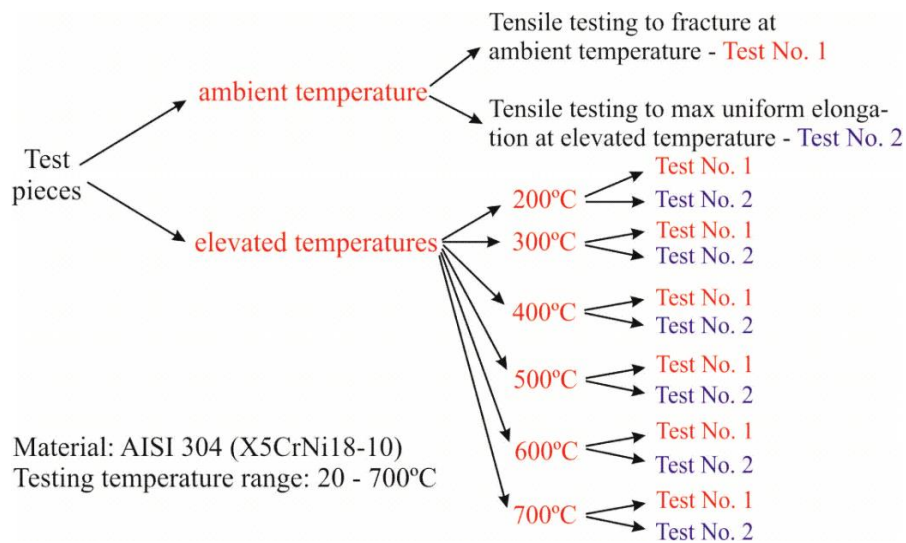
Fig. 3. Schematic presentation of the experiment plan.
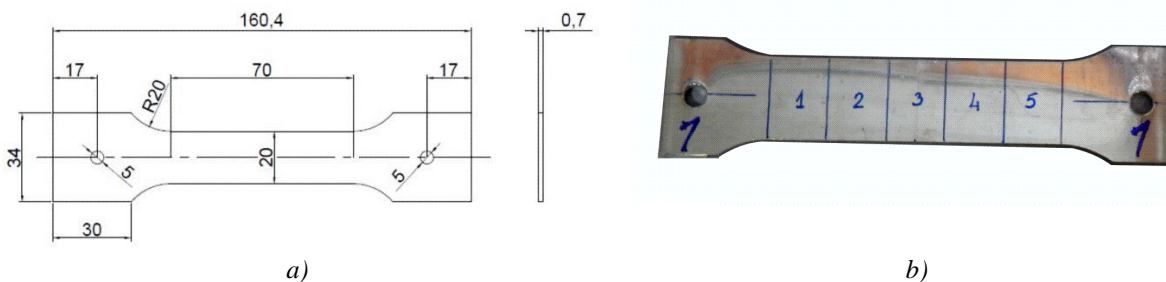*(full colour version available online)*

a)   *b)*
Fig. 4. Thin sheet sample: a) Technical drawing; b) Physical appearance.
(full colour version available online)

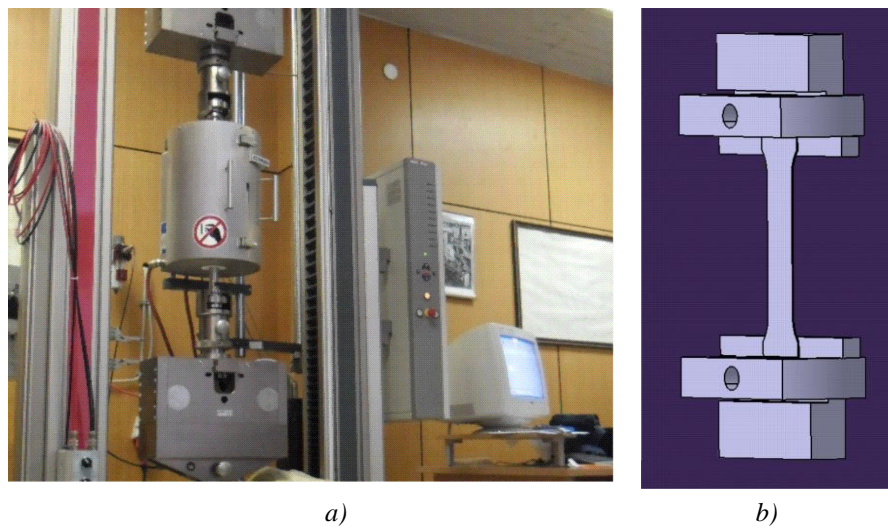*a)*   *b)*

Fig. 5. a) Heating chamber; b) Sample in jaws immediately prior to clamping.
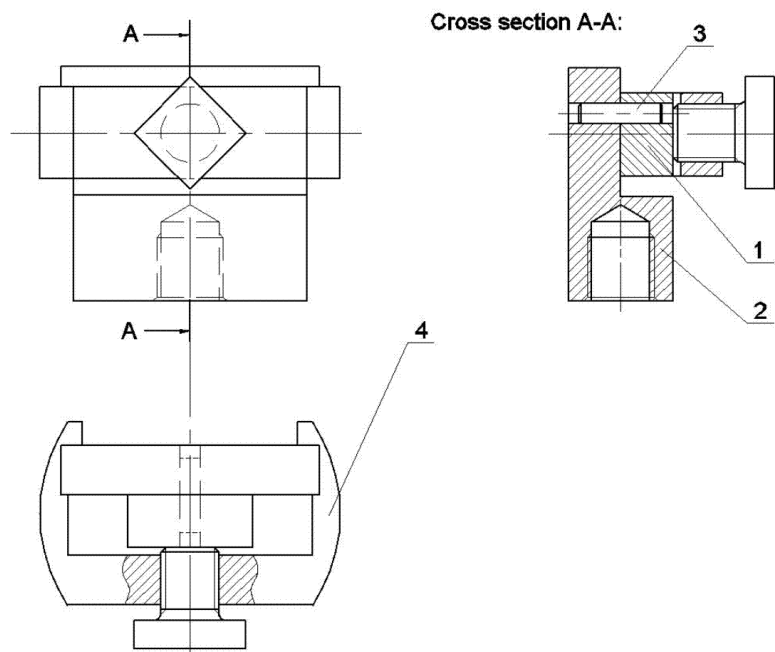*(full colour version available online)*

Fig. 6. Technical drawing of the element for samples clamping.

Technical drawing of the clamping element assembly is presented in Fig. 6. The sample is placed on the pin (3) between the holder (2) and the platelet (1) and then it is clamped by the fork and screw.

4. Experimental results

Obtained experimental results are presented in forms of tables and diagrams. In Table 4 are shown results obtained by testing of 10 samples, while in Figures 7 and 8 are shown the tension diagrams of the thin sheet samples tested at room and elevated temperatures. For samples tested at 20 and 700 °C, the tension process was stopped at 35 % and 15 %, respectively, so that samples would remain in the region of the material homogeneous deformation. This is done so that results obtained in this way would be relevant for calculation of the r-value. The samples' appearances after tests are presented in Fig. 9.

Table 4

Experimental results obtained by tension test at room and elevated temperatures.

Sample #	Testing temperature (°C)	S_0 (mm²)	L_0 (mm)	$R_{p0.2}$ (MPa)	R_m (MPa)	A_g (%)	A (%)
1	20	14.07	70.10	247.85	610.37	57.63	63.31
2		14.07	70.10	251.92	585.17	48.90	-
3	200	14.07	70.10	202.54	459.16	36.64	45.66
4	300	14.07	71.10	182.80	391.13	18.98	28.47
5	400	14.07	71.10	164.84	349.49	16.77	19.57
6		14.07	71.10	160.13	371.90	20.58	23.83
7	500	14.07	71.10	150.17	366.48	20.42	24.44
8	600	14.07	71.10	140.86	360.32	20.23	22.50
9	700	14.07	71.10	137.06	316.34	25.11	30.72
10		14.07	71.10	132.29	308.28	20.88	-

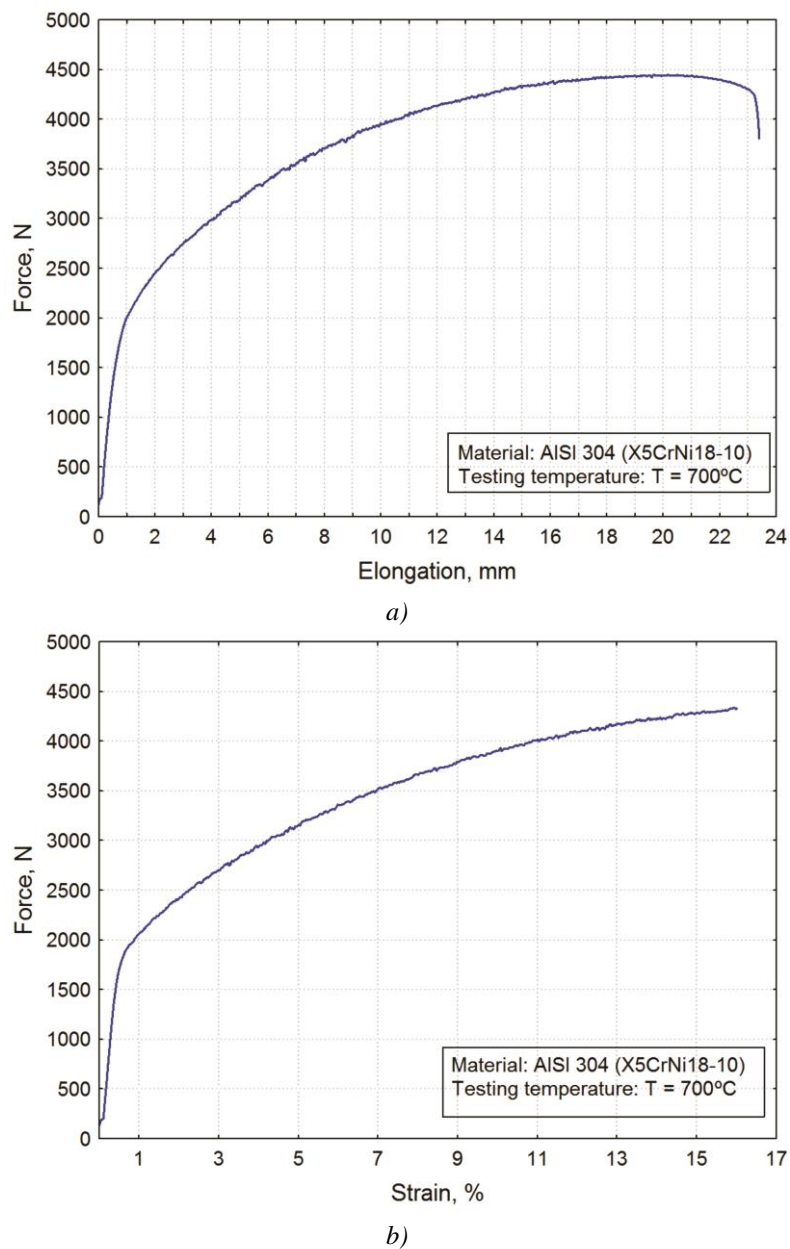*Shaded fields represent results shown in diagrams in Fig. 7 and 8.*
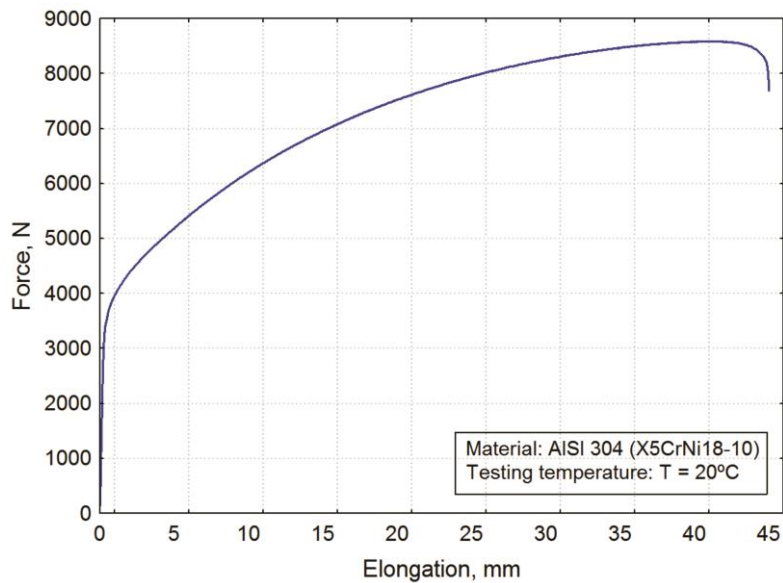
a)
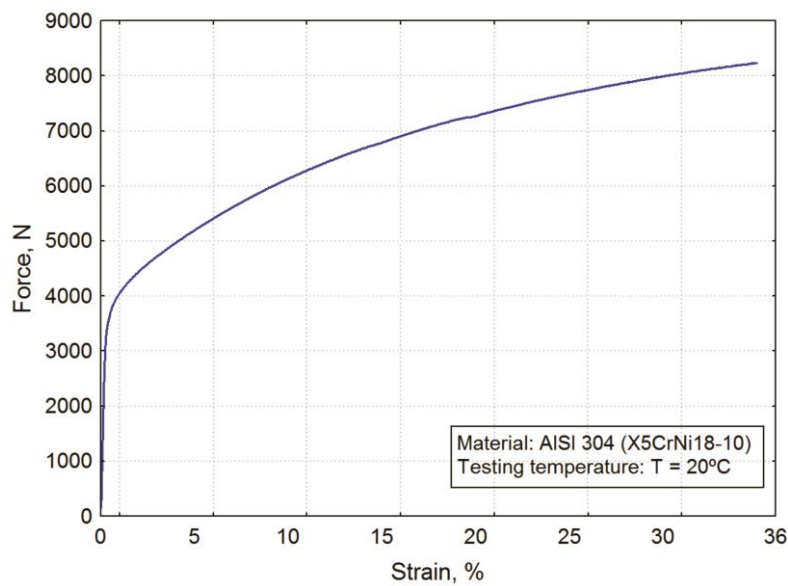
b)

Fig. 7. Tension diagrams at 20 °C: a) Tension diagram; b) The r-value determination
(tension stopped at 35 % of the sample's elongation); absolute sample's elongation was Δl ≈ 26.5 mm.

a)

b)

Fig. 8. Tension diagrams at 700 ℃: a) Tension diagram; b) The r-value determination
(tension stopped at 15 % of the sample's elongation); absolute sample's elongation was Δl ≈ 11.2 mm.
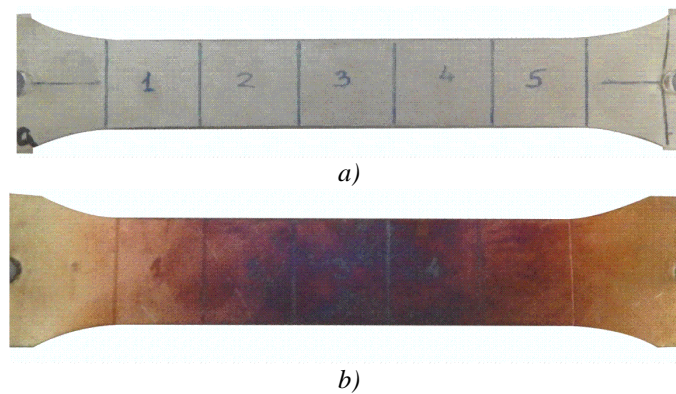

a)

b)

Fig. 9. Appearance of samples subjected to tension within the region of homogeneous deformation:
a) 35 % of sample's elongation – T = 20 ℃; b) 15 % of sample's elongation – T = 700 ℃.
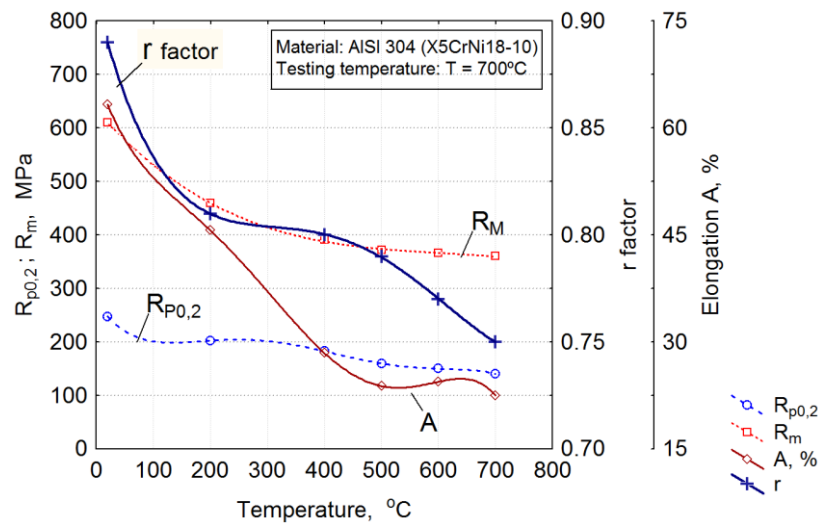*(full colour version available online)*

Fig.10. Diagram of the r-value, yield stress, tensile strength and elongation variation with temperature [14].
(full colour version available online)

Table 5

Experimental results of the r-value calculated based on expression (2).

Temperature (ºC)	20	200	400	500	600	700
r-value	0.889	0.811	0.797	0.793	0.768	0.752

In Fig. 10 is presented a diagram of the most important material mechanical properties ($R_{p0,2}$ and R_m) variation with temperature increase. By analyzing this diagram, one can conclude that with temperature increase, as expected, the decrease of material mechanical properties occurs. However, one can also notice that the deformation properties are also decreasing, more precisely, the elongation at tearing. That points to the fact that this material has better plasticity at room temperature than at elevated temperatures.

It should also be emphasized that during the tensile test the local deformation was occurring in the area of the hole on the specimen. This was especially influenced by irregularities in preparation of the sample. Those problems did not appear in any of the cases where the axis of the hole coincided with the longitudinal sample axis.

As already stressed, the objective of performing the experiments was to determine the value of the normal anisotropy coefficient at room and elevated temperatures of the thin sheets made of stainless steels. Characteristic values of width (*b*) and length (*l*) were measured on tested samples (Fig. 4b). Width was measured at 6 points. Then, the r-value was calculated according to expression (2). Obtained values are shown in Table 5 and in Fig. 11.

Through analysis of obtained results one can conclude that up to temperature of 300 °C the intensive decrease of the tensile strength was noticed, as well as decrease of the yield stress, with somewhat less intensity (Fig. 10). What concerns the r-value of the AISI 304 (X5CrNi18-10) steel, it can be seen that the anisotropy coefficient is dropping at elevated temperatures.

That drop is the most prominent in the range from 200 to 300 °C, but the trend of decreasing is maintained (Fig. 11). The r-value has dropped for 0.14 (in absolute amount), namely from value 0.89 at 20 ºC to 0.75 at 700 ºC.
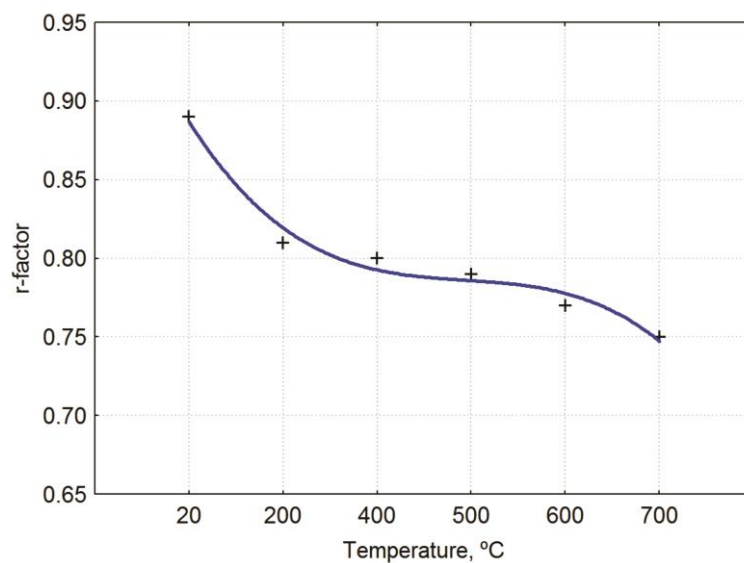
Fig. 11. Diagram of the r-value variation with temperature.

5. Conclusion

Anisotropy represents the very important material property, especially in the case of thin sheets forming. The normal anisotropy coefficient is monitored with respect to the rolling direction (0º, 45º, 90º), since certain materials exhibit different properties in different directions. For instance, the low carbon steels possess the best properties in the rolling direction, while the stainless steels and some colored metals have the best material in direction at 45° to the rolling direction.

The objective of this work was to investigate the variation of the normal anisotropy coefficient of thin sheets, made of stainless steel AISI 304, at elevated temperatures. Experiments were conducted on 7 samples within temperature range 20 to 700 °C. The primary goal was to monitor the normal anisotropy coefficient – the r-value, but the behavior of mechanical properties of material was monitored, as well.

Analysis of obtained experimental results provided the conclusion that the r-value is dropping at elevated temperatures, namely during the forming the thin sheet is more deforming in the thickness direction (thinning) than in the sheet's plane. The drop of the r-value was not large from 0.89 at 20 °C to 0.75 at 700 °C (15.7 %). The decrease of the most important material's mechanical properties (the tensile strength and yield stress) was also recorded, as well as of the elongation at break. All these point to conclusion that this material should be used in cold conditions, i.e., at room temperature, since heating causes worsening of the material deformation properties.

Note

The shorter version of this work was presented at "SEMDOK 2015" Conference in Terchova, Slovakia, 28-30 January 2015 – reference [14].

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