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Fire resistance of austenitic stainless steels Polarit 725 (EN 1.4301) and Polarit 761 (EN 1.4571)

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ABSTRACT

The main purpose of the study was to determine the behaviour of austenitic stainless steel at elevated temperatures. The stress-strain relationship of a material at elevated temperatures is required to determine the load-bearing capacity of structures under fire conditions. The study is limited to austenitic stainless steels, which are the most commonly used group for structural applications.

Stress-strain relationships at elevated temperatures were determined with steady-state tensile tests at elevated temperatures for two austenitic stainless steels Polarit 725 (conforming to material number EN 1.4301 and AISI 304) and Polarit 761 (conforming to material number EN 1.4571 and AISI 316 Ti). The material properties were determined for both virgin sheet and cold-worked material; steady-state tensile tests were performed up to 900 °C for Polarit 725 and 950 °C for Polarit 761.

At temperatures above 500 - 600 °C the yield strength (stress at a proof strain of 0.2%) of austenitic stainless steels Polarit 725 and Polarit 761 does not decrease as strongly as that of carbon steels determined according to Eurocode 3, Part 1.2 (ENV 1993-1-2 1995). As much as 50% of the yield strength of Polarit 761 remains at 800 °C. It should noted, however, that mechanical properties determined with steady-state tests are optimistic compared with transient-state tensile test results when only small strains are involved. On the other hand, the yield strength values of carbon steel determined according to Eurocode 3, Part 1.2 correspond to a total strain of 2%. The modulus of elasticity of austenitic stainless steels decreases more slowly than that of carbon steels.

Increased strength due to the cold-forming process remains constant up to 600 °C, after which the strength begins to decrease and the influence of cold-forming totally disappears at 900 °C. The elongation to fracture of cold-formed material is much lower than that of the virgin sheet.

The load-bearing capacities of certain stainless steel structures were calculated. The thermal material properties used in the calculations were based on the literature. The results of this study are promising concerning the application possibilities of austenitic stainless steels when fire resistance is required.

PREFACE

The main purpose of the project was to determine the behaviour of austenitic stainless steel at elevated temperatures. The stress-strain relationship of a material at elevated temperatures is necessary to determine the load-bearing capacity of structures under fire conditions. Full utilization of the special features of stainless steels has not been possible due to lack of technical data on e.g. the fire resistance of stainless steel structures. The mechanical material properties were determined with steady-state tensile tests.

The co-ordinator of the project was Mr. Unto Kalamies from the Finnish Constructional Steelwork Association. The steady-state tests were carried out by Outokumpu Oy. Ms. Tiina Ala-Outinen (project manager) from the Technical Research Centre of Finland (VTT) evaluated the steady-state test results and wrote the report.

The project was supported by the Technology Development Centre (TEKES), Outokumpu Oy, Stala Oy, Jaro Oy and the Finnish Constructional Steelwork Association (TRY). All participants who helped finance the project are gratefully acknowledged.

The advisory committee of the project comprised Mr. Raimo Viherma, Chairman, Outokumpu Oy; Mr. Pekka Huomo, Stala Oy; Mr. Terho Torvinen, Jaro Oy; Mr. Esko Rautakorpi, A-Insinöörit Oy Te-em; Mr. Unto Kalamies, Finnish Constructional Steelwork Association, and Mr. Asko Talja, VTT Building Technology.

The author would like to thank all members of the advisory committee. I am also grateful to Mr. Hannu Nilimaa and Mr. Hannu Sikanen from Outokumpu Oy. Thanks also to Ms. Erja Schlesier for her text processing expertise.

Tiina Ala-Outinen

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1 INTRODUCTION

There is increasing interest in building load-bearing structures of stainless steels because of their corrosion resistance, ease of maintenance, attractive appearance and the low life-cycle costs. Full utilization of the special features of stainless steels has not been possible due to lack of technical data on e.g. the fire resistance of stainless steel structures. At present the special features of stainless steels in fire cannot be taken into account when designing stainless steel structures in accordance with Eurocode 3.

The metallurgical microstructure of stainless steels may be ferritic, martensite, austenitic or austenitic-ferritic. Each group has different properties with respect to strength, corrosion resistance and ease of fabrication. This study is limited to austenitic stainless steels, which are the most commonly used group for structural applications. Austenitic stainless steels have high ductility, are easily formed and readily weldable, and offer good corrosion resistance. Their strengths are reasonable and they only can be hardened by cold-working. Austenitic stainless steels, as their name implies, have an austenitic microstructure at room temperature and contain relatively high amounts of nickel.

From the designer’s viewpoint the most important difference between stainless and carbon steels is the shape of the stress-strain curve. The stress-strain relationship of austenitic stainless steel is non-linear and there is no well-defined yield stress. The stress-strain relationships of stainless steel at elevated temperatures are necessary for determining the load-bearing capacity of structures under fire conditions.

Stress-strain relationships at elevated temperatures were determined with steady-state tensile tests performed at high temperatures were for two austenitic stainless steel types, Polarit 725 (conforming to material number EN 1.4301 and AISI 304) and Polarit 761 (conforming to material number EN 1.4571 and AISI 316 Ti). The material properties were determined for both virgin sheet and cold-worked material. The mechanical strength of a rectangular hollow section may be substantially different from that of virgin sheet before roll-forming. The coupons were cut from both a virgin sheet and a strongly strain-hardened rectangular hollow section 60 x 60 x 5 to determine the remaining increased strength at elevated temperature. The steady-state tensile tests were carried out for Polarit 725 up to 900 °C and for Polarit 761 to 950 °C.

The load-bearing capacities of certain stainless steel structures were calculated. The thermal material properties used in the calculations were based on the literature. In the calculations the measured values of mechanical properties were used and the gas temperature is assumed to rise according to the relationship specified in ISO 834 (1975). On the basis of calculations, new applications of austenitic stainless steel structures in buildings are proposed.

2 THERMAL PROPERTIES OF AUSTENITIC STAINLESS STEELS

The fire analysis of a structure can be divided into two parts: thermal analysis and structural analysis. In thermal analysis the temperature distribution in the cross-section is determined, and in structural analysis the bearing capacity of the structure is calculated.

The heat is transferred to the structure by convection and radiation. The main thermal properties required for accurate calculation of the temperature distribution in structure are specific heat, thermal conductivity and emissivity. The temperature rise in the cross-section can be described by the following approximate formula:

$$\frac{\partial T}{\partial t} = \frac{\lambda(T)}{c(T)\cdot\rho(T)}\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right] \tag{1}$$

where T is the temperature at the point considered
t is time
$\lambda(T)$ is thermal conductivity
$c(T)$ is the specific heat
$\rho(T)$ is density

The thermal elongation factor is necessary to determine deformations in structures.

2.1 THERMAL CONDUCTIVITY

Thermal conductivity indicates the rate at which a material transmits heat. If a thermal gradient of one degree per unit length is established over a material of unit cross-sectional area, then the thermal conductivity is defined as a quantity of heat transmitted per unit time. The thermal conductivity of austenitic stainless steels AISI 304 and AISI 316 (Lewis 1977) is compared in Figure 1 with that of carbon steel determined according to Eurocode 3, Part 1.2 (ENV 1993-1-2 1995). Below 800 °C the thermal conductivity of austenitic stainless steel is much lower than that of carbon steels.

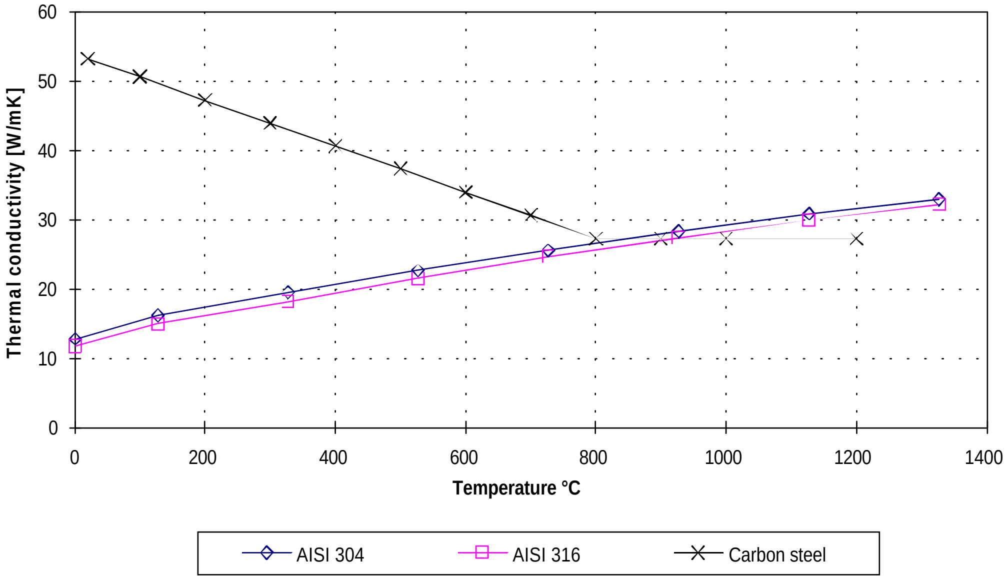


Figure 1. Thermal conductivity of austenitic stainless steels AISI 304 and AISI 316 (Lewis 1977) compared with that of carbon steel.

2.2 SPECIFIC HEAT

The quantity of heat required to change by one degree the temperature of a body of material of unit mass is called the specific heat. Figure 2 shows the specific heat for austenitic stainless steels AISI 304 and AISI 316 (Lewis 1977) and for carbon steel determined according to Eurocode 3, Part 1.2 (ENV 1993-1-2 1995). The specific heat of austenitic stainless steels increases smoothly, in contrast to that of carbon steels which peaks sharply (at around 740 °C).

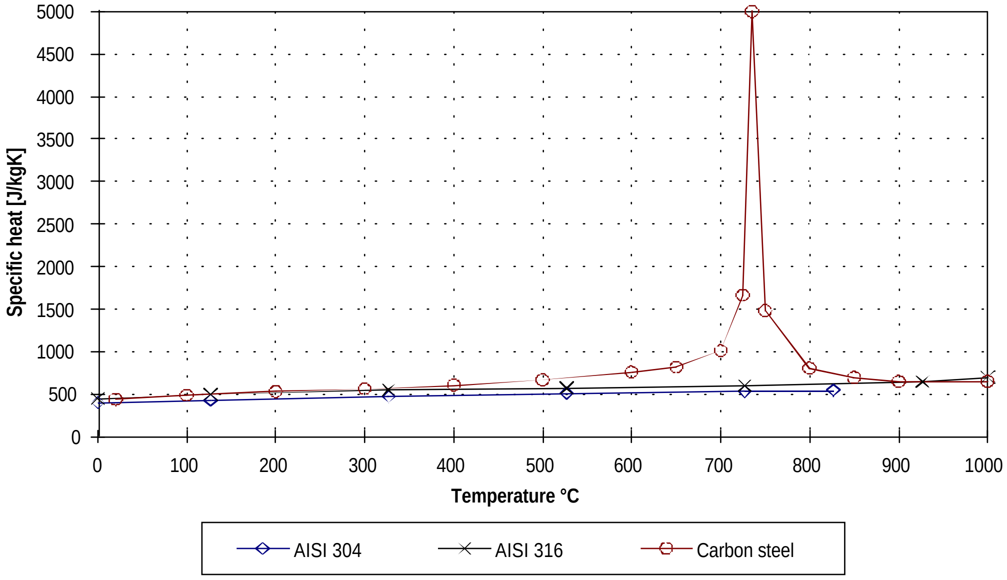


Figure 2. Specific heat of austenitic stainless steels AISI 304 and AISI 316 (Lewis 1977) compared with that of carbon steel.

2.3 EMISSIVITY

The emissivity of stainless steels is lower than that of carbon steels and depends naturally on the surface finish making it difficult to determine accurately. In the calculations below the assumed value of emissivity for stainless steel is 0.4 (Incropera & DeWitt 1981).

2.4 THERMAL ELONGATION

The coefficient of thermal elongation of austenitic stainless steels AISI 304 and AISI 316 (Lewis 1977) is compared in Figure 3 with the thermal elongation of carbon steel determined according to Eurocode 3, Part 1.2 (ENV 1993-1-2 1995). The coefficient of thermal expansion of austenitic stainless steels, which is almost 50% greater than for carbon steels, should especially be taken into account when welding austenitic stainless steels.

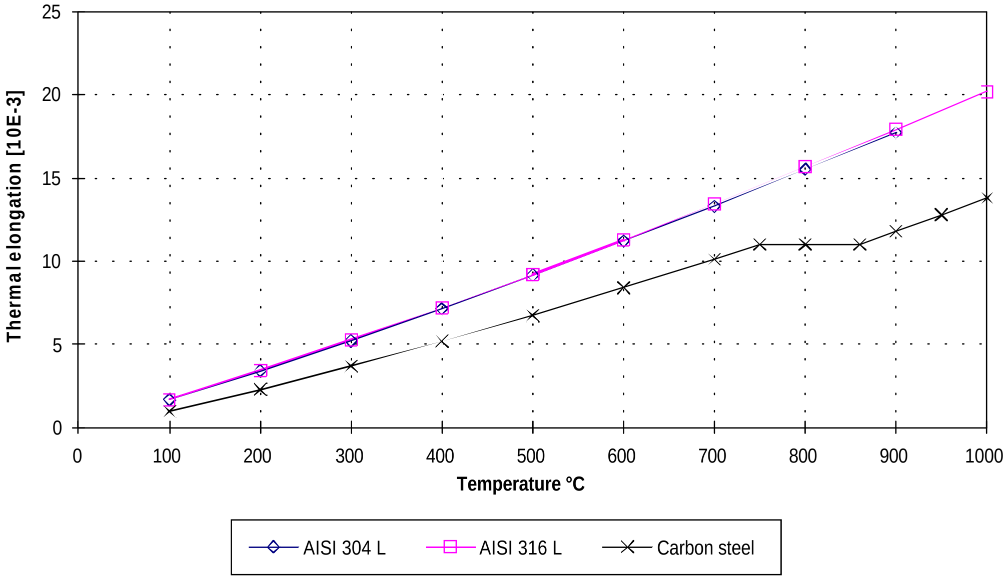


Figure 3. Thermal elongation of austenitic stainless steels AISI 304 and AISI 316 (Lewis 1977) compared with the thermal elongation of carbon steel.

2.5 THERMAL ANALYSIS

The temperature distribution in the cross-section was calculated with the LIPA program (1990), which uses the finite element method in connection with a conditionally stable time integration scheme to calculate the temperature distribution. The finite element method divides the cross-section into an assemblage of discrete elements of possibly variable size and shape connected at a finite number of nodal points. The use of the finite-element makes the change of thermal properties of different elements very easy and the same program can be used for calculating different kinds of cross-sections.

The effect of thermal properties on the temperatures of carbon steel and stainless steel cross-sections was considered. The gas temperature was assumed to rise according to the relationship specified in ISO 834 (1975), known as the standard time-temperature curve. In the calculations the emissivity of carbon steel was taken as 0.7 and that of stainless steel as 0.4. Figure 4 shows the maximum temperatures in the cross-section as a function of time for stainless and carbon steels of cross-section 60 x 60 x 5 and 300 x 300 x 12.5.

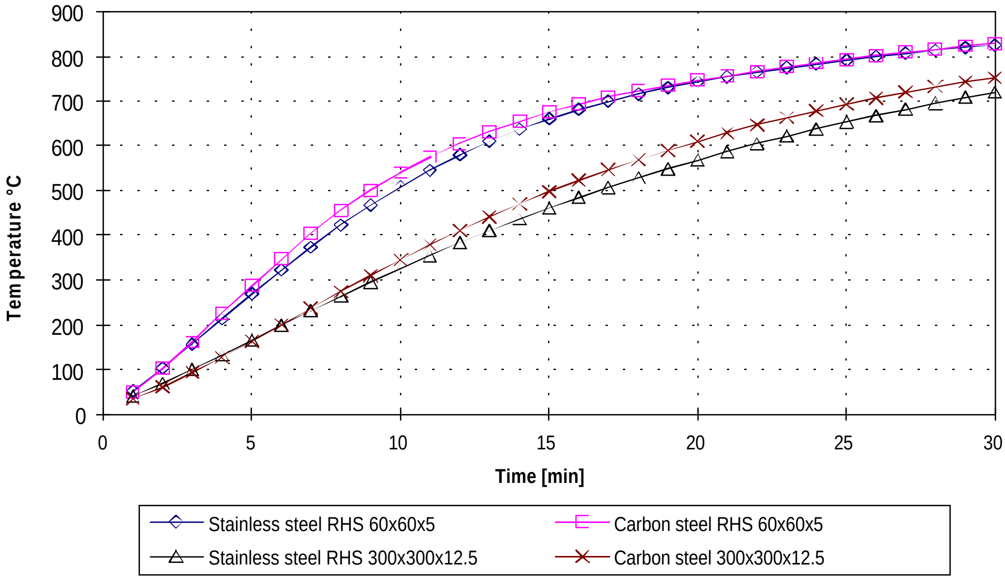


Figure 4. Maximum temperatures in the cross-section as a function of time for stainless steel and carbon steel.

As seen in the Figure 4, the maximum temperatures in the cross-section strongly depend on the dimensions of the cross-section. Also, the difference between temperatures of stainless steel and carbon steel cross-sections increases with thickness.

3 MECHANICAL PROPERTIES OF AUSTENITIC STAINLESS STEELS AT ELEVATED TEMPERATURES

3.1 THE THEORETICAL STRESS-STRAIN RELATIONSHIP

For numerical computations the stress-strain relationship of a material is required in mathematical formulation. The total strain ε_{total} at elevated temperatures can be described by the following expression:

$$\varepsilon_{total} = \varepsilon_{th}(T) + \varepsilon_{\sigma}(T,\sigma) + \varepsilon_{cr}(t,T,\sigma) \tag{2}$$

where $\varepsilon_{th}(T)$ is the thermal strain
$\varepsilon_{\sigma}(T,\sigma)$ the stress-dependent strain
$\varepsilon_{cr}(t,T,\sigma)$ a warm-creep term

Thermal strain takes into account the pure thermal expansion of the material due to the elevated steel temperature. The warm-creep term takes into account the influence of warm-creep effects. Combining the terms gives the temperature-dependent stress-strain relation of the material.

The stress-dependent strain ε [combining $\varepsilon_{\sigma}(T,\sigma)$ and $\varepsilon_{cr}(t,T,\sigma)$] comprises the elastic and plastic strain.

The rounded stress-strain relationship may be defined by the Ramberg-Osgood formulation (Kay & Hancock 1993). The elastic strain is σ/E, and the plastic strain has been found to be comparable to the stress raised to a given power dependent on the material. Thus:

$$\varepsilon = \frac{\sigma}{E} + k\left(\frac{\sigma}{E}\right)^{n} \tag{3}$$

where k and n are constants determined experimentally. Equation 3 can also be expressed in the following form:

$$\varepsilon = \frac{\sigma}{E} + \frac{p}{100}\left(\frac{\sigma}{\sigma_{p}}\right)^{n} \tag{4}$$

Factor n describes the sharpness of the knee of the material stress-strain curve and is the stress at which the plastic component of the strain is p per cent. At normal temperature this is often specified as 0.2% proof strain. The limiting case of $n = \infty$ represents elastic perfectly plastic material behaviour.

3.2 STEADY-STATE TESTS AT ELEVATED TEMPERATURES

The stress-strain relationships of the material at elevated temperatures are required for determining the load-bearing capacity of structures under fire conditions. Tests for the determination of mechanical properties at elevated temperatures are classified as steady-state and transient-state tests. In the traditionally used steady-state tests the temperature is kept constant, while in transient-state tests it is the load that remains unchanged. The transient-state test is claimed to give a more realistic description of material behaviour in fire conditions, but the required number of tests is greater than with the steady-state test. In steady-state and transient-state tensile tests the rate in the tests has an effect on the test results. The stress at a given strain tends to decrease with decreasing strain rate (Diercks & Burke 1974).

Under stress the behaviour of a material at elevated temperature is quite different from that at normal temperature. Creep, a slow continuous deformation, may occur. Numerous tests have been developed for measuring long-time service behaviour, but time-dependent behaviour is of less concern at temperatures below about 500 °C. In fire design the short-time mechanical properties of material must be known.

Stainless steels may behave quite differently under tension and under compression. The stress-strain curves tend to be more non-linear in tension than in compression, but not always (Dier 1991). This has not been taken into account here when considering stress-strain curves at elevated temperatures.

This study deals with austenitic stainless steels, and the stress-strain relationships at elevated temperatures were determined with steady-state tensile tests performed by Outokumpu Oy. The tensile tests at elevated temperatures were carried out for two austenitic stainless steel types, Polarit 725 (conforming to material number EN 1.4301 and AISI 304) and Polarit 761 (conforming to material number EN 1.4571 and AISI 316 Ti).

The material properties were determined for both virgin sheet and for strongly strain-hardened material. Tests coupons were cut from a stainless steel sheet of nominal thickness 5 mm, longitudinally to the rolling direction. The strength of a tensile transverse coupon test tends to be weaker than that of a longitudinal coupon test.

Steady state tests were performed for the base material at temperature intervals of 50 °C, and for cold-formed material at intervals of 100 °C. The steady-state tensile tests were carried out for Polarit 725 up to 900 °C and for Polarit 761 to 950 °C. Two equal tests were performed at each temperature and if where there was a significant disparity in the results, a third test was performed. Tensile tests at room temperature were also carried out to determine the mechanical properties at room temperature.

The strength of a material increases due to cold work in the fabrication process, and the remaining of this increased strength at elevated temperatures was studied.

Coupons were cut from rectangular hollow sections 60 x 60 x 5 and manufactured by Stala Oy in Lahti. The manufacturing process of this section involved cold-forming into a circular shape, welding and sizing into a rectangular shape. The test coupons were cut longitudinally from the face opposite the welded seam.

The chemical compositions of the virgin sheets are given in Table 1 and the chemical compositions of the RHS sections in Table 2. Composition details were provided by the manufacturer (Outokumpu Oy).

Table 1. Chemical composition of virgin sheets Polarit 725 and Polarit 761.

Virgin sheet	Chemical composition (percentage weight)								
Type	C	Cr	Ni	Mo	Si	Mn	P	S	Ti
Polarit 725 (1.4301, AISI 304)	0.04	18.3	8.6	0.12	0.53	1.56	0.024	0.002	-
Polarit 761 (1.4571, AISI 316 Ti)	0.021	16.7	10.7	2.08	0.56	1.73	0.028	0.002	0.37

Table 2. Chemical composition of RHS section Polarit 725 and Polarit 761.

RHS-section	Chemical composition (percentage weight)								
Type	C	Cr	Ni	Mo	Si	Mn	P	S	Ti
Polarit 725 (1.4301, AISI 304)	0.040	18.3	8.6	0.16	0.47	1.53	0.027	0.004	-
Polarit 761 (1.4571, AISI 316 Ti)	0.033	16.8	10.7	2.15	0.55	1.69	0.024	0.003	0.33

3.3 TESTING DEVICE

The coupons were tested in accordance with SFS-EN 10002-5 (1992) using an Instron testing machine. The straining rate in the tests was 0.5 mm/min in strains below 0.2% proof strain. Calculating the straining rate with the parallel length L_c = 75 mm (Figure 5) gives a value of 0.0067/min or 112 με/s, which is higher than the required straining rate (0.001...0.005/min) according to SFS-EN 10002-5 (1992). After 0.2% proof strain the straining rate was increased up to 10 mm/min.

The transition radius in the coupon is quite large, and the parallel length in tests might be assessed to be greater than 75 mm in which case the straining rate would be lower. In earlier tests performed by Outokumpu Oy (Rukajärvi 1987) the straining rate was 1.0 mm/min in strains below 1.0% proof strain and the parallel length was L_c = 90 mm, that is 0.0111/min. Comparing the stress in relation to 0.2% proof strain with these results, the relative strength was about 7% higher at a roughly 60% faster straining rate.

The testing oven was heated with a three resistor zone. Specimens were left in the oven about 10 minutes before loading to ensure a steady temperature. Extension of the test coupon was measured with an extensometer using a gauge length of L_e = 50 mm. The stress values were obtained by dividing the measured load by the area of the coupon based on the initial dimensions measured before testing. The dimensions of the coupons conform to the standard SFS-EN 10002-5 (1992). The gripped ends were welded to the coupon (Figure 5). The test coupon and testing device are shown in Figure 6.

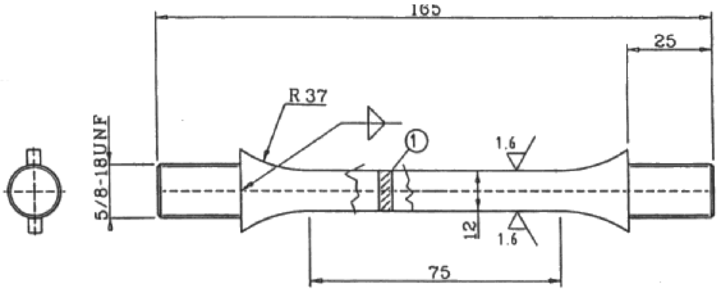


Figure 5. Dimensions of the test specimen.

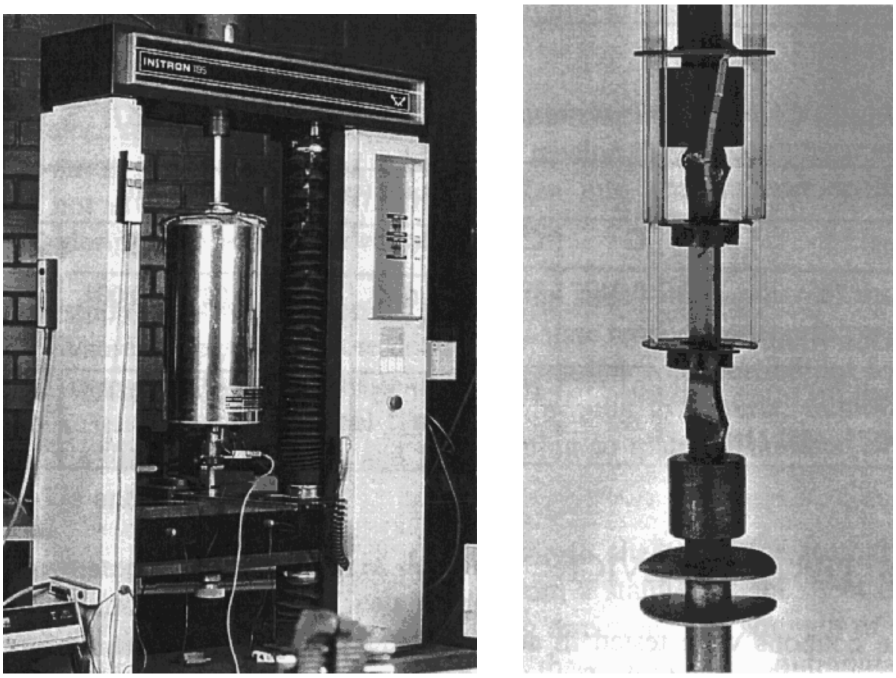


Figure 6. The steady-state tensile testing device.

3.4 MECHANICAL MATERIAL PROPERTIES OF VIRGIN SHEET

In contrast to carbon steels the stress-strain relationship of an austenitic material is strongly non-linear. Because the material has no precise yield point, the yield stress is usually defined by reference to 0.2% proof strain. The stress-strain relationships of austenitic stainless steels Polarit 725 and Polarit 761 were determined by steady-state tests as described above. The stress-strain curves determined for a virgin sheet of Polarit 725 and Polarit 761 are shown in Appendices 1 and 2.

The stress values in relation to proof strains of 0.2% and 1.0% and to the tensile strength and values of modulus of elasticity, are given in Appendices 1 and 2 for virgin sheets of Polarit 725 and Polarit 761. Figure 7 shows the stress in relation to proof strains of 0.2% and 1.0% and to the tensile strength of Polarit 725. The difference between stress values corresponding to proof strains of 0.2% and 1.0% is fairly unassuming. Figure 8 shows the corresponding stress values for Polarit 761.

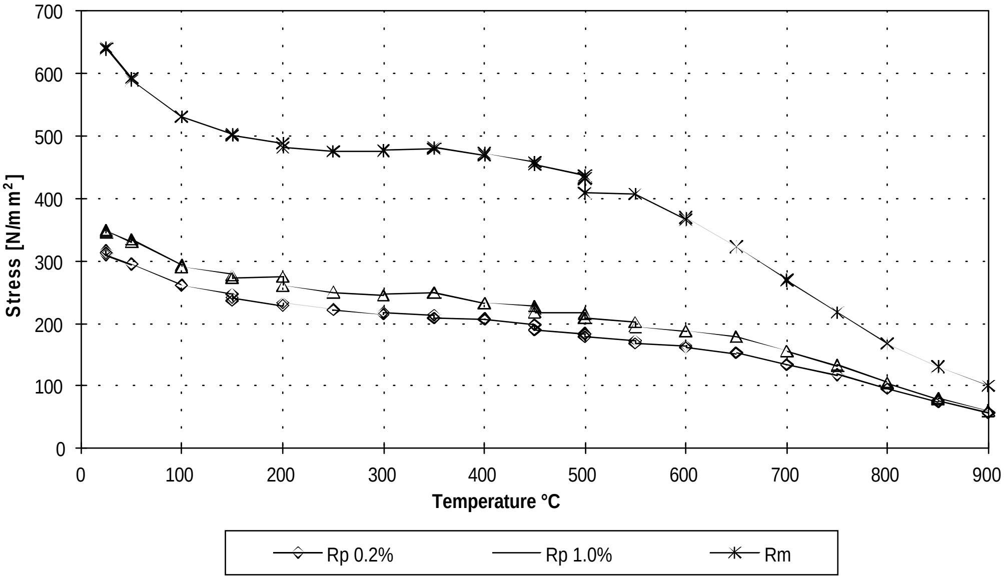


Figure 7. Stress values corresponding to proof strains of 0.2% and 1.0% and to the tensile strength of Polarit 725.

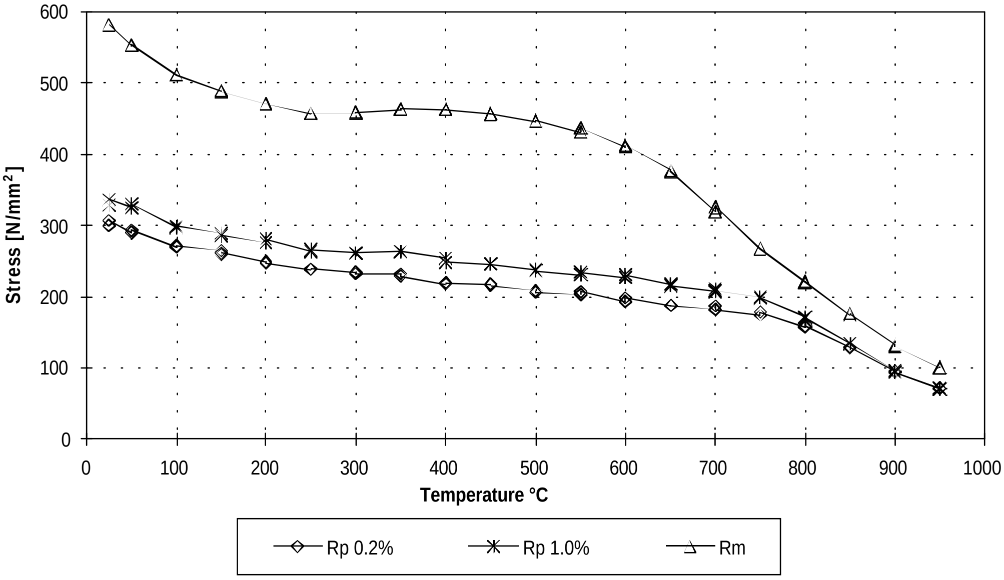


Figure 8. Stress values corresponding to proof strains of 0.2% and 1.0% and to the tensile strength of Polarit 761.

Figure 9 compares the reduction factor of yield strength of austenitic stainless steels Polarit 725 and Polarit 761 with the yield strength of carbon steel. The stress values of stainless steels correspond to proof strains of 0.2% and the yield strength of carbon steel is determined according to Eurocode 3, Part 1.2 (ENV 1993-1-2 1995).

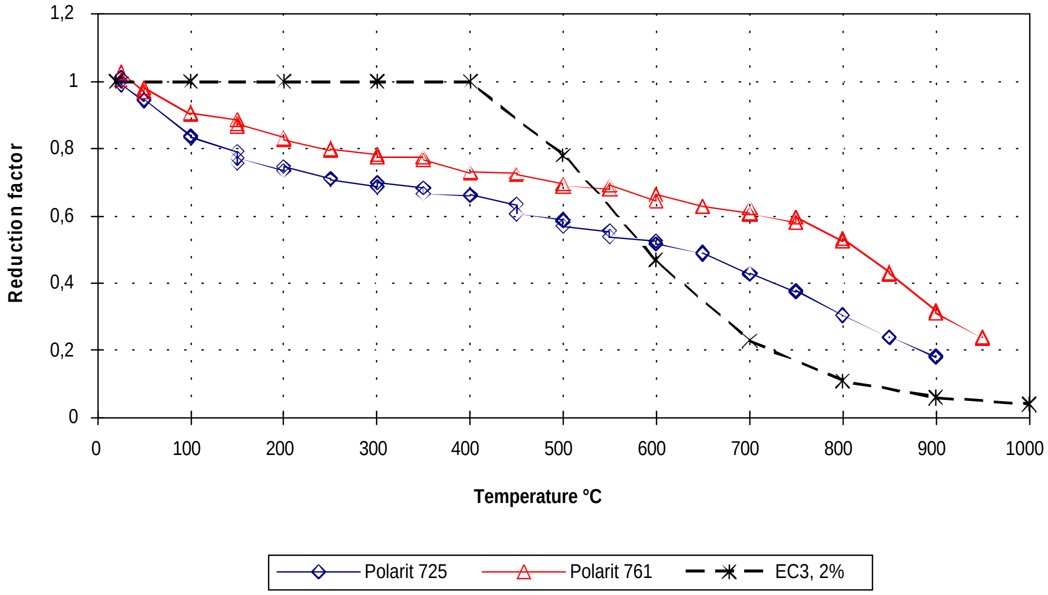


Figure 9. Reduction factor of yield strength of austenitic stainless steels Polarit 725 and Polarit 761 compared with the yield strength of carbon steel determined according to Eurocode 3, Part 1.2.

In Eurocode 3, Part 1.2 the yield strength is determined in relation to the total strain of 2% and the material model is based on transient-state tensile tests. It can be seen that the relative strength values of austenitic stainless steels are higher than those of carbon steel above 500 - 600 °C. As much as 50% of the yield strength of Polarit 761 remains at 800 °C. However, it should be remembered that the mechanical properties determined by steady-state tests are optimistic when only small strains are involved. On the other hand, the yield strength values of carbon steel according to Eurocode 3, Part 1.2 (ENV 1993-1-2 1995) are determined corresponding to a very high strain.

The modulus of elasticity at elevated temperatures was determined on the basis of stress-strain curves measured in steady-state tensile tests. The exact determination of the modulus of elasticity at elevated temperatures is very difficult, as the proportion limit of austenitic stainless steel is very low. Even the smallest inaccuracy in the measured curves has a very significant influence on the modulus of elasticity, thus the dispersion in values of the modulus of elasticity determined from measured stress-strain curves is quite remarkable. The values of modulus of elasticity determined from steady-state tensile tests of virgin sheet for Polarit 725 and Polarit 761 are shown in Figures 10 and 11.

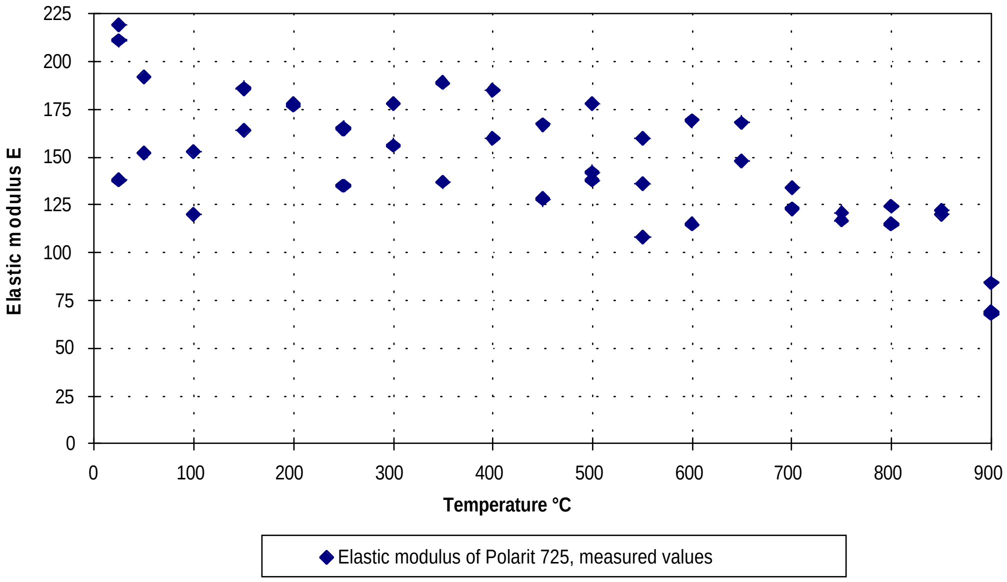


Figure 10. Modulus of elasticity of Polarit 725 (virgin sheet) at elevated temperatures.

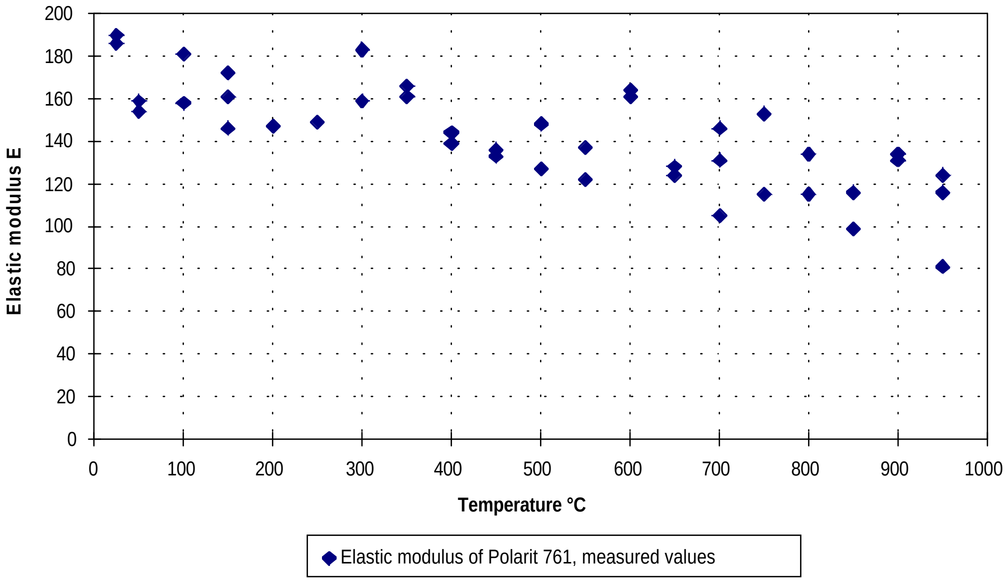


Figure 11. Modulus of elasticity of Polarit 761 (virgin sheet) at elevated temperatures.

Figure 12 shows the reduction factor of modulus of elasticity of Polarit 725 compared with the modulus of elasticity of carbon steels according to Eurocode 3, Part 1.2. The reduction factor is determined on the basis of steady-state tests and is the average values at each temperature. Also shown is the modulus of elasticity of AISI 304 at elevated temperatures according to the Handbook of stainless steels (Hoke 1977).

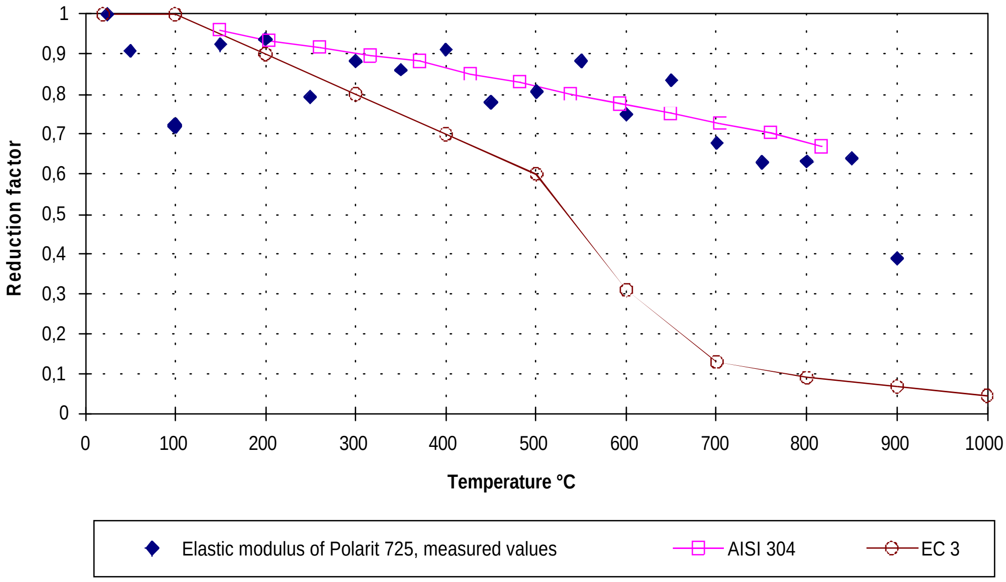


Figure 12. Reduction factor of the modulus of elasticity of Polarit 725 at elevated temperatures compared with the modulus of elasticity of carbon steel.

It can be seen that the modulus of elasticity of austenitic stainless steel decreases more slowly at elevated temperatures than that of structural steel.

Permanent elongation of the gauge length after fracture is expressed as a percentage of the original length. Figure 13 shows the percentage elongation after fracture for virgin sheets of Polarit 725 and Polarit 761 determined in steady-state tests.

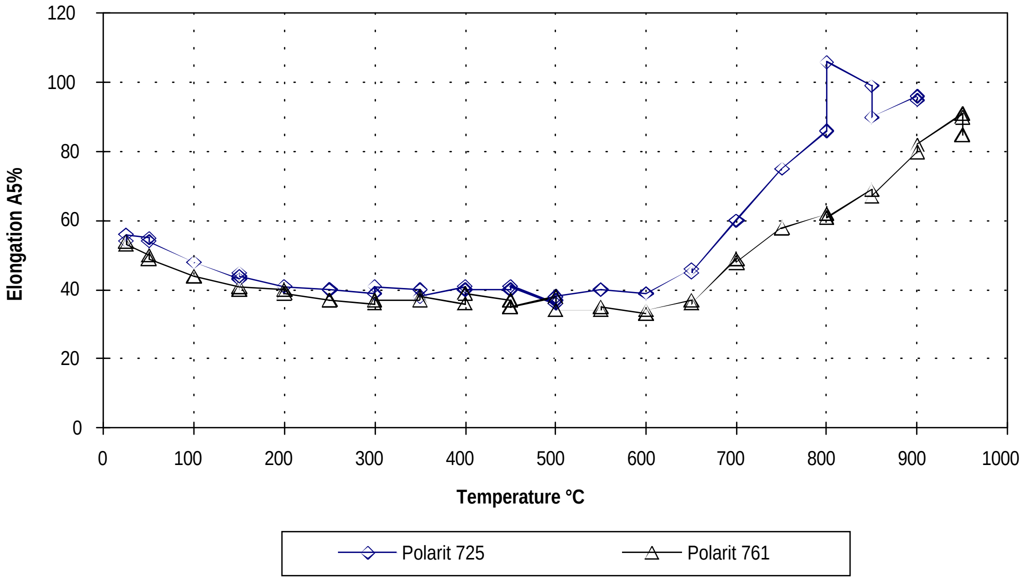


Figure 13. Percentage elongation after fracture for virgin sheets of Polarit 725 and Polarit 761.

The toughness of austenitic stainless steel is greater than that of carbon steels. The elongation of carbon steels is normally below 30%. Elongation of austenitic stainless steel decreased until about 250 °C and was constant to 600 °C, above which it increased strongly.

3.5 MECHANICAL MATERIAL PROPERTIES OF COLD-FORMED MATERIAL

Characteristic of austenitic stainless steels is the significant strain hardening during the cold-working process. The strain hardening of austenitic stainless steel is caused by plastic deformation and martensite transformation.

Many features of austenitic stainless steels differ markedly from the respective features of other steels because austenitic steels have a face-centred cubic microstructure, whereas the typical microstructure of other steels is body-centred cubic ferritic. Thus austenitic stainless steel behaves differently under load and exhibits a non-linear stress-strain relationship where there is no precise yield point and plastic deformations appear even when the stress is low.

When the steel comprises more than 6% nickel, the temperature at which martensite transformation occurs (M_s) is below room temperature and the microstructure remains permanently austenitic. Austenitic stainless steels with M_s temperature slightly below room temperature are metastable, and transformation to martensite can be induced by deformation at temperatures above M_s. Due to the martensite transformation the strength of the steel increases during the cold-working process. The upper temperature limit at which martensite is formed in this manner is called M_d. Above this temperature austenite is more steady than martensite and no martensite transformation occurs. Adding more than 30% nickel to the steel makes it stable. Stable austenitic stainless steels are those with microstructures that remain austenitic even after exposure to a high straining rate. Martensite transformation usually occurs following a strain of 10 to 15%.

The increase in strength due to cold work which remains at elevated temperatures was studied. Test specimens were cut longitudinally from the face opposite the welded seam of a rectangular hollow section 60 x 60 x 5. The stress-strain curves determined by steady-state tests for cold-formed Polarit 725 and Polarit 761 are given in Appendices 3 and 4, as are the mechanical properties of cold-formed Polarit 725 and Polarit 761.

The measured values of stress at a proof strain of 0.2% at elevated temperatures for a virgin sheet and cold-formed material of Polarit 725 are compared in Figure 14. Figure 15 shows the corresponding values for the austenitic stainless steel Polarit 761.

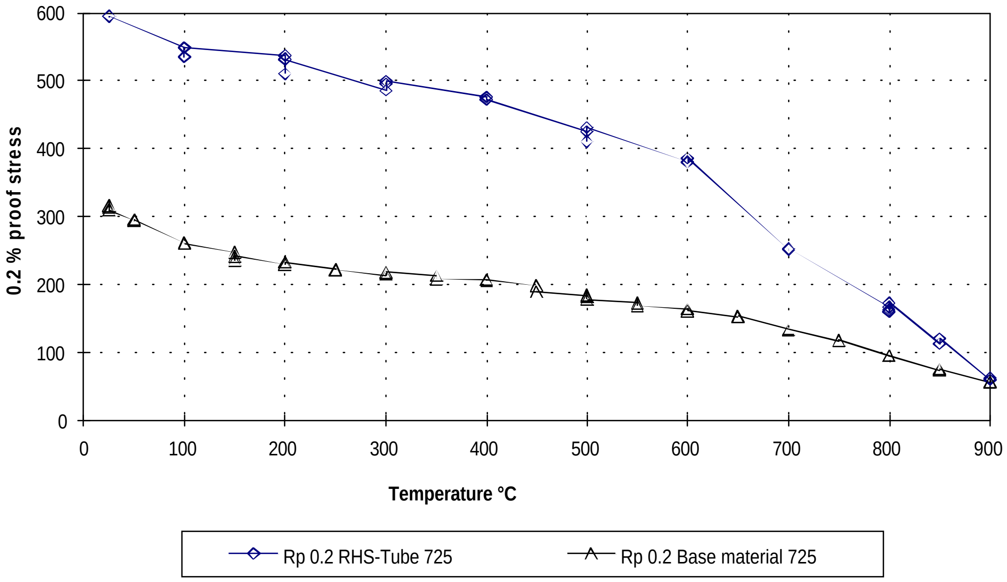


Figure 14. Remaining increased strength of Polarit 725 due to cold work at elevated temperatures.

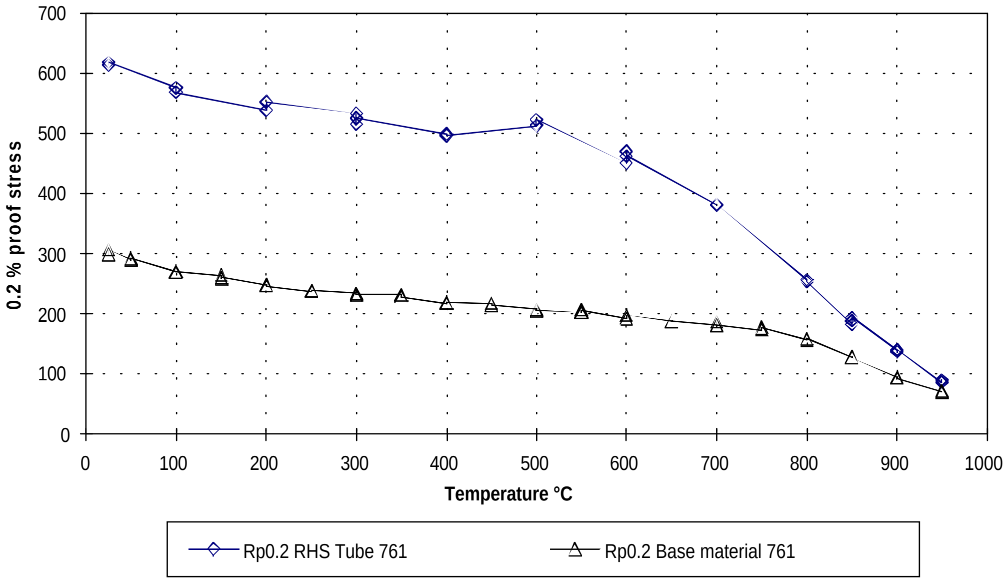


Figure 15. Remaining of increased strength of Polarit 761 due to cold work at elevated temperatures.

Figures 14 and 15 show that the increased strength due to the cold-forming process remains constant unto 600 °C. Beyond this the strength begins to decrease and the influence of cold-forming totally disappears at 900 °C.

The values of modulus of elasticity of cold-formed material based on the performed steady-state tensile tests are documented in Figures 16 and 17.

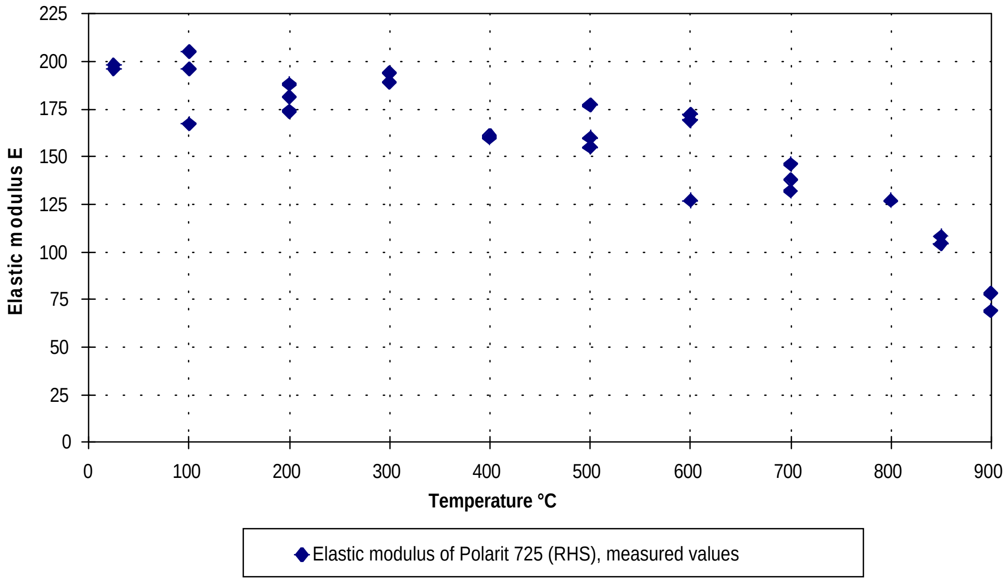


Figure 16. Modulus of elasticity of Polarit 725 (cold-formed material) at elevated temperatures.

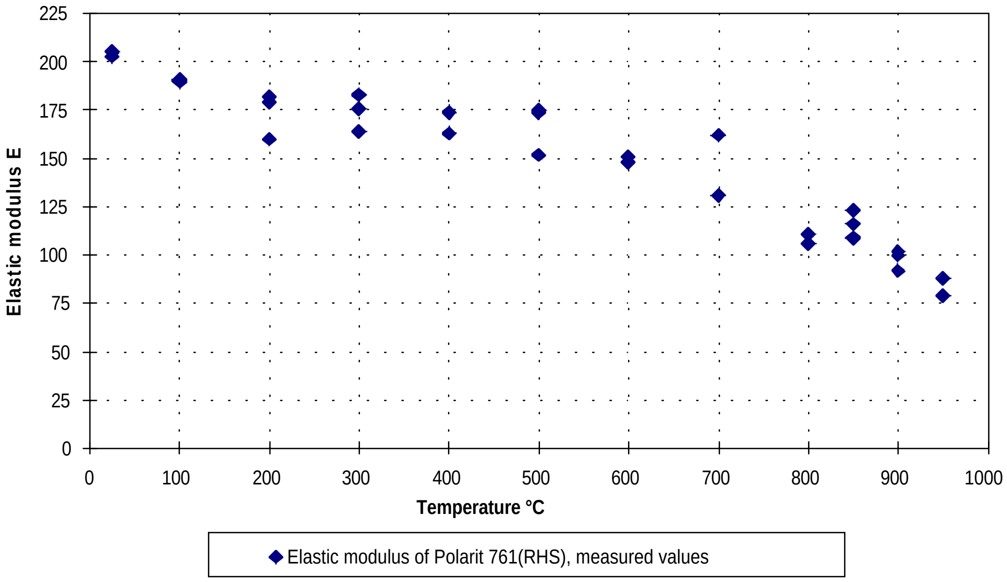


Figure 17. Modulus of elasticity of Polarit 761 (cold-formed material) at elevated temperatures.

Permanent elongation of the gauge length after fracture is expressed as a percentage of the original length. Figure 18 shows the percentage elongation after fracture for cold-formed Polarit 725 and Polarit 761 determined in steady-state tests.

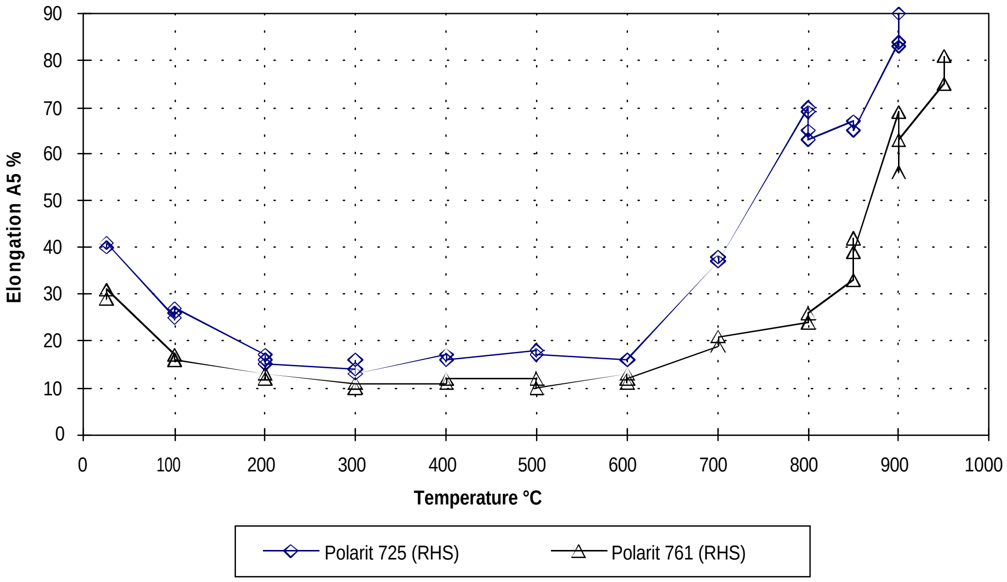


Figure 18. Percentage elongation after fracture for cold-formed Polarit 725 and Polarit 761.

The elongation to fracture of cold-formed material is much smaller than that of the virgin sheet. The cold-forming process decreases the elongation of stainless steel due to plastic deformation. The elongation of cold-formed austenitic stainless steel decreases up to about 250 °C and is constant to 600 °C, above which it increases strongly. The toughness of titanium stabilized austenitic stainless steel is lower than that of the conventional austenitic stainless steel.

4 STAINLESS STEEL COLUMNS

4.1 ULTIMATE BUCKLING LOAD UNDER FIRE ACTION

The fire resistance of some structures was calculated. The temperature distribution was determined using the thermal properties given in Section 2. In the calculations the gas temperature was assumed to rise according to the relationship specified in ISO 834 (1975). The value of emissivity of stainless steel used in the calculations was 0.4. The temperature distribution was calculated with the LIPA program (1990), which uses the finite element method in connection with a conditionally stable time integration scheme to calculate the temperature distribution in cross-section. The finite element method divides the cross-section into an assemblage of discrete elements of possibly variable size and shape connected at a finite number of nodal points. The method greatly facilitates the observation of changes in thermal properties of different elements, and the same program can be used for calculating different kinds of cross-sections.

The mechanical properties (modulus of elasticity and yield strength) are reduced at elevated temperature. The increased strength of cold-formed material has not been utilized in the calculations below. The strength was determined corresponding to a 0.2% proof strain of the base material following the test results for a virgin sheet at elevated temperatures. In the buckling equation the used imperfection factor of a cold-formed hollow section was 0.49. The modulus of elasticity used at normal temperature was 200 000 N/mm^2 and was reduced at elevated temperatures according to values determined on the basis of steady-state tests.

The calculation of load-bearing capacities with the LIPA program was based on a simplified method, according to which one quarter or half of the column is divided into elements. In the thermal analysis, the temperatures of element nodes have been calculated as a function of time. The node temperatures have been changed to average temperatures of elements. The mechanical material properties of elements are functions of the average temperature value of each element.

The plastic load-bearing capacity N_{PT} of a centrally loaded cross-section at temperature T can be calculated as follows:

$$N_{PT} = \sum\left(\Delta A_e f_{yeT}\right) \tag{5}$$

where ΔA_e is the area of each element
f_{yeT} the yield strength of steel at temperature T

The Euler buckling load N_{ET} at temperature T is calculated as

$$N_{ET} = \frac{\pi^2}{L_c^2}\sum\left(\Delta A_e E_{yT} y_{ie}^2\right) \tag{6}$$

where E_{eT} is the elastic modulus of the material of the element
y_{ie} the distance of the centred of an element
L_c the buckling length of the column

The modified slenderness factor λ is defined by:

$$\lambda = \sqrt{\frac{N_{PT}}{N_{ET}}} \tag{7}$$

In a buckling situation the cross-sectional strength is decreased by coefficient χ, which is a function of the reference situation.

$$\chi = \beta - \sqrt{\beta^2 - \frac{1}{\lambda^2}}$$

$$\beta = \frac{1 + \alpha(\lambda - \lambda_0) + \lambda^2}{2\lambda^2} \tag{8}$$

The imperfection factor α is 0.49 for cold-formed hollow sections and λ_0 is the limiting slenderness for buckling. For stainless steels $\lambda_0 = 0.4$, whereas for carbon steel the limiting slenderness has been taken as 0.2.

The ultimate buckling load under fire action for a central load is:

$$N_{UT} = \chi N_{PT} \tag{9}$$

Figures 19 and 20 below show the calculated ultimate buckling loads at normal temperature after 15 and 30 minutes. The ultimate buckling load is shown for materials Polarit 725 and Polarit 761 when the cross-section is RHS 60 x 60 x 5. The gas temperature was assumed to rise according to the relationship specified in ISO 834 (1975). The ultimate buckling load is shown as a function of buckling length.

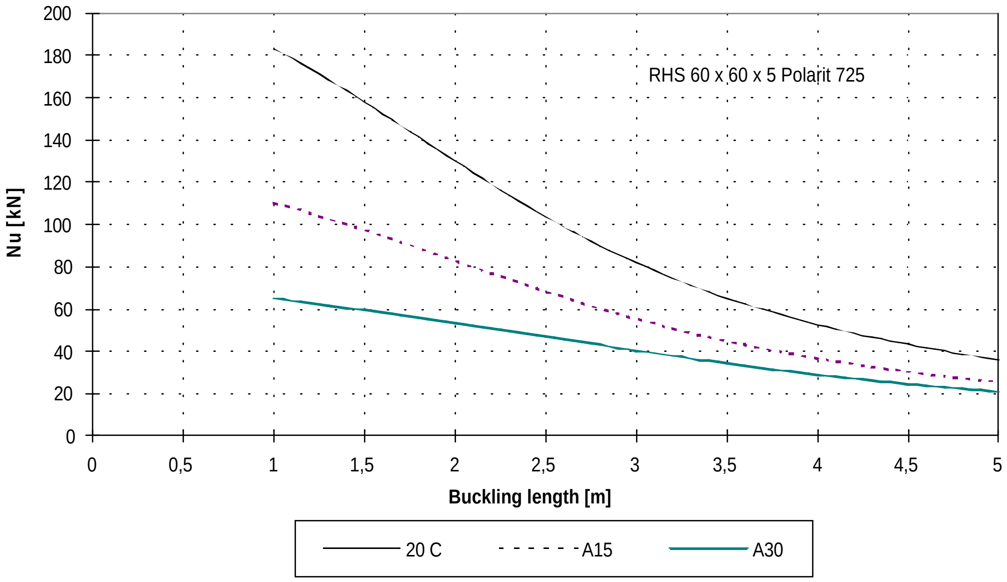


Figure 19. Calculated ultimate buckling load N_u of RHS 60 x 60 x 5 of Polarit 725.

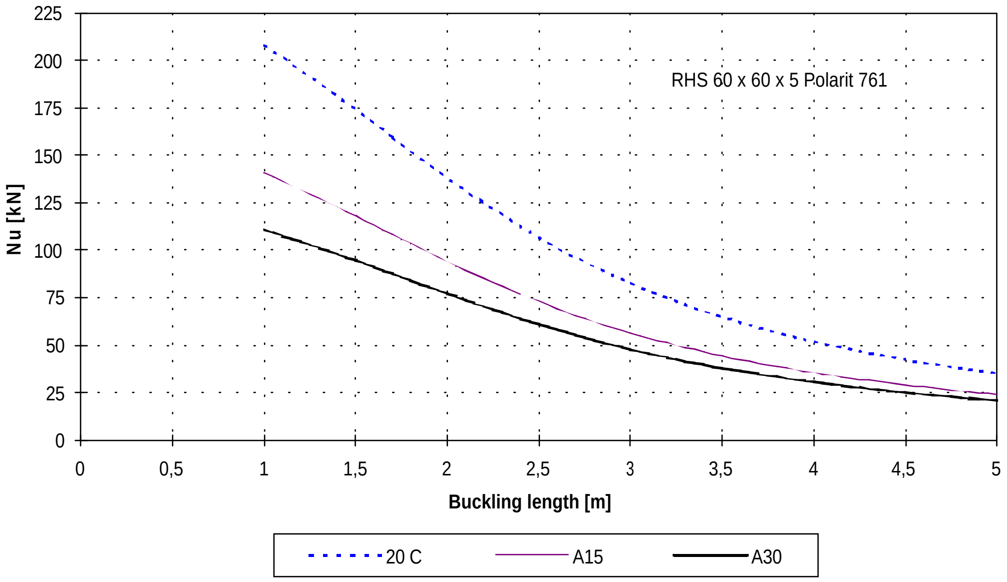


Figure 20. Calculated ultimate buckling load N_u of RHS 60 x 60 x 5 of Polarit 761.

Figures 21 and 22 show the ultimate buckling loads for cross-section RHS 150 x 100 x 6 and for materials Polarit 725 and Polarit 761. The ultimate buckling loads are shown as a function of buckling length.

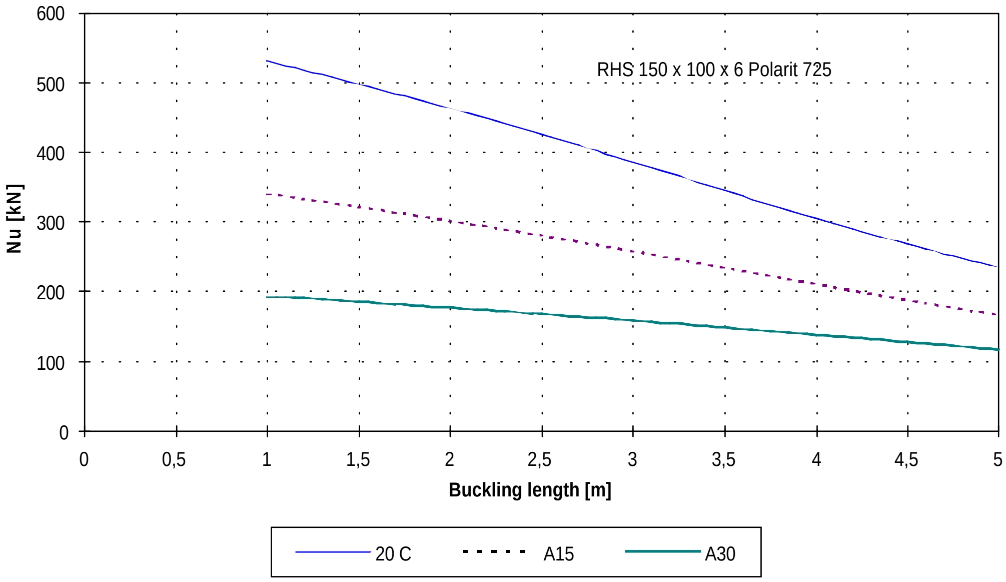


Figure 21. Calculated ultimate buckling load of RHS 150 x 100 x 6 of Polarit 725.

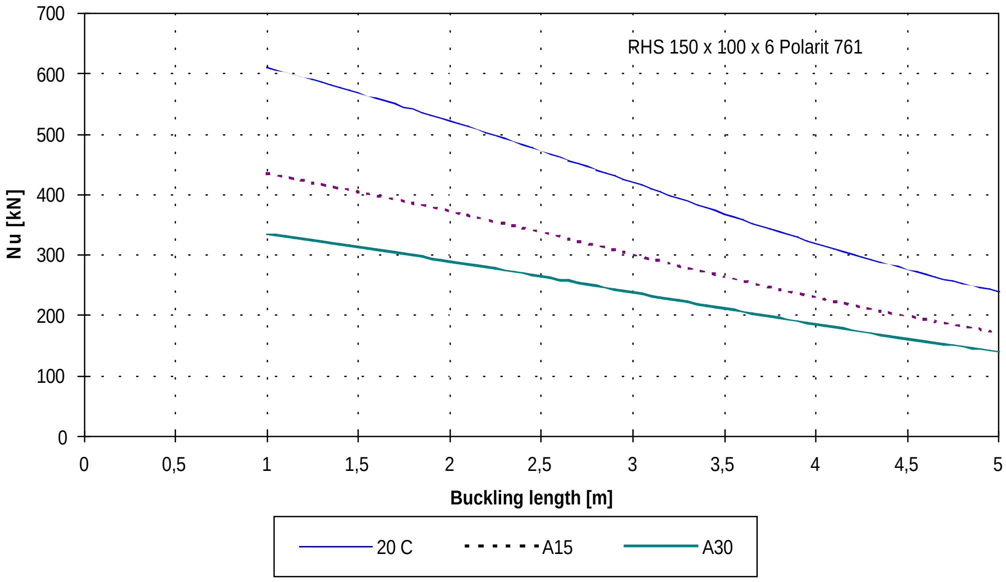


Figure 22. Calculated ultimate buckling load of RHS 150x100x6 of Polarit 761.

From the Figures 21 and 22 above it can be seen that as buckling length increases, the difference between ultimate buckling loads at normal and at elevated temperatures decreases. The reason is that the modulus of elasticity of austenitic stainless steels decreases more slowly than the stress at a proof strain of 0.2% at elevated temperatures.

The ultimate buckling loads of austenitic stainless steel columns and carbon steel columns were considered. In the calculations the strength at normal temperature was assumed to be equal for both carbon and stainless steels. The value of emissivity of stainless steel used in the calculations was 0.4 and that of carbon steel 0.7. The mechanical properties, the stress at a proof strain of 0.2% and modulus of elasticity, were reduced at elevated temperatures, according to the tests results for a Polarit 761 virgin sheet. The material model of carbon steel used in the calculations was as determined in Eurocode 3, part 1.2 (ENV 1993-1-2 1995). The gas temperature was assumed to rise according to the relationship specified in ISO 834 (1975). The ultimate buckling load is shown as a function of buckling length.

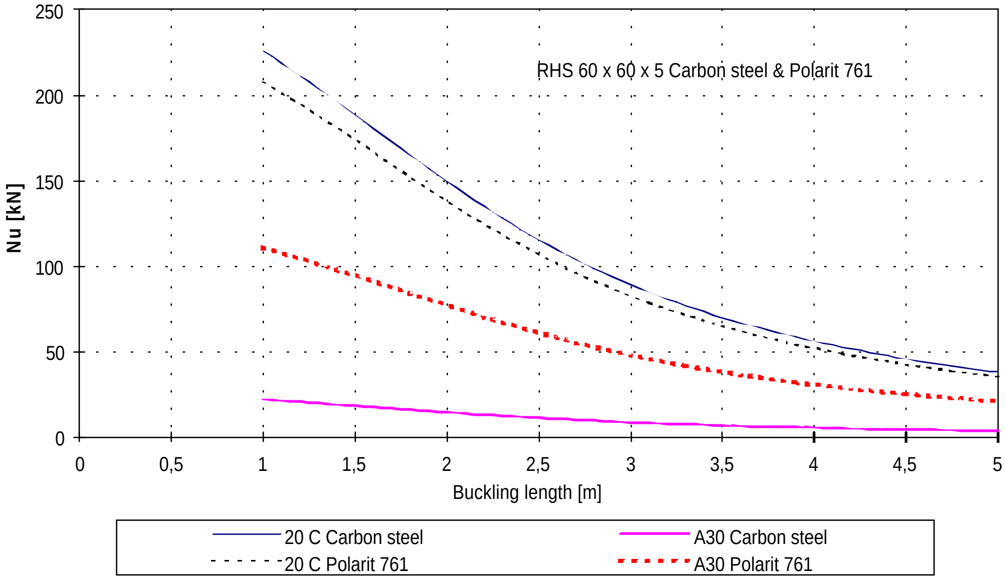


Figure 23. Calculated ultimate buckling load of RHS 60 x 60 x 5 of stainless steel (Polarit 761) compared with that of RHS 60 x 60 x 5 of carbon steel.

As seen from the Figure 23 the column made of carbon steel has entirely lost its fire resistance after 30 minutes in a standard fire, whereas that of austenitic stainless steel still has about half of its fire resistance.

4.2 LOAD LEVEL IN FIRE

At increased temperature the load-bearing capacity is decreased, and once the load-bearing capacity falls below the actual load the structure will collapse. When the effects of actions do not increase during fire exposure, they may be deduced from those applied in normal temperature design (ENV 1991-2-2 1992).

$$E_{fi,d} = \eta_{fi} E_d$$

where E_d is the design value of the relevant effects of actions
$E_{fi,d}$ the corresponding design value for the fire situation
η_{fi} is the reduction factor for the design load level for the fire situation

The ratio between the main variable and permanent actions can be expressed as follows:

$$\eta_{fi} = \left(\frac{\gamma_{GA} + \psi_{1,1}\xi}{\gamma_G + \gamma_Q\xi} \right) \tag{10}$$

where ξ is the ratio between the main variable and permanent actions
γ_{GA} the safety factor for permanent actions in an accidental situation
γ_G the partial safety factor for a permanent action
γ_Q the partial safety factor for a variable action
$\psi_{1,1}$ is combination factor

Depending on the relation between permanent and variable loads and the value of the combination factors, which in turn depends on the type of building and load, the design load in fire will normally be of the order of 0.50 to 0.70 of the design load at normal temperature.

Appendix 5 gives a calculation example, where the critical temperature is determined for a carbon steel column and for a stainless steel column of cross-section 300 x 300 x 12.5. On the basis of critical temperature, the fire resistance time is determined where the gas temperature is assumed to rise according to the relationship specified in ISO 834. According to the example, the critical temperature of carbon steel corresponds to a fire resistance time of 19 minutes, that of stainless steel Polarit 725 to 25 minutes and that of stainless steel Polarit 761 to 41 minutes in a standard fire. The fire resistance time depends on the strength of the material, on the dimensions and shape of the cross-section, on the buckling length of the column and, naturally, on the reduction factor for the design load level for a given fire situation.

5 NEW APPLICATIONS OF STAINLESS STEEL STRUCTURES IN BUILDINGS

According to Finnish building code E1 (1981), buildings are categorised according to their fire resistance into three classes: fire proof, fire retentive and fire retarding. The class of a building depends on its height, the number of storeys, the use to which it is put, the number of persons using it, the total floor area, the floor area of the fire resistant compartment and, the city plan.

The load-bearing elements of a structure, the separating elements, and the protective lining are classified according to their fire resistance periods, so that the given time is at least as long as the minimum permissible time in minutes for the assigned class. The fire resistance period is the time in minutes during which an element of the structure has been found to meet the given requirements for fire resistance in an officially conducted fire test, or as mathematically calculated. The fire load is the total amount of heat in a fire resistant compartment when the material in this compartment burns completely. The fire load group of fire proof structures is based mainly on the purpose of each structure.

A building must be constructed to be fire proof if it has three or more storeys. Also a building of one or two stories must be of fire proof construction if there are special premises. A fire retentive building may have no more than two storeys or be no more than 7 metres high. Unless special circumstances dictate otherwise, one-storey industrial and storage buildings, and agricultural production and storage buildings may be higher than this. The second storey of a fire retentive building may contain premises other than residences only if the areas directly below them belong to the same premises. A fire retarding building may have no more than two storeys or be no more than 7 metres high. Unless special circumstances dictate otherwise, one-storey industrial and storage buildings, and agricultural production and storage buildings may be higher than this, but may nonetheless not exceed 14 meters in height. Premises for nursing, special care, or punishment may not be located in fire retarding buildings. The second or upper storey of a fire retarding building may contain premises other than residences only if their lower storey belongs to the same premises.

Structural elements and protective linings are divided in two classes, A and B. A-class structural elements and protective linings are made of non-combustible building materials, or may contain combustible materials in such small quantities and in such locations that they do not cause damage. B-class structural elements and protective linings may contain combustible building materials; protective linings, however, may contain only small amounts. A-class structural elements are made of e.g. steel, reinforced concrete or brick.

Table 3 shows the class requirements for load-bearing structures and fire resistant elements of structures according to Finnish building code E1 (1981).

Table 3. Class requirements for load-bearing structures and fire resistant elements of structures (Finnish building code E1 1981).

Element of structure	Fire retarding	Fire retentive	Fireproof Fire load f (MJ/m^2)			
			$f \leq 100$	$100 < f \leq 200$	$200 < f \leq 400$	$f > 400$
	1	2	3	4	5	6
A. Horizontal or vertical load-bearing elements of structure which help support the framework during a fire 1)						
a) building of no more than 2 storeys						
- in general	-	B30	A30	A60	A90	A120
- buildings with attics, those elements in the upper storey and roof which form an essential part of the supporting framework 2)	-	B30	B30	B60	B60	B60
- buildings with attics, those elements in the upper storey and roof which do not form an essential part of the supporting framework 2)	-	B10	B10	B10	B10	B30
b) building of no more than 4 storeys	-	-	A30	A60	A120	A180
c) buildings of no more than 8 storeys	-	-	A60	A60	A180	A240
d) buildings of over 8 storeys	-	-	A90	A120	A240	A240
e) basement storeys situated beneath the topmost basement storey, unless a higher class is required for them in part d) above	A60	A60	A60	A90	A180	A240
B. Fire resistant elements of structure with the exeption of exterior walls in						
- buildings of no more than 8 storeys	B30	B30	B30	B60	B90	B120
- buildings of over 8 storeys	-	-	A30	A60	A90	A120
C. On the attic level, walls and ceilings surrounding a space used as other than an attic, unless a higher class is required in points A and B above	-	B30 3)	B30 3)	B30 3)	B60 3)	B120 3)
D. Exits which fulfil the requirements for fire resistant compartments, and on each storey a separated space adjacent to exits	-	B30	A30	A60 4)	A120 4)	A120 4)
E. Fire walls						
a) fire walls in general	A120	A120	A120	A120	A180	A240
b) joint fire walls	A120	A120	A120	A240	A240	A240
c) fire resistant wall used instead of a fire wall	A60 B90	A120 B180				

Notes to the Table:

1) Does not apply to those roof structures located in attics or roof cavities which are not an essential part of the supporting framework or are not structures which help support the framework during a fire.

2) These class requirements apply only to buildings which do not contain overnight accommodations or day-care premises, and in cases where no special danger exists of having to evacuate the building or of a fire spreading in the surroundings. Essential parts of the load-bearing framework are usually the main girders and, in case of fire, essentially stabilising elements. The insulation in the roof must be non-combustible or of a building material specially approved for this purpose.

3) These class requirements are meant for the prevention of interior fires.

4) Staircases, landings and passageways which lead from a fire resistant compartment to a separated exit must fulfil class A30 requirements when their fire-load is not more than 200 MJ/m^2, and class A60 requirements when the fire load is greater than 200 MJ/m^2.

So-called natural fires are ones where the temperature-time history is determined by the fire load or combustible contents and ventilation conditions of a compartment. Natural fires are different in nature and in effect and may be considered to be more realistic than the standard fire. Steel structures can benefit considerably from this approach as it is often possible to demonstrate that no fire protection is needed for buildings with low fire loads. Examples are buildings of large volume, such as sport halls, some retail premises, car parks, and railway and airport terminals. (BS 5950 1990).

For unprotected carbon steel columns subjected to the standard fire test, failure occurs already after 10 to 30 minutes depending on the load level and the dimensions and shape of the cross-section. According to Lennon (1995), the cost of fire protection is typically 30% of the total material cost of a multi-storey steel frame.

The possibilities to use austenitic stainless steels in load-bearing structures without fire protection seem quite realistic on the basis of the results of this study, when the required fire resistance time is 30 minutes or less. However, this requires further examination especially concerning the material properties determined by transient-state tests.

If a structure does not require fire protection, surface treatments do not restrict design, maintenance costs are lower, and the structure is easy to clean and has good wear resistance. The fire resistance properties and good corrosion properties of austenitic stainless steels may be beneficial, for example, in the frames of greenhouses, in composite columns, in corrugated steel sheets, in fire resistant elements of structures, and in load-bearing structures of the paper, chemical and chemical wood pulp industries.

6 CONCLUSIONS

Stress-strain relationships at elevated temperatures were determined by the steady-state tensile tests for two austenitic stainless steel types, Polarit 725 (material number 1.4301 and AISI 304) and Polarit 761 (material number 1.4571 and AISI 316 Ti). The material properties were determined for both virgin sheet and strongly strain-hardened material. The remaining increased yield strength at elevated temperatures was studied with steady-state tests of coupons cut from a rectangular hollow section 60 x 60 x 5.

The effect of thermal properties on the temperatures of carbon steel and stainless steel cross-sections was considered by calculations based on the finite element method. The gas temperature was assumed to rise according to the relationship specified in ISO 834 (1975), which is known as the standard time-temperature curve. The maximum temperatures in a cross-section strongly depend on its dimensions. The difference between temperatures of stainless steel and carbon steel cross-sections increases with the thickness of the cross-section.

At temperatures above 500 - 600 °C the yield strength (stress at a proof strain of 0.2%) of austenitic stainless steels Polarit 725 and Polarit 761 does not decrease as strongly as that of carbon steels. As much as 50% of the yield strength of Polarit 761 remains at of 800 °C. However, it should be noted that the mechanical properties determined with steady-state tests are optimistic when only small strains are involved. On the other hand, the yield strength values of carbon steel are according to Eurocode 3, Part 1.2, determined corresponding to a total strain of 2%. The straining rate in tests was 0.5 mm/min (0.0067/min) in strains below 0.2% proof strain. The straining rate was higher than the required straining rate (0.001...0.005/min) according to SFS-EN 10002-5 (1992).

The modulus of elasticity of stainless steels was determined from the tensile tests and compared with values based on the literature and with the modulus of elasticity of carbon steel determined in accordance with Eurocode 3. Part 1.2 (ENV 1993-1-2 1995). The modulus of elasticity of austenitic stainless steels decreases more slowly than that of carbon steels.

The increase in strength from the cold-work process which remains at elevated temperatures was studied with steady-state tests of coupons cut from RHS 60x60x5. The test results show that the effect of work-hardening is kept constant up to 600 °C and that above this the strength corresponding to a proof strain of 0.2% of cold-worked material is reduced. The strength of both virgin sheet and cold-worked material are similar at 900 °C. The elongation to fracture of cold-formed material is much smaller than that of a virgin sheet. The cold-forming process decreases the elongation of stainless steel due to plastic deformation. The toughness of titanium stabilised austenitic stainless steel is lower than that of conventional austenitic stainless steel.

A calculation example was given where the critical temperature was determined for a carbon steel column and for a stainless steel column of cross-section 300 x 300 x 12.5. On the basis of critical temperature, the fire resistance time is determined where the gas temperature was assumed to rise according to the relationship specified in ISO 834. According to the example, the critical temperature of carbon steel corresponds to a fire resistance time of 19 minutes, that of stainless steel Polarit 725 to 25 minutes and that of stainless steel Polarit 761 to 41 minutes in a standard fire. The fire resistance time depends on the strength of the material, on the dimensions and shape of the cross-section, on the buckling length of the column and, naturally, on the reduction factor for the design load level for a given fire situation.

The results of this study are promising concerning the application possibilities of austenitic stainless steels when fire resistance is required. The possibilities to use austenitic stainless steels in load-bearing structures without fire protection seem quite realistic on the basis of the results of this study, when the required fire resistance time is 30 minutes or less. However, this requires further study especially concerning the material properties determined by transient-state tests.

If a structure does not require fire protection, surface treatments do not restrict design, maintenance costs are lower, and the structure is easy to clean and has good wear resistance. The fire resistance properties and good corrosion properties of austenitic stainless steels may be beneficial, for example, in the frames of greenhouses, in composite columns, in corrugated steel sheets, in fire resistant elements of structures, and in load-bearing structures of the paper, chemical and chemical wood pulp industries.

REFERENCES

Dier, A. 1991. Design manual for structural stainless steel. Joint industry study. London: Steel Construction Institute (SCI). 236 p. (document SCI-RT-256, Rev. 0).

Diercks, D.R. & Burke, W.F. 1974. Elevated temperature true stress-true strain tensile behaviour of AISI Type 304 stainless steel. In: Schaefer, A.O. (eds.) Elevated temperature properties of austenitic stainless steels. Miami Beach, 1974 ASME pressure vessels and piping conference. Pp. 20-30.

ENV 1991-2-2. 1992, Eurocode 1, Basis of design and actions on structures - Part 2.2: Actions on structures exposed to fire. Brussels: European Committee for Standardization (CEN). 32 p.

ENV 1993-1-2. 1995. Eurocode 3, Design of steel structures - Part 1.2: Structural fire design. Brussels: European Committee for Standardization (CEN). 64 p.

Hoke, J.H. 1977. Mechanical properties of stainless steels at elevated temperatures. In: Peckner, D. & Bernstain, I.M. (eds.) Handbook of stainless steels. Pp. 21-1 - 21-20.

Incropera, F.P. & DeWitt, D. P. 1981. Fundamentals of heat and mass transfer. School of Mechanical Engineering Purdue University. 819 p.

ISO 834. 1975. Fire resistance tests. Element of building construction. Switzerland: International Organization of Standardization.

Kay, P.W. & Hancock, G.J. 1993. A finite strip method for the elastic-plastic large displacement analysis of thin-walled and cold-formed steel sections. Thin-Walled Structures, Vol. 16, pp. 3 - 29.

Lawson, R.M. & Newman, G.M. 1990. Fire resistant design of steel structures. A handbook of BS 5950, Part 8. London: Steel Construction Institute (SCI). 132 p. (document SCI-P-080).

Lennon, T. 1995. Portable furnaces. New Steel Construction, Vol. 3, pp. 21 - 24.

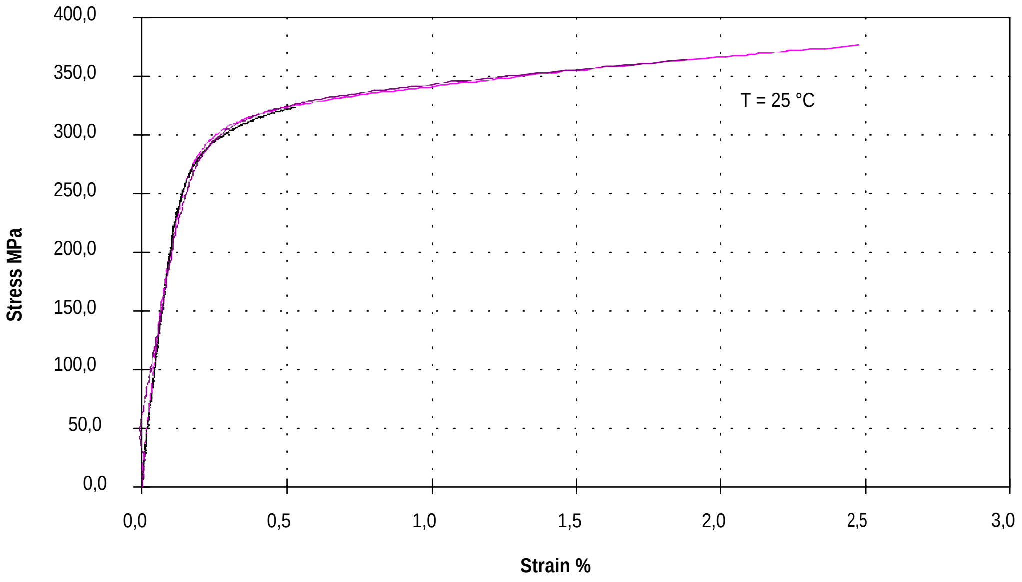
Lewis, J.R. 1977. Physical properties of stainless steels. In: Peckner, D. & Bernstain, I.M. (eds.) Handbook of stainless steels. Pp. 19-1 - 19 -36.

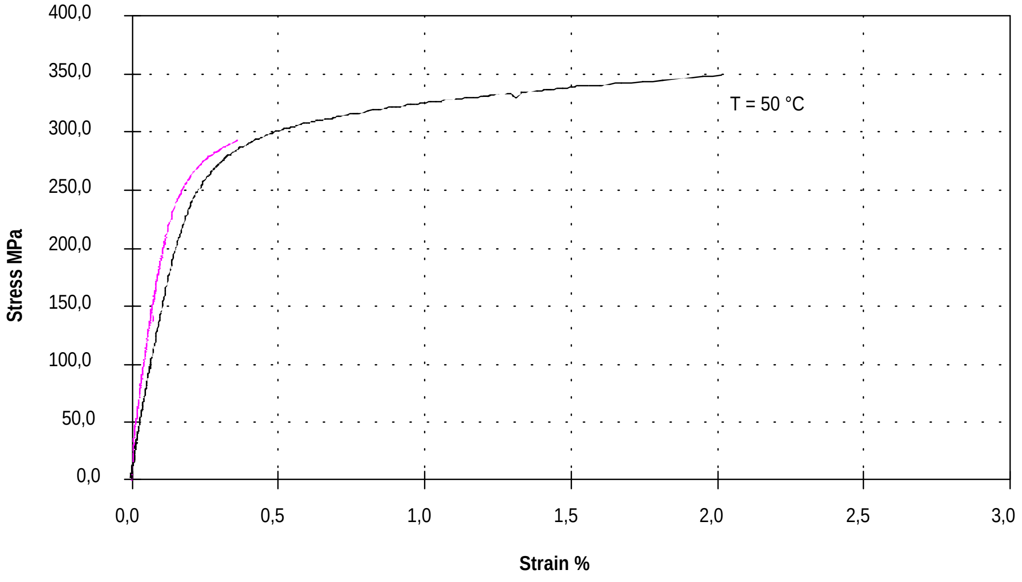
Rakenteellinen paloturvallisuus. 1981. Määräykset. (Finnish building code E1 for structural fire safety). Helsinki, sisäasiainministeriö, Suomen rakennusmääräyskokoelma, Osa E1. 19 p.

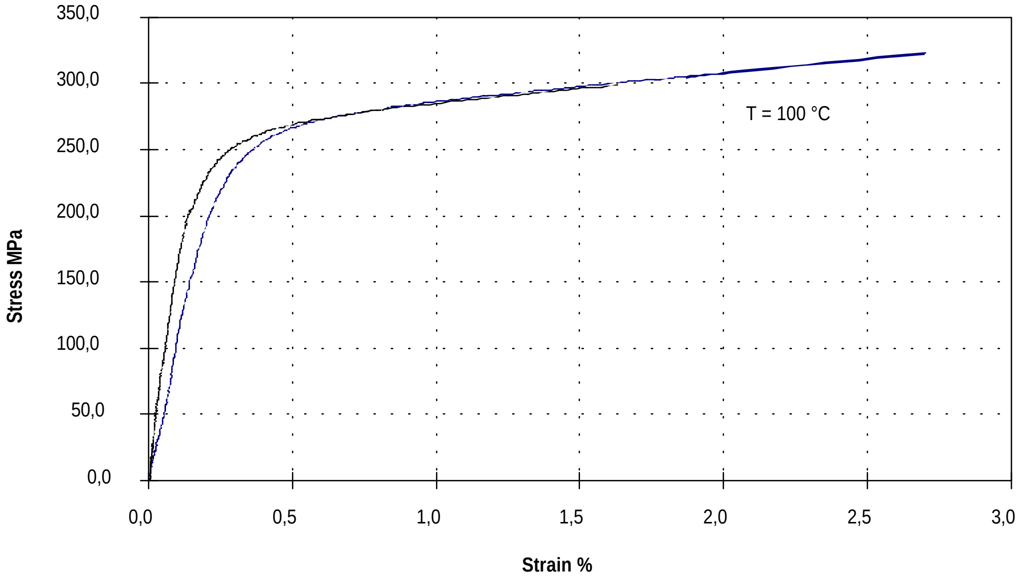
Rukajärvi, J. 1987. Polarit 725 ja 757 kuumalujuudet. Tornio: Outokumpu Oy. 10 p. (Raportti 5397-155/87).

SFS-EN 10002-5. 1992. Metallin vetokoe. Osa 5. Kuumavetokoe. (Metallic materials. tensile testing. Part 5: Method of testing at elevated temperatures.) Helsinki: Suomen Standardoimisliitto. 35 p.

STRESS-STRAIN CURVES AND MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES OF VIRGIN SHEET OF POLARIT 725



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Strain %
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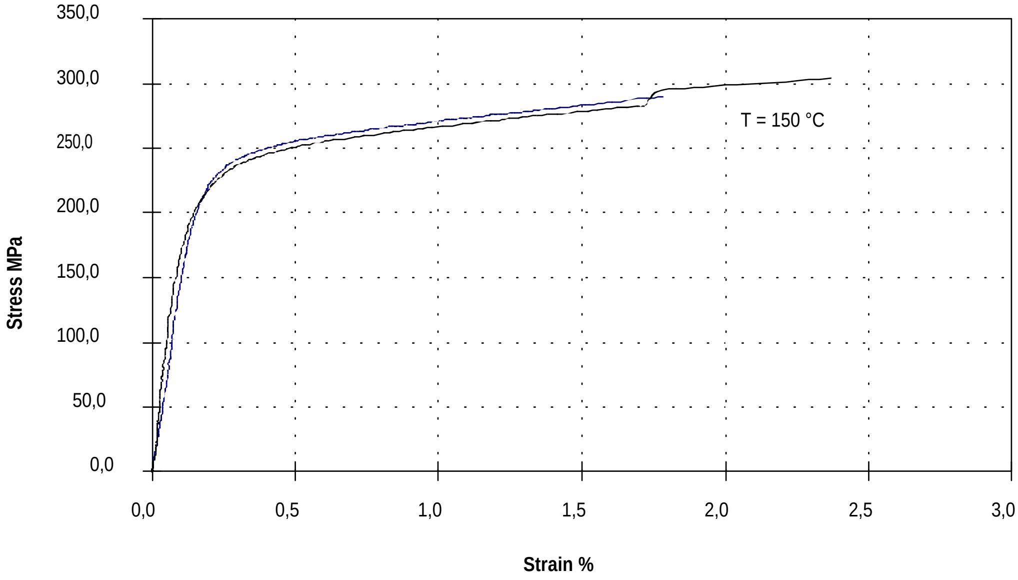
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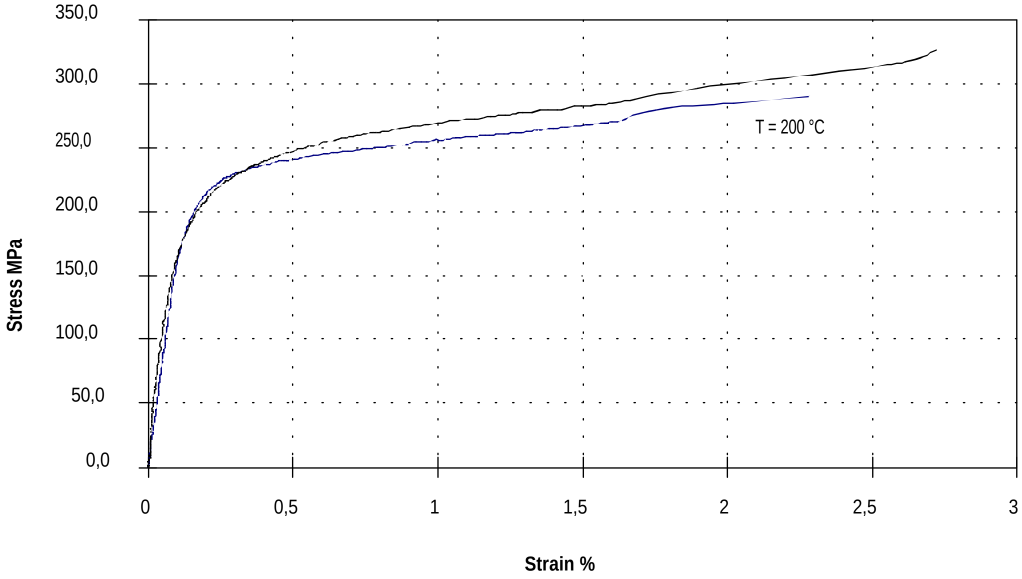
Strain %
T = 150 °C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Strain %
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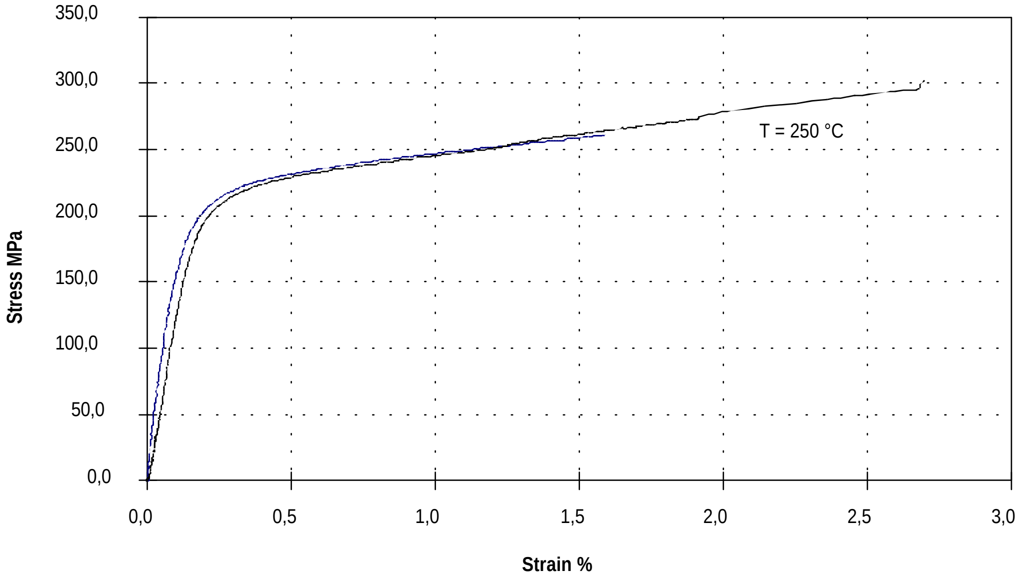
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Strain %
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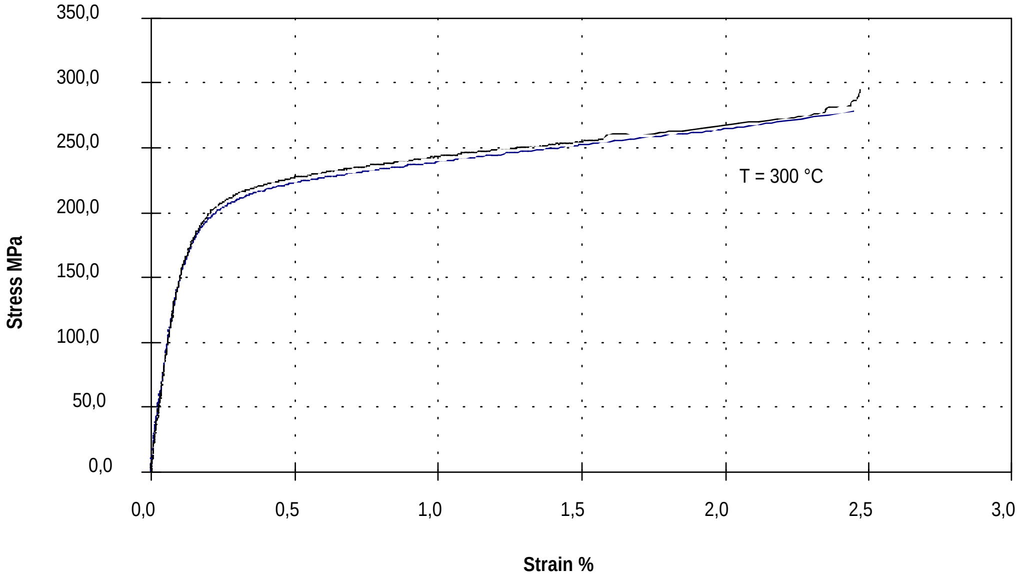
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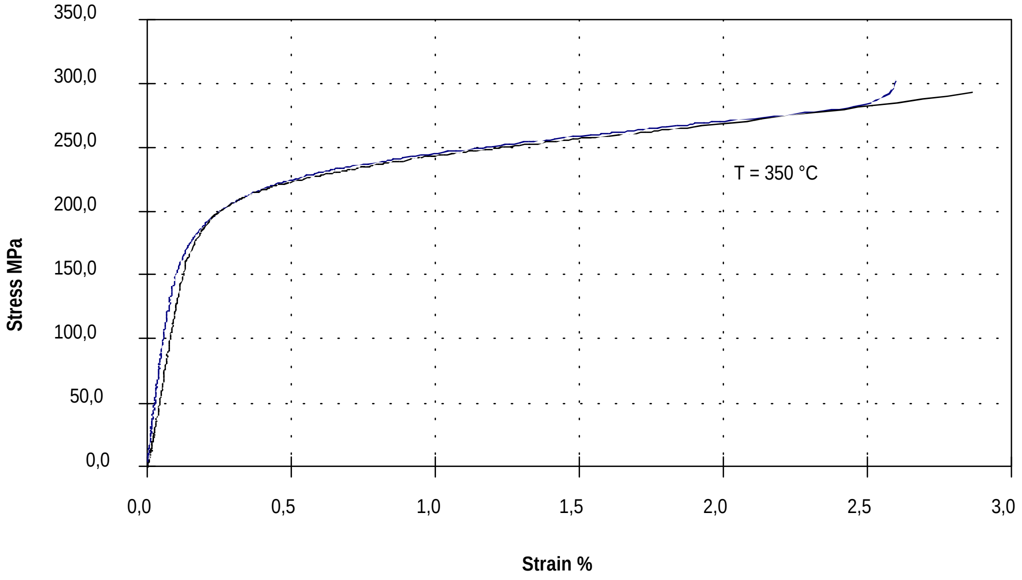
Strain %
T = 300 °C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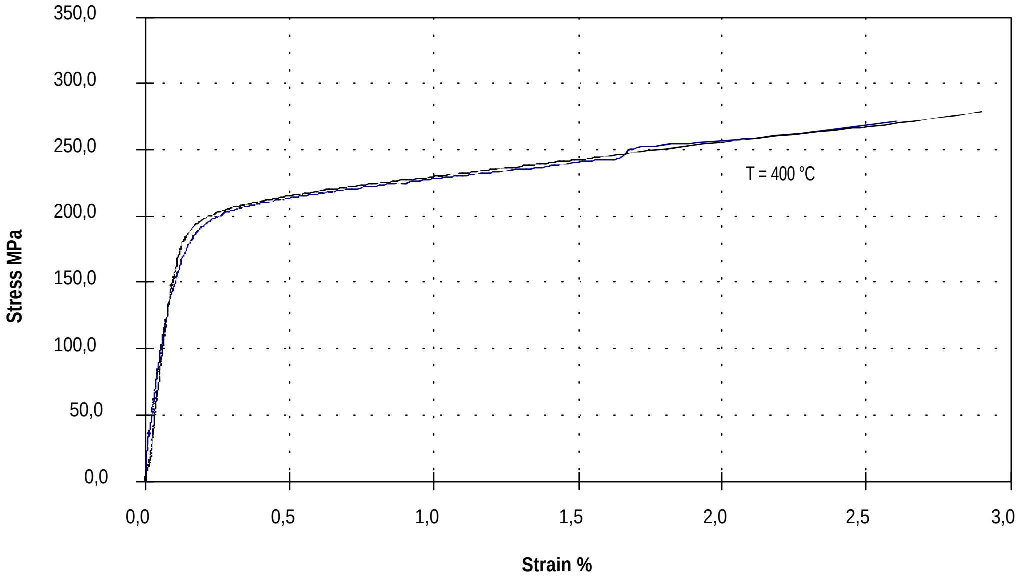
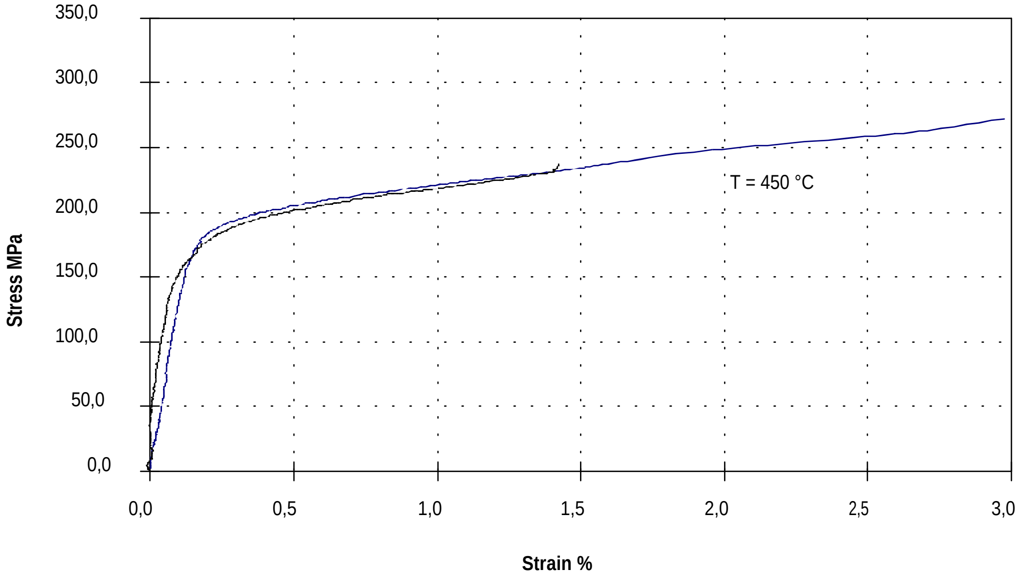
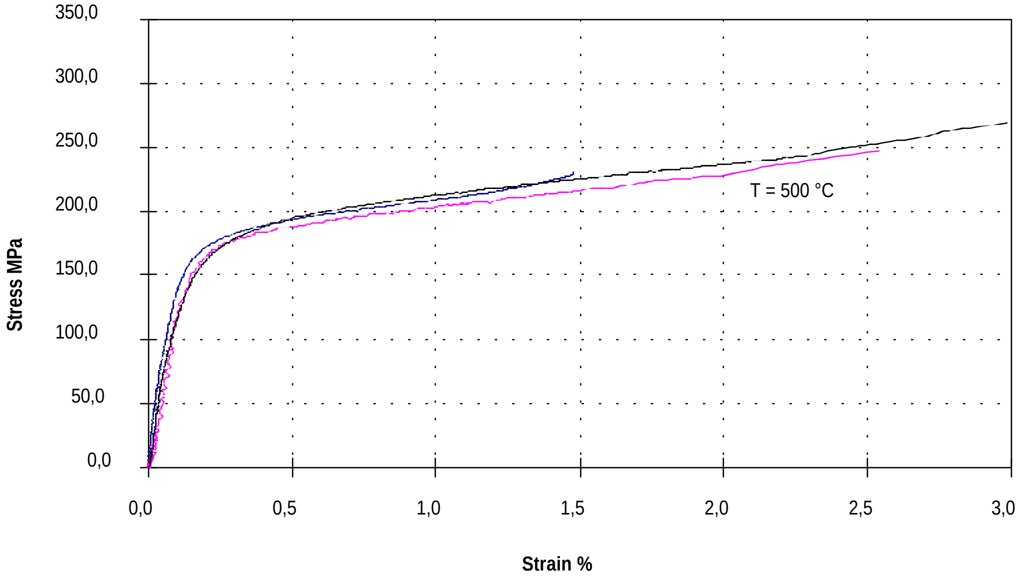
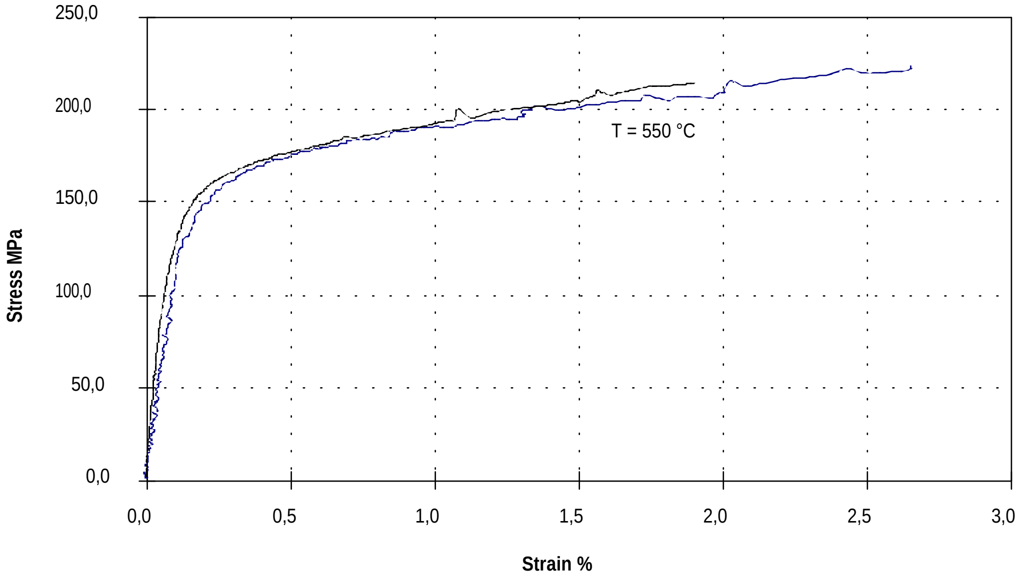
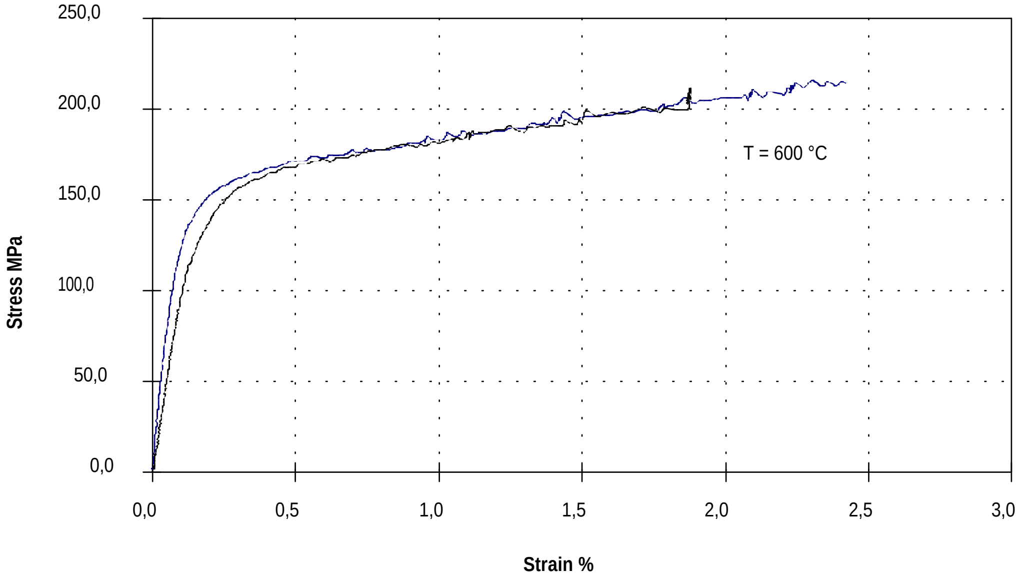
2,5
3,0
Strain %
T = 350 °C

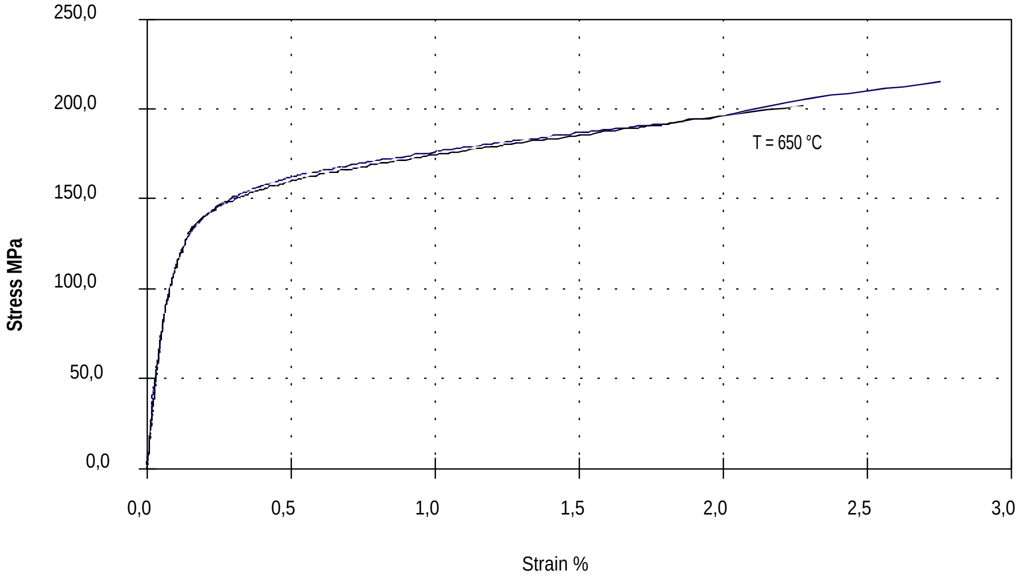

Stress MPa
350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 400 °C

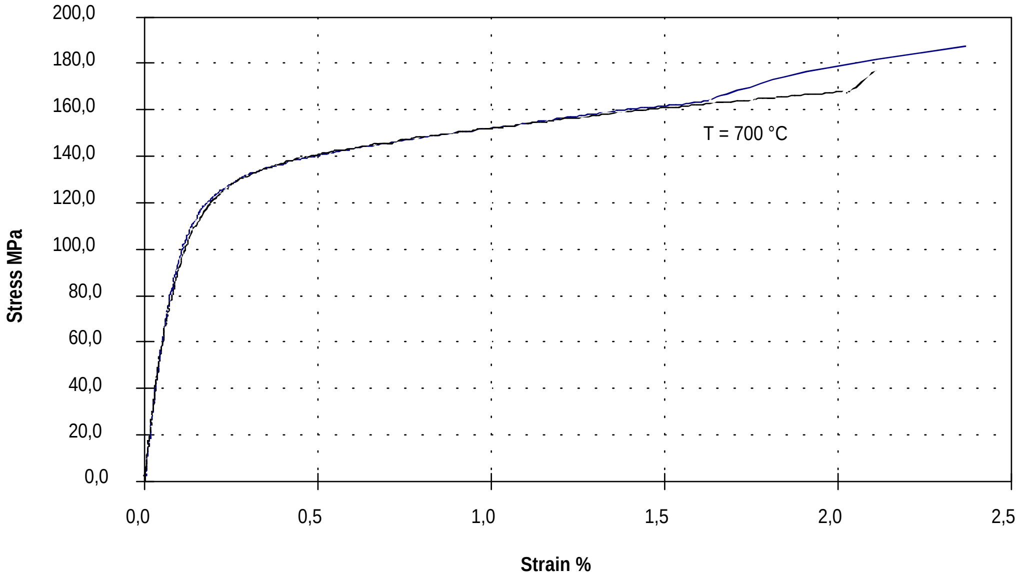

Stress MPa
350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 450 °C

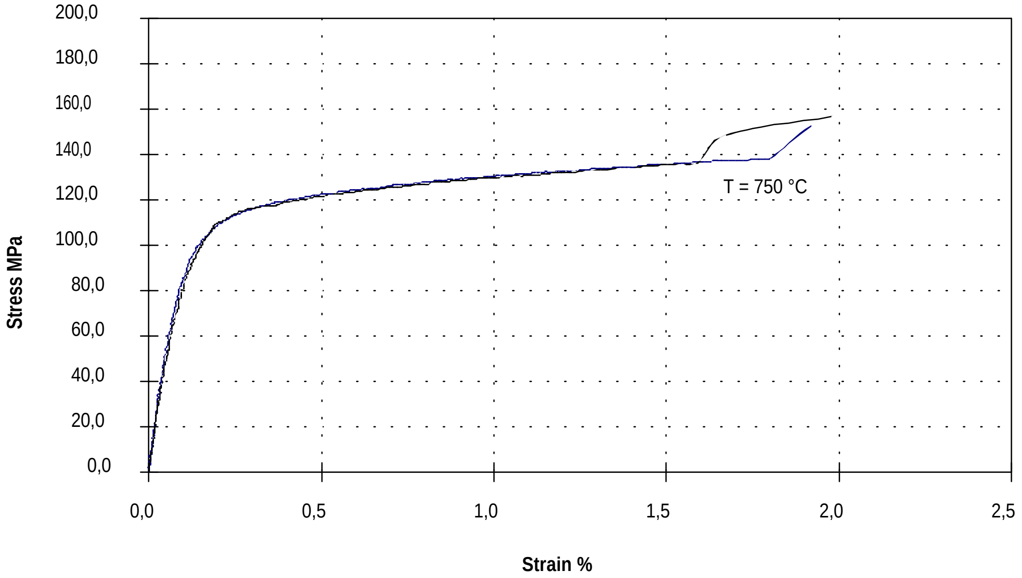

Stress MPa
350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 500 °C

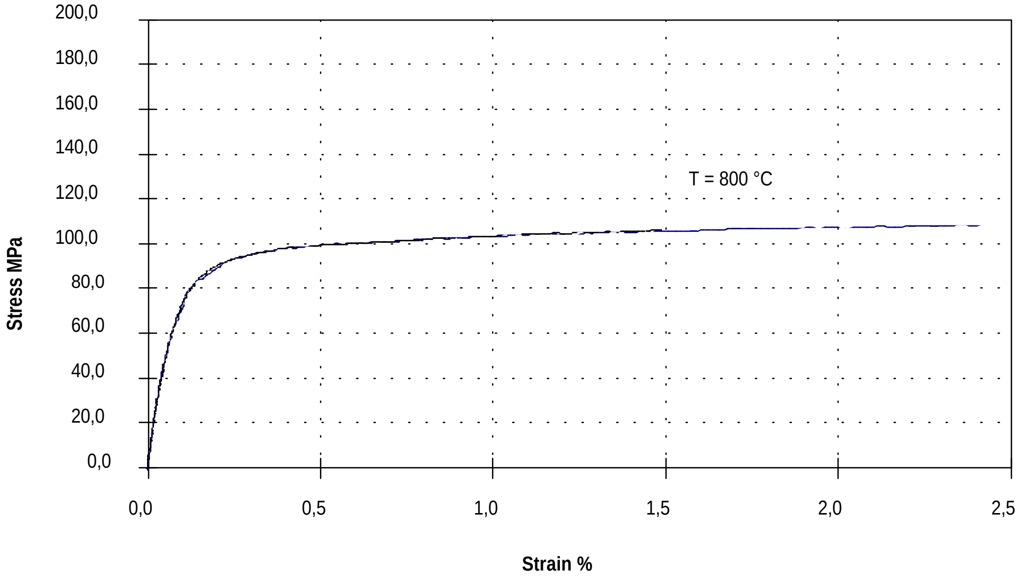

250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 550 °C

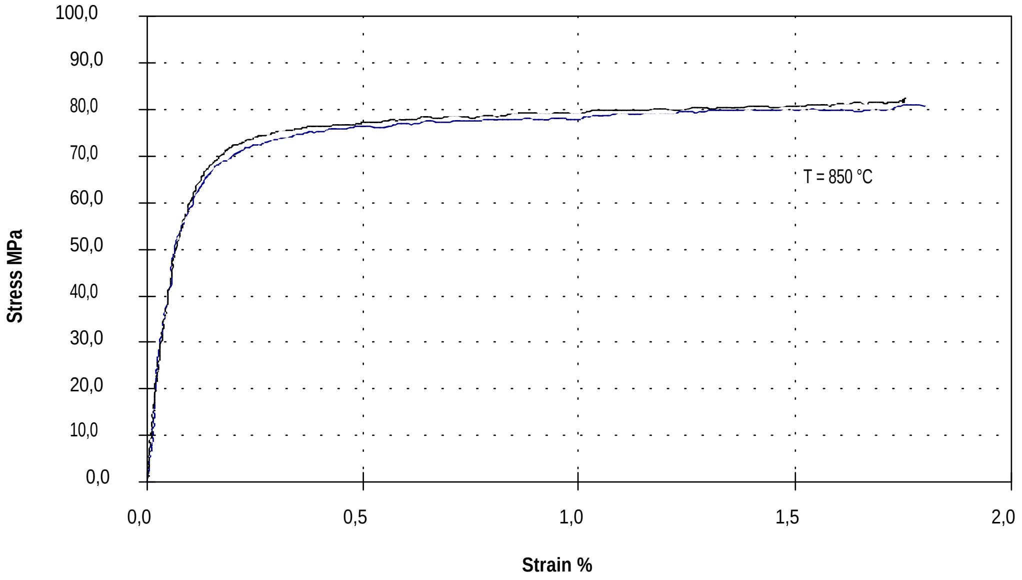

250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 600 °C


250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 650 °C


200,0
180,0
160,0
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
Stress MPa
T = 700 °C
0,0
0,5
1,0
1,5
2,0
2,5
Strain %


200,0
180,0
160,0
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
Stress MPa
T = 750 °C
0,0
0,5
1,0
1,5
2,0
2,5
Strain %


200,0
180,0
160,0
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
Stress MPa
T = 800 °C
0,0
0,5
1,0
1,5
2,0
2,5
Strain %


100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
Strain %
T = 850 °C

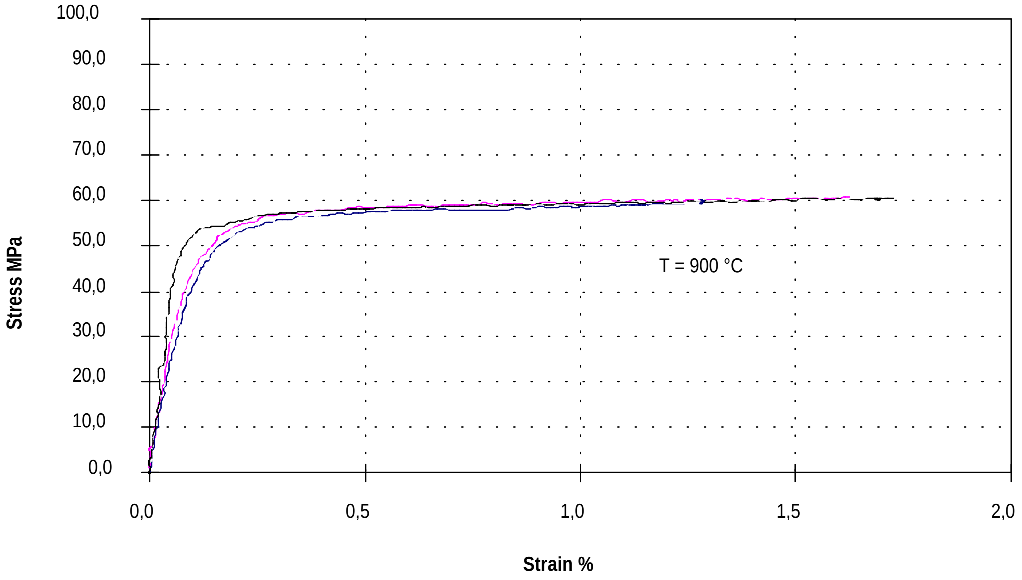
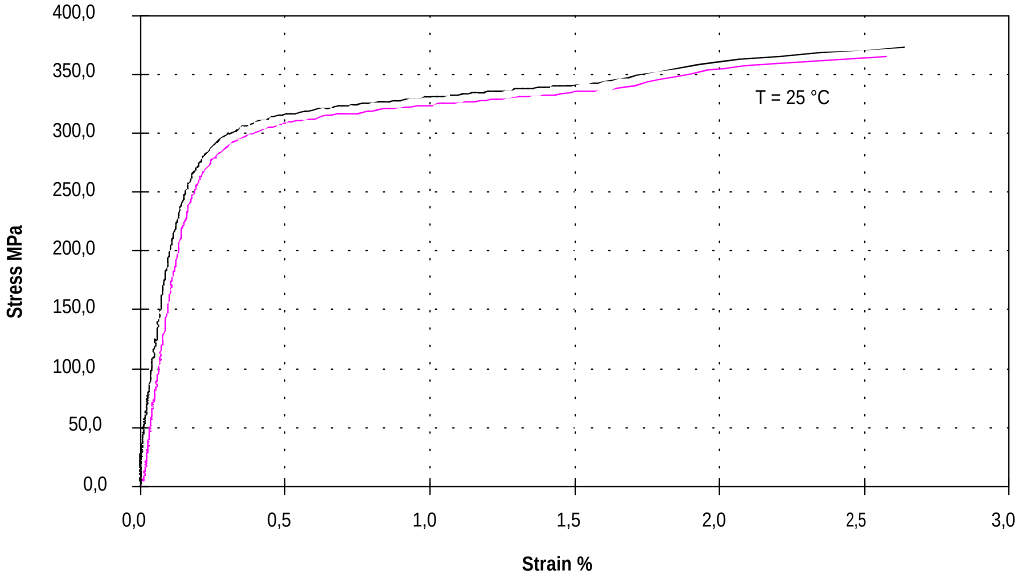
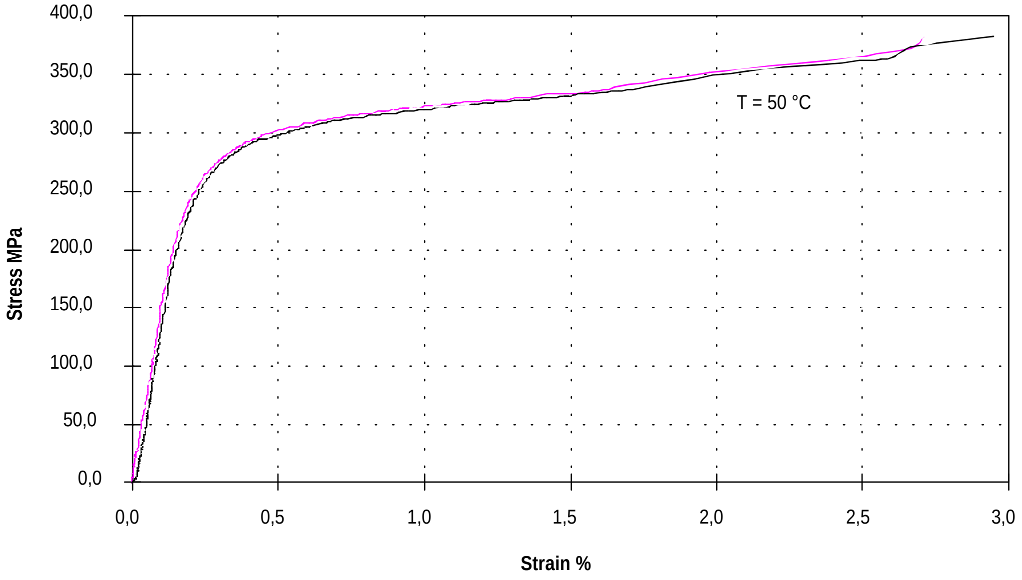

100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
Strain %
T = 900 °C

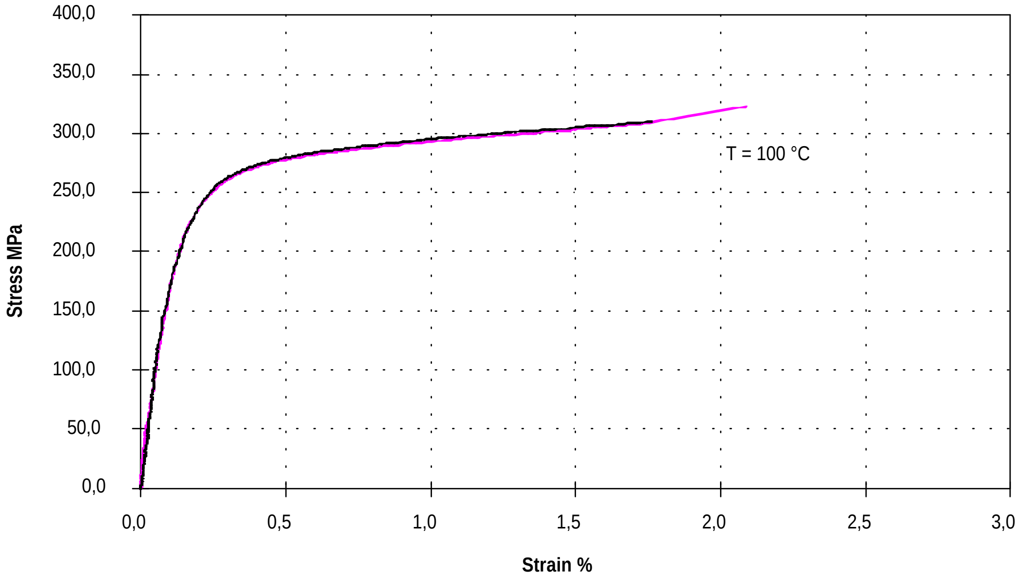
Table 1. The mechanical material properties of virgin sheet of Polarit 725.

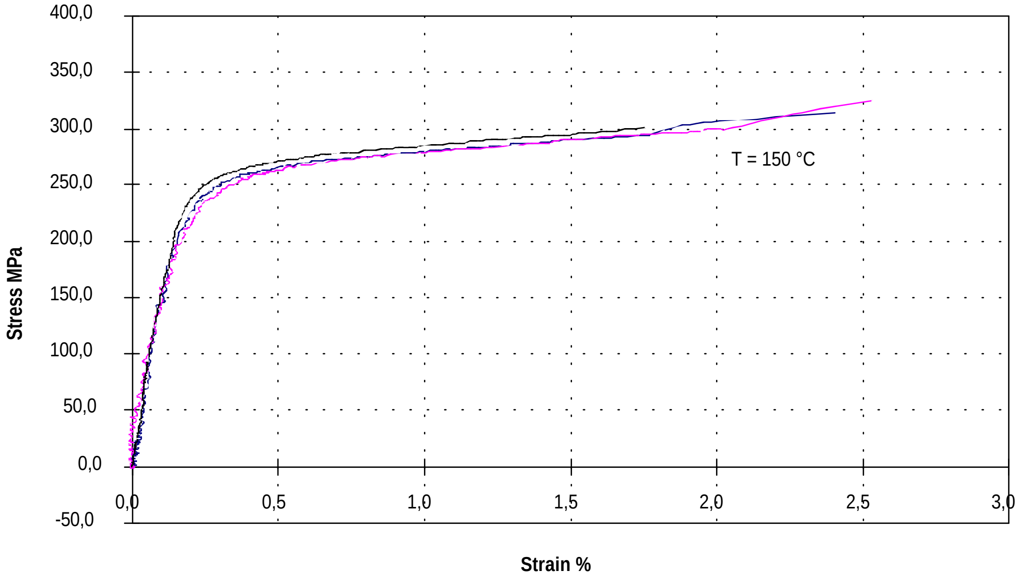
Specimen	Temperature [°C]	The modulus of elasticity [N/mm^2]	0.2%-proof stress $R_{p0.2}$ [N/mm^2]	1.0%-proof stress $R_{p1.0}$ [N/mm^2]	Tensile strength R_m [N/mm^2]	Elongation after fracture A_5
RA 1	25	219	312	345	639	56
RA 2	25	138	316	349	638	54
RA 3	25	211	309	348	642	56
RA 4	50	192	294	330	592	55
RA 5	50	152	295	334	589	54
RB 1	100	120	261	293	531	48
RB 2	100	153	260	290	531	48
RB 4	150	164	247	277	503	43
RB 6	150	186	241	272	501	44
RC 2	200	178	229	274	488	41
RC 3	200	177	233	260	481	41
RC 4	250	165	222	250	476	40
RC 5	250	135	221	250	475	40
RD 1	300	156	214	245	476	39
RD 2	300	178	218	248	477	41
RD 4	350	137	213	249	479	40
RD 5	350	189	208	249	482	38
RE 1	400	160	206	232	469	41
RE 2	400	185	207	233	472	40
RE 4	450	128	198	227	459	40
RE 5	450	167	189	223	458	41
RE 6	450	164	189	218	454	41
RF 1	500	178	183	216	436	36
RF 2	500	142	184	214	432	37
RF 3	500	138	182	209	431	38
RF 4	550	136	173	202	408	40
RF 5	550	108	168	195	407	39
RF 6	550	160	166	196	407	39
RG 1	600	169	164	187	365	39
RG 2	600	115	161	188	369	39
RG 4	650	148	152	178	322	46
RG 5	650	168	153	179	322	45
RH 1	700	134	133	156	269	60
RH 2	700	123	134	155	268	60
RH 4	750	121	117	132	218	75
RH 5	750	117	118	133	218	75
RI 1	800	115	95	105	168	86
RI 2	800	124	95	104	167	106
RI 4	850	122	74	79	130	99
RI 5	850	120	75	80	130	90
RJ 1	900	68	56	60	100	96
RJ 2	900	84	57	60	100	96
RJ 3	900	69	57	60	100	95

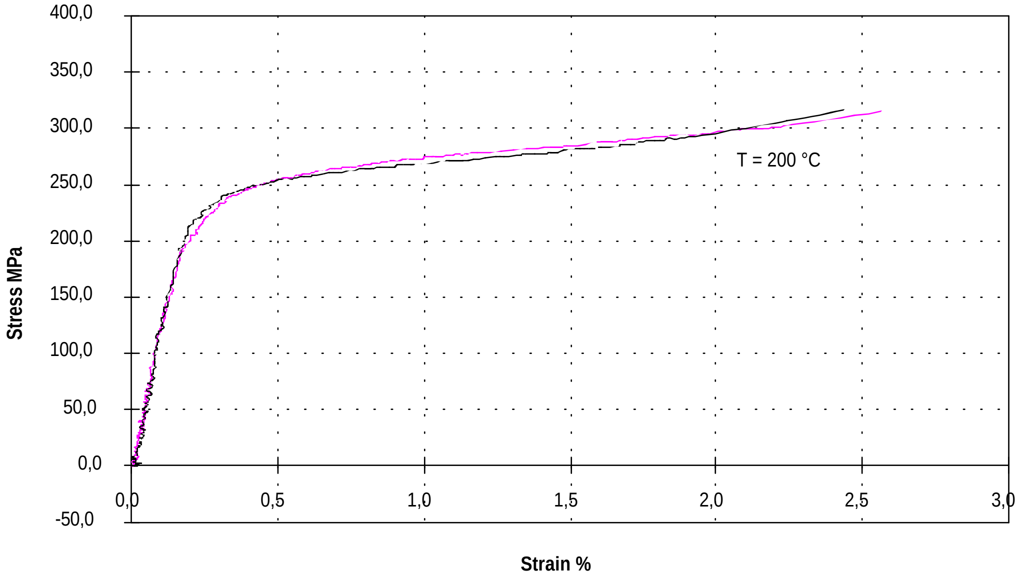
STRESS-STRAIN CURVES AND MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES OF VIRGIN SHEET OF POLARIT 761

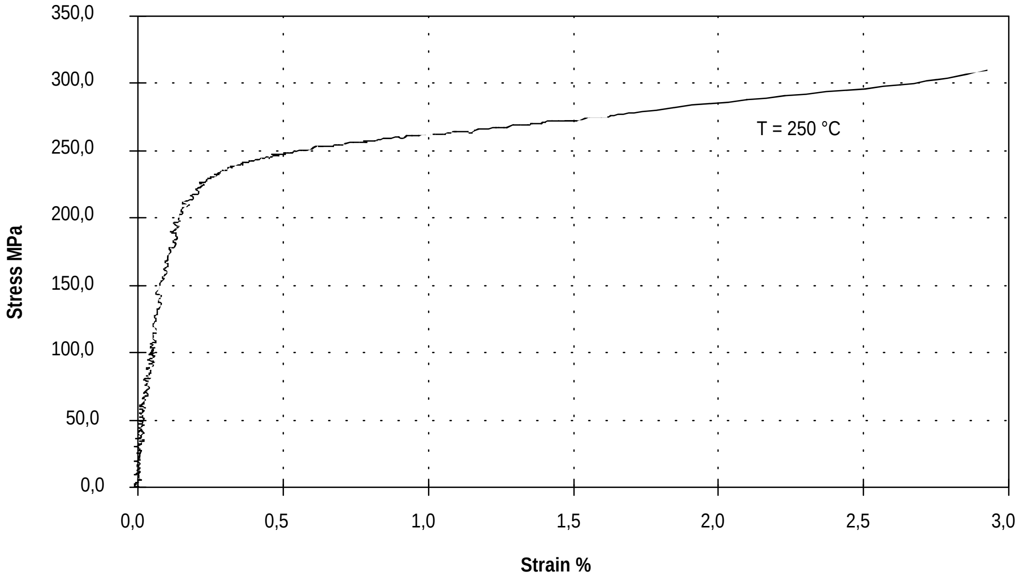


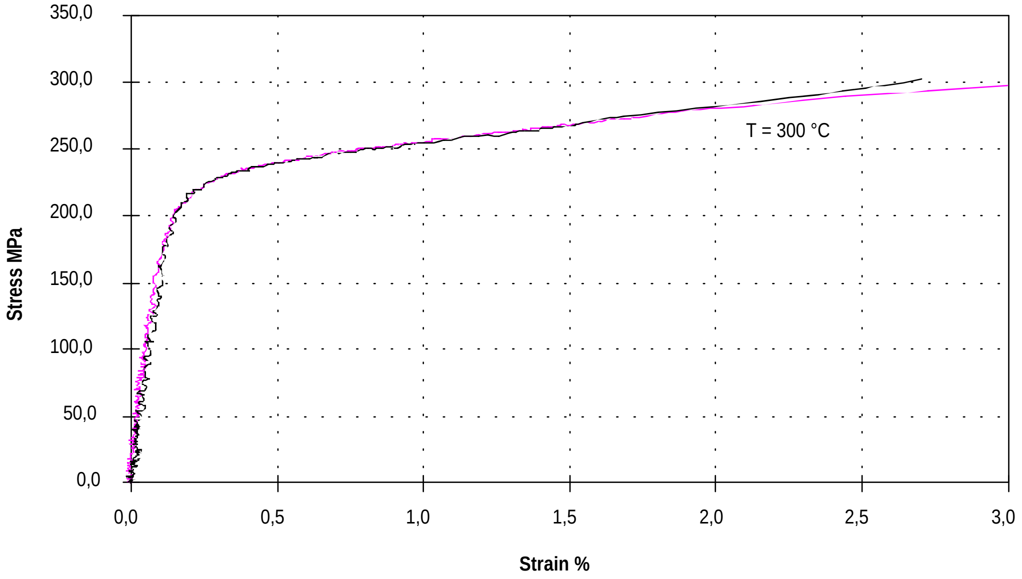


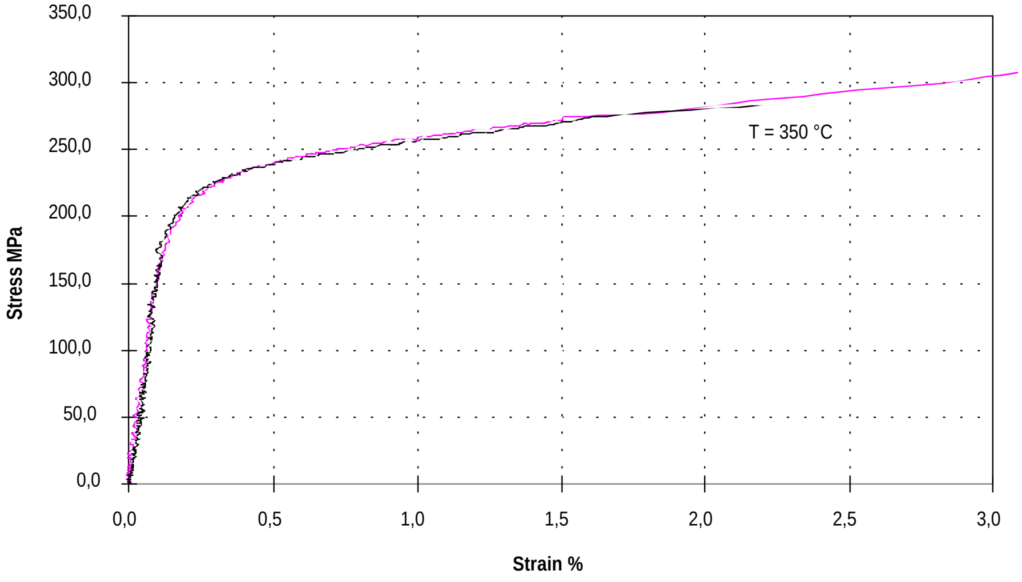

400,0
350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 100 °C

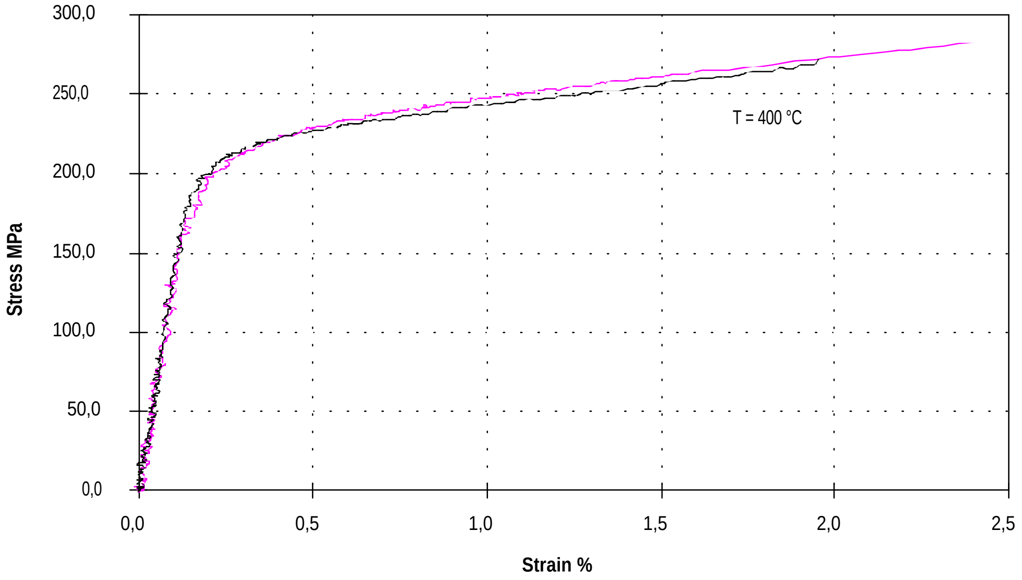

400,0
350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
-50,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 150 °C

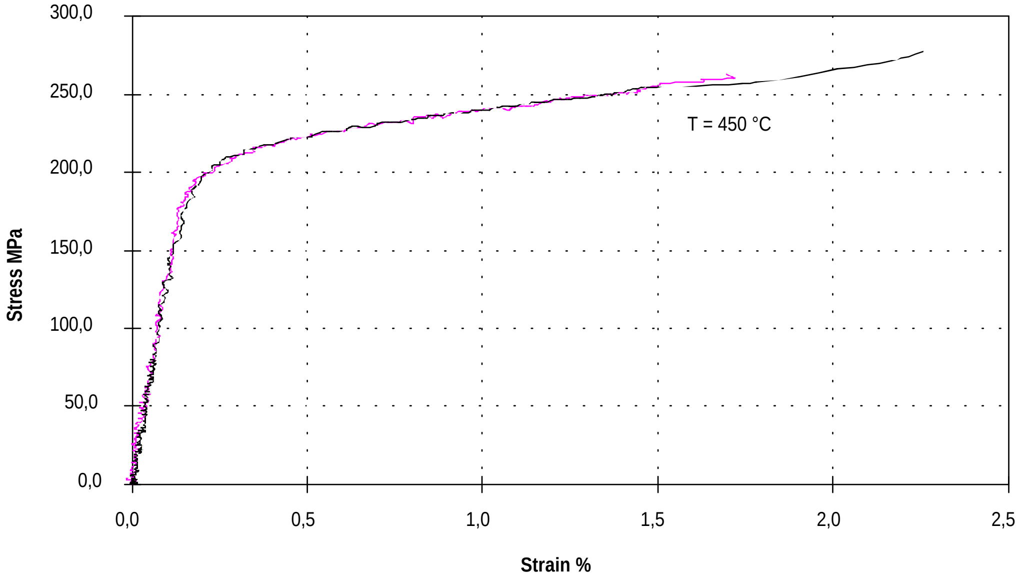

400,0
350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
-50,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 200 °C

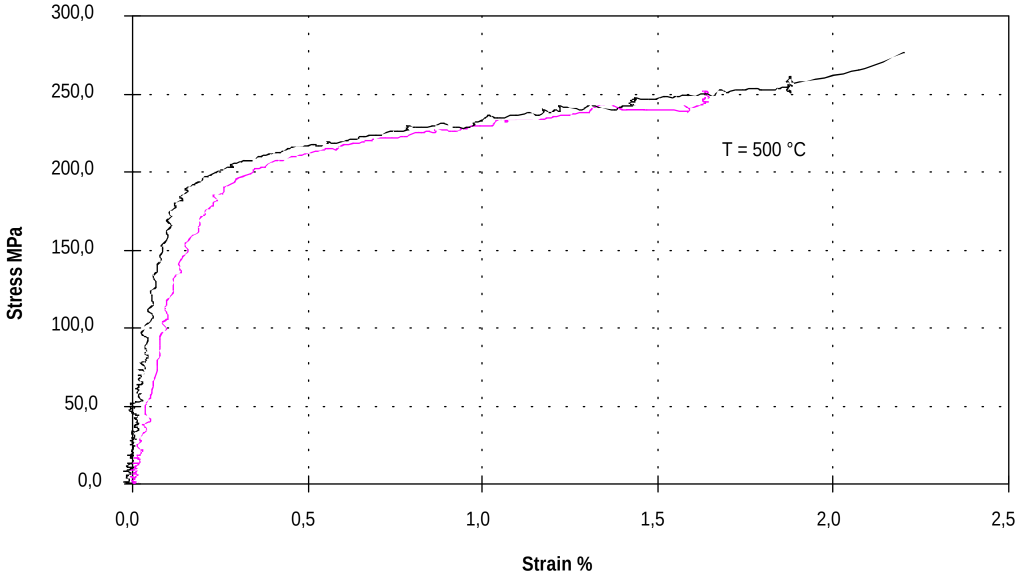

350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 250 °C

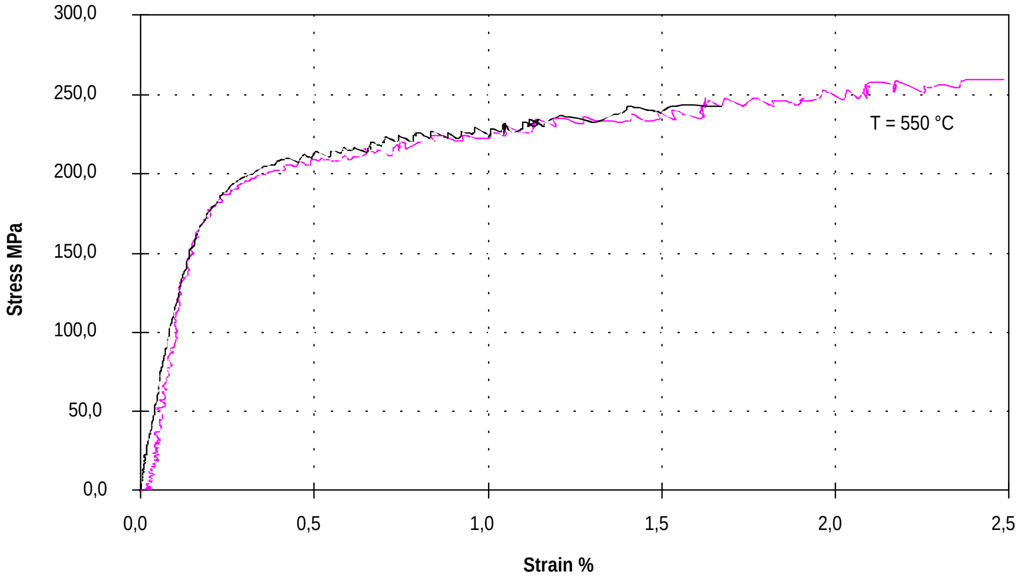

350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 300 °C

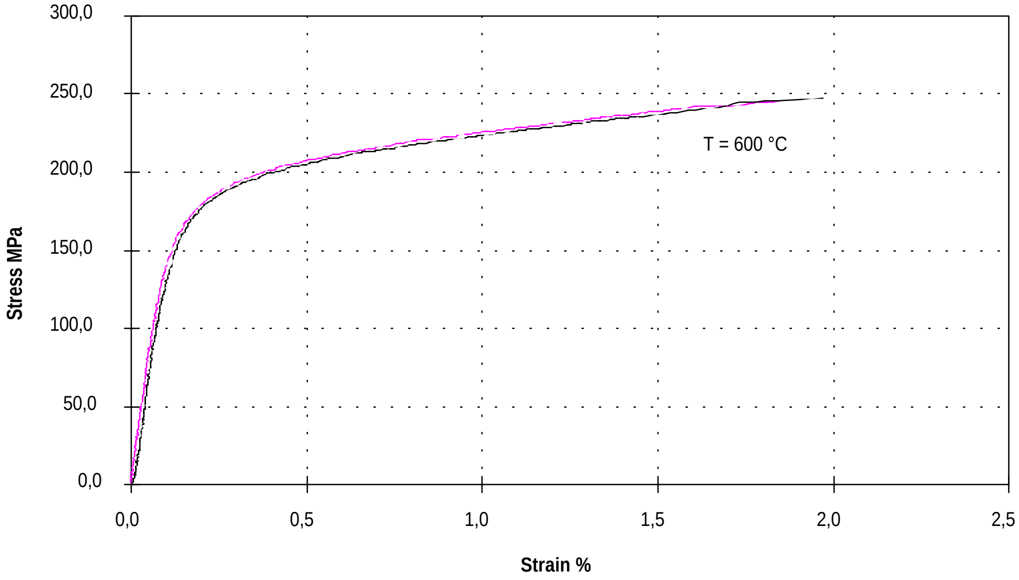

350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 350 °C

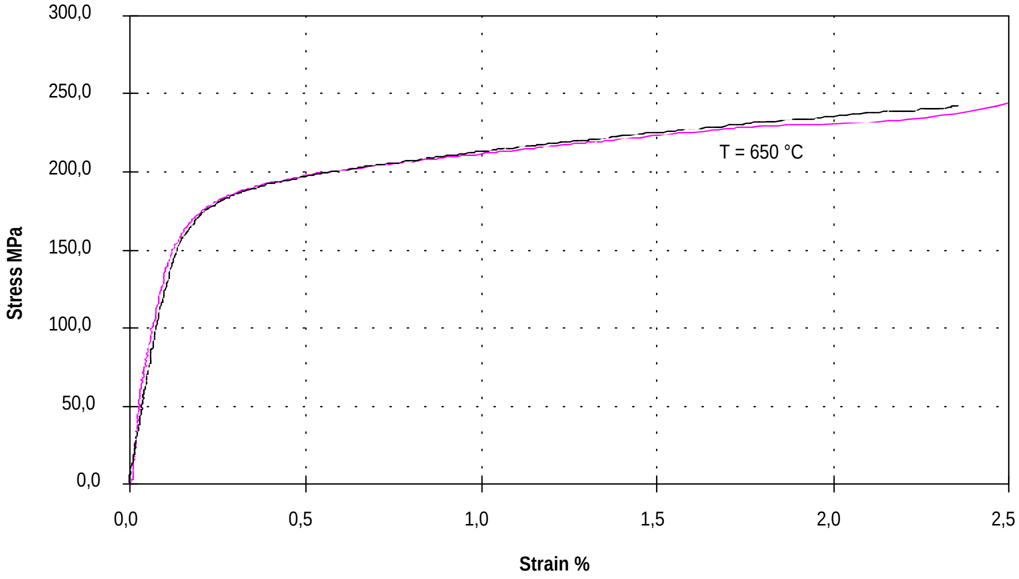

300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 400 °C

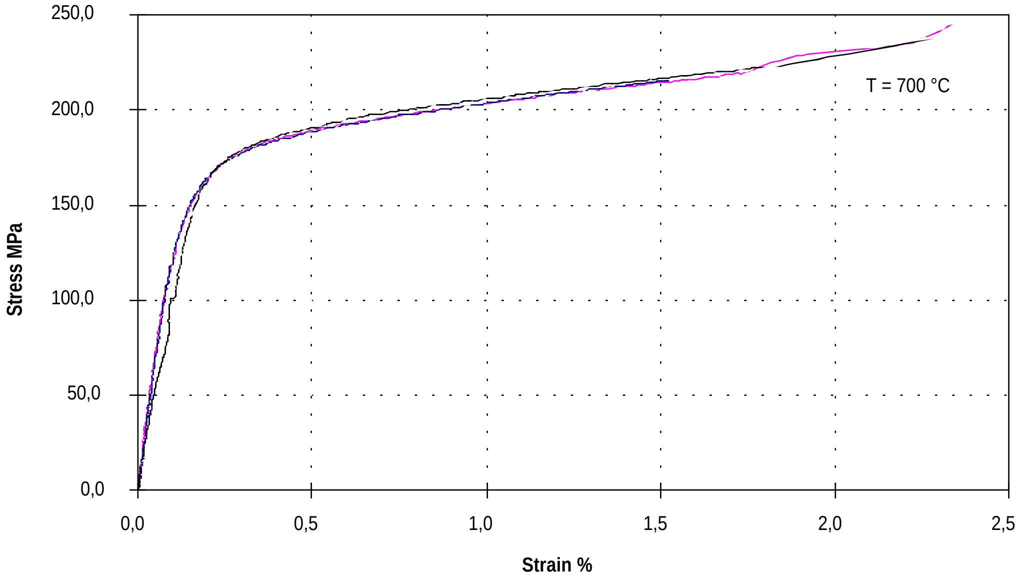

300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 450 °C


300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 500 °C

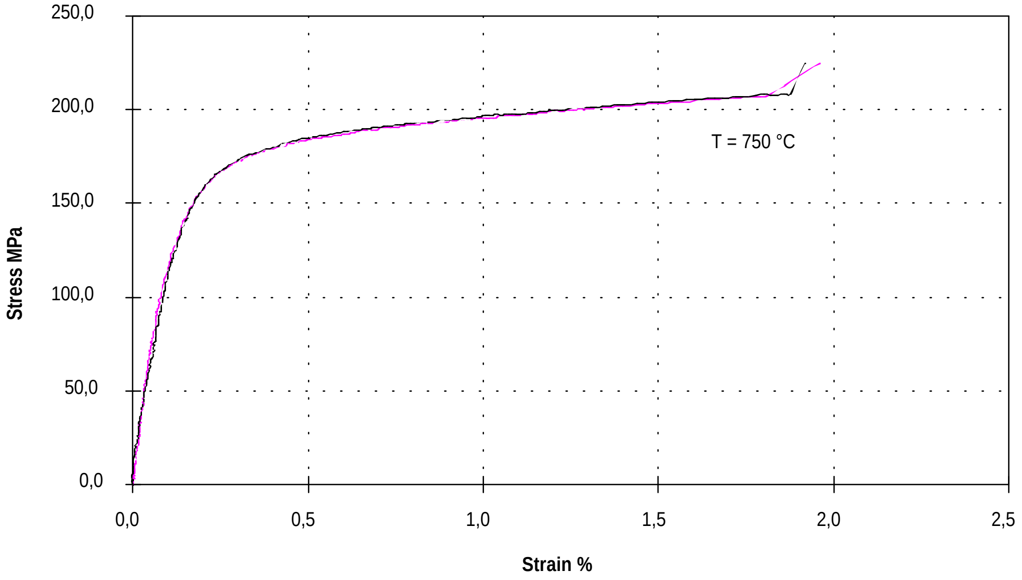

300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 550 °C


300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 600 °C

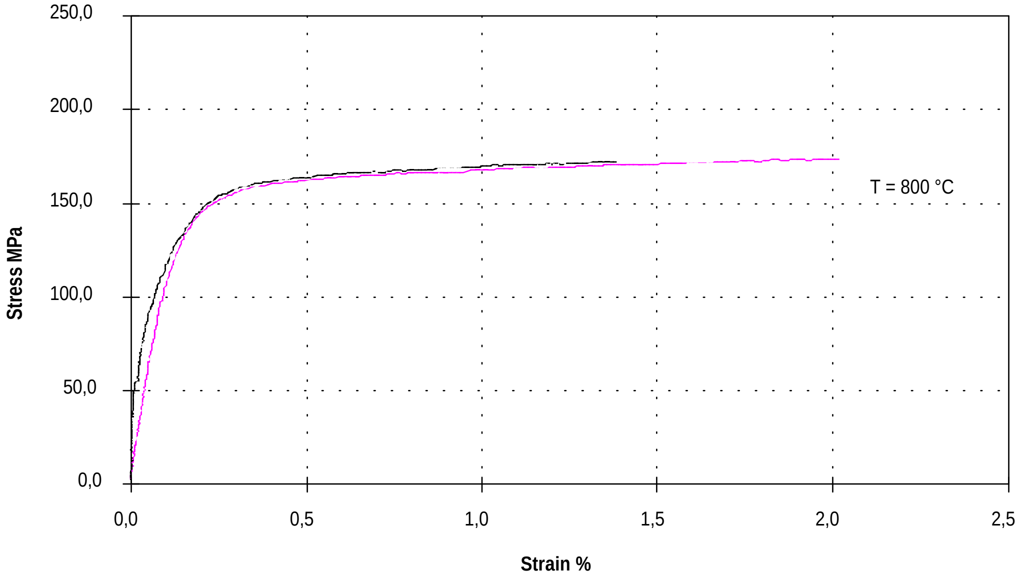

300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 650 °C



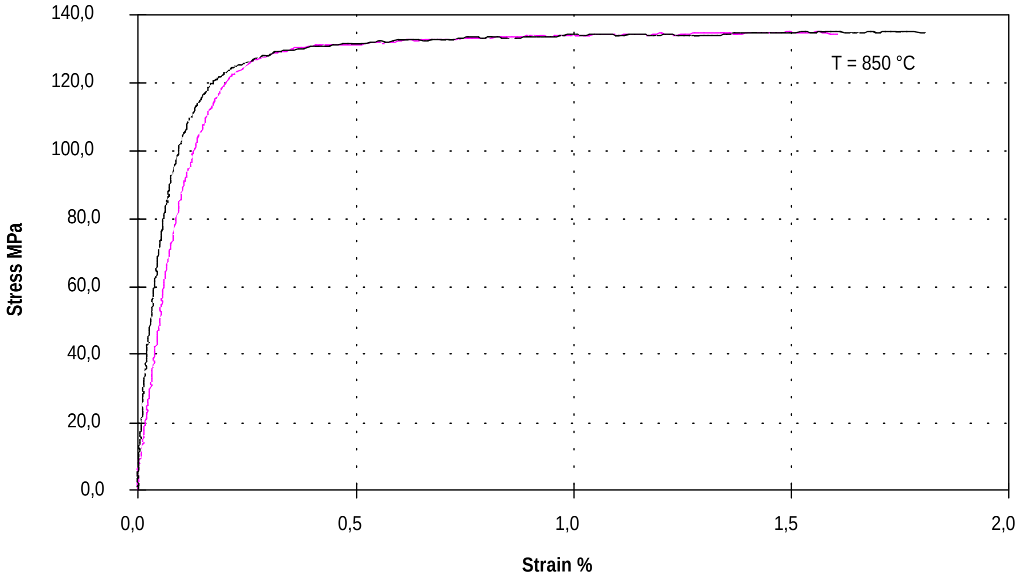
Stress MPa
250,0
200,0
150,0
100,0
50,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 700 °C

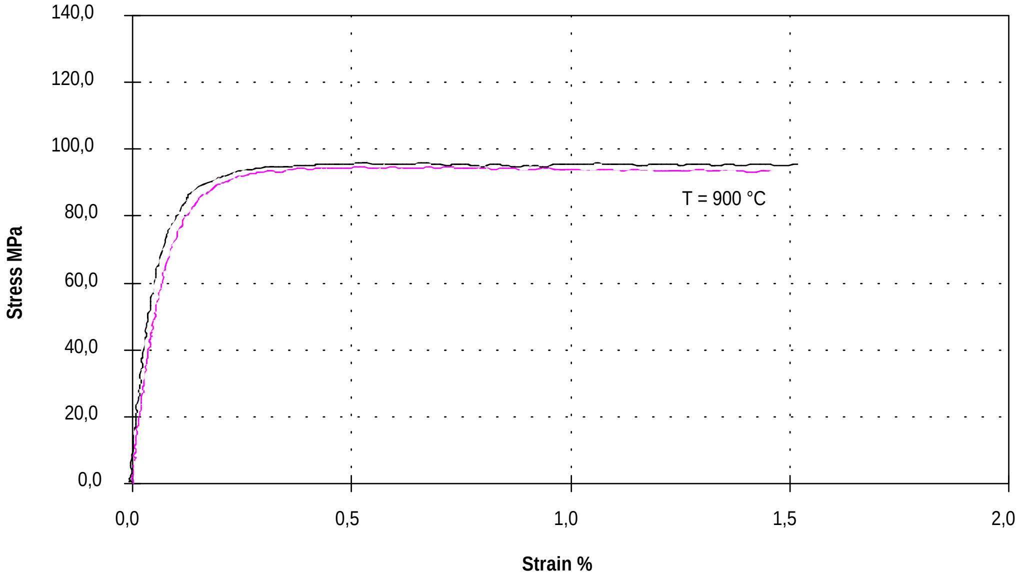


Stress MPa
250,0
200,0
150,0
100,0
50,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 750 °C



Stress MPa
250,0
200,0
150,0
100,0
50,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 800 °C


Stress MPa
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
0,0
0,5
1,0
1,5
2,0
Strain %
T = 850 °C


Stress MPa
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
0,0
0,5
1,0
1,5
2,0
Strain %
T = 900 °C

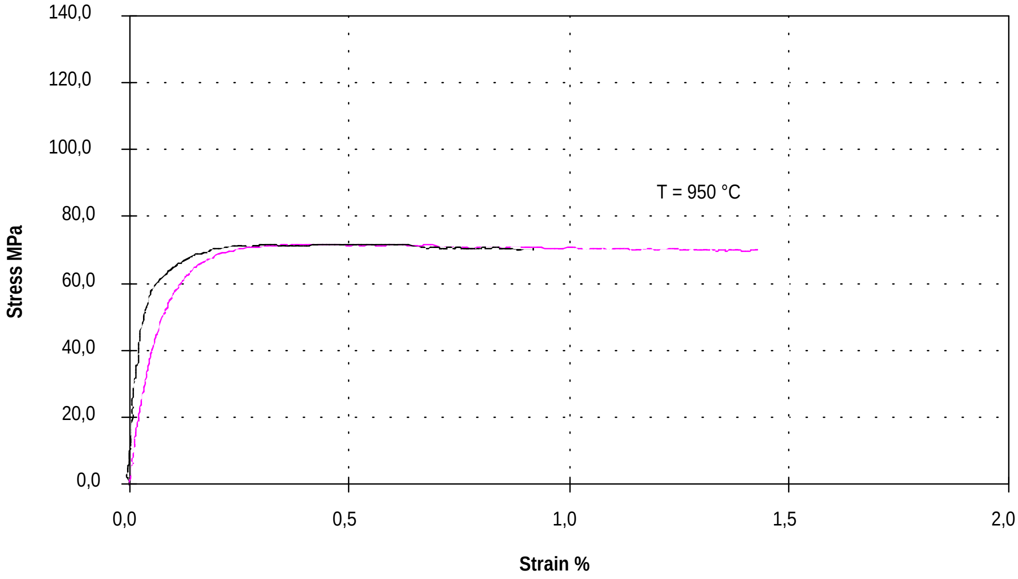
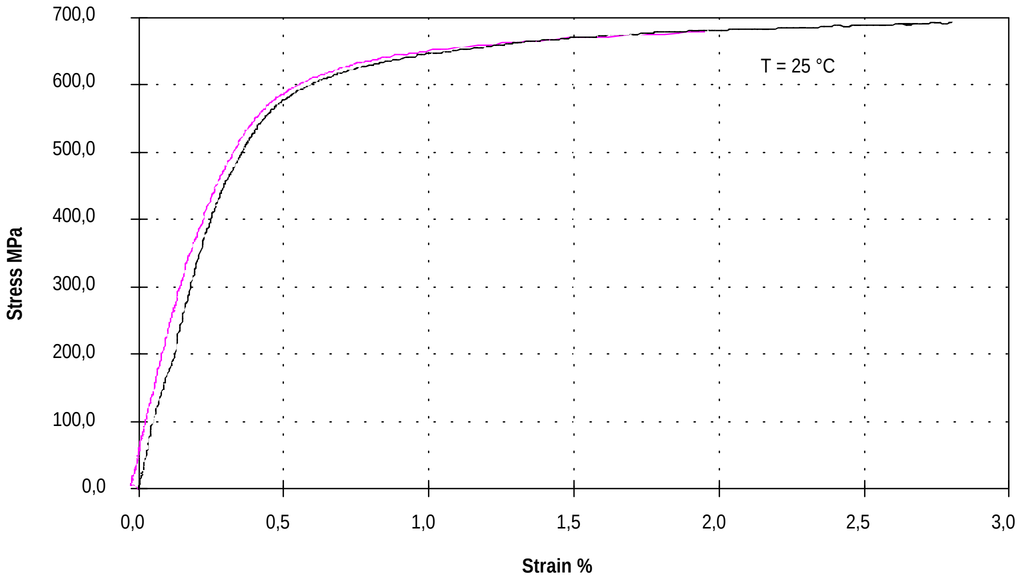
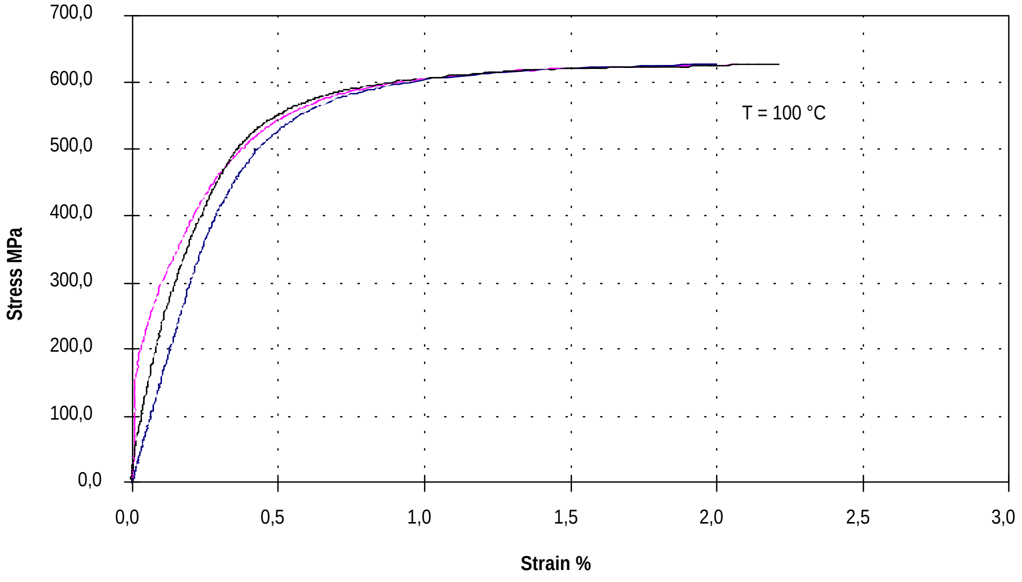

Stress MPa
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
0,0
0,5
1,0
1,5
2,0
Strain %
T = 950 °C

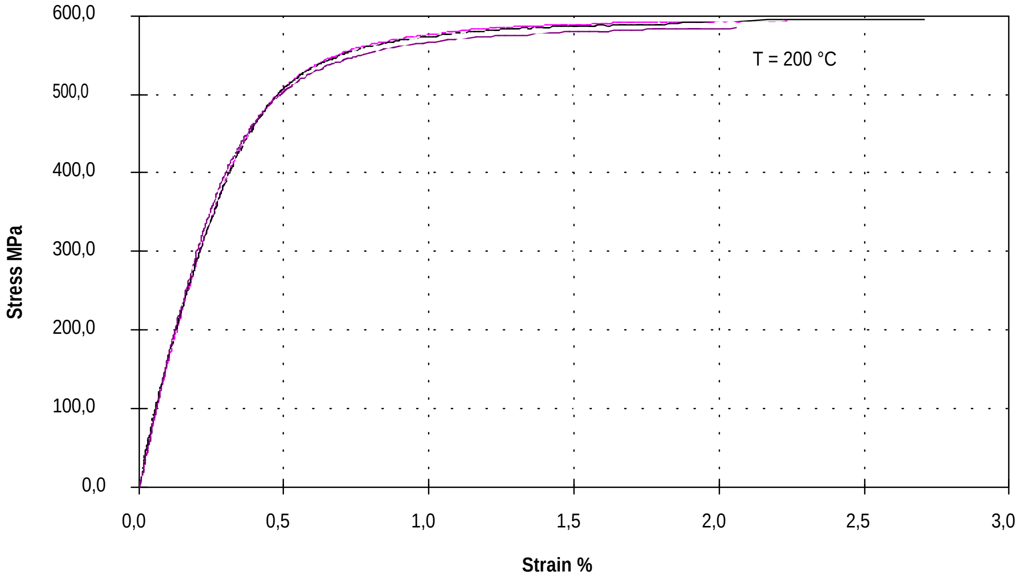
Table 1. The mechanical material properties of virgin sheet of Polarit 761.

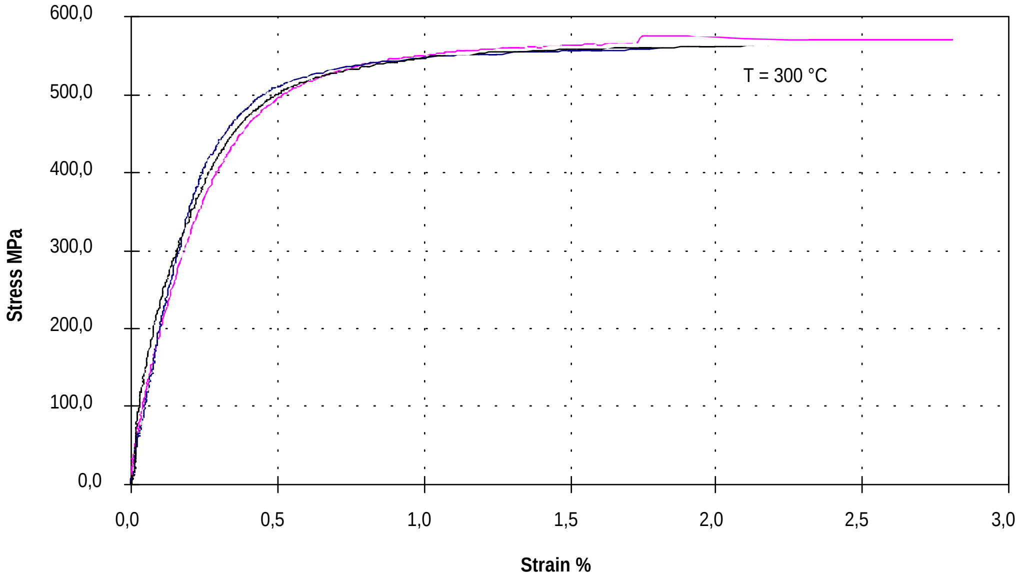
Specimen	Temperature [°C]	The modulus of elasticity [N/mm^2]	0.2%-proof stress $R_{p0.2}$ [N/mm^2]	1.0%-proof stress $R_{p1.0}$ [N/mm^2]	Tensile strength R_m [N/mm^2]	Elongation after fracture A_5
TA 1	25	190	300	329	582	54
TA 2	25	186	307	336	582	53
TA 4	50	159	290	325	553	50
TA 5	50	154	293	330	554	49
TB 2	100	158	270	297	511	44
TB 3	100	181	271	299	511	44
TB 4	150	172	265	289	489	41
TB 5	150	146	259	286	490	40
TB 6	150	161	261	286	488	41
TC 1	200	147	249	276	471	40
TC 2	200	147	247	281	471	39
TC 5	250	149	239	266	458	37
TD 2	300	159	234	261	458	36
TD 3	300	183	232	261	459	37
TD 4	350	166	232	263	463	37
TD 5	350	161	229	264	464	38
TE 1	400	139	218	254	463	36
TE 2	400	144	219	248	462	39
TE 4	450	133	218	246	457	37
TE 5	450	136	216	246	456	35
TF 1	500	148	208	238	446	38
TF 2	500	127	206	236	447	34
TF 4	550	137	203	231	431	34
TF 5	550	122	207	234	437	35
TG 1	600	161	193	227	410	33
TG 2	600	164	198	231	412	34
TG 4	650	128	188	217	378	37
TG 5	650	124	188	215	376	36
TH 1	700	131	182	207	319	49
TH 2	700	105	187	211	332	49
TH 3	700	146	181	208	326	48
TH 4	750	153	174	199	267	58
TH 5	750	115	178	198	268	58
TI 2	800	134	157	170	221	62
TI 3	800	115	159	170	220	61
TI 4	850	99	129	134	174	69
TI 5	850	116	128	134	176	67
TJ 1	900	131	95	96	133	80
TJ 2	900	134	93	94	130	82
TJ 4	950	124	71	70	100	91
TJ 5	950	116	71	70	100	90
TJ 6	950	81	72	71	101	85

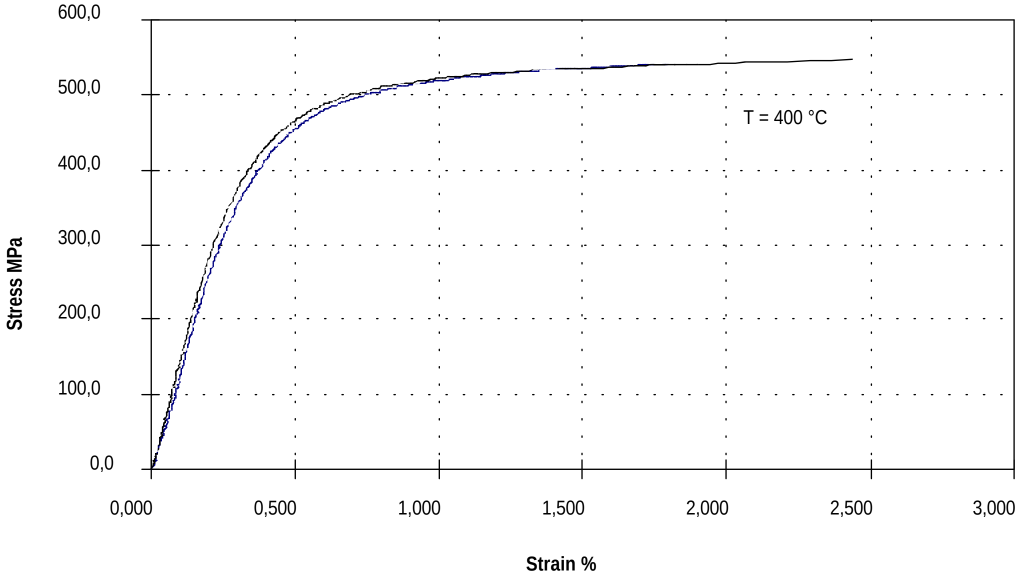
STRESS-STRAIN CURVES AND MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES OF COLD-FORMED MATERIAL OF POLARIT 725






600,0
500,0
400,0
300,0
200,0
100,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 200 °C


600,0
500,0
400,0
300,0
200,0
100,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 300 °C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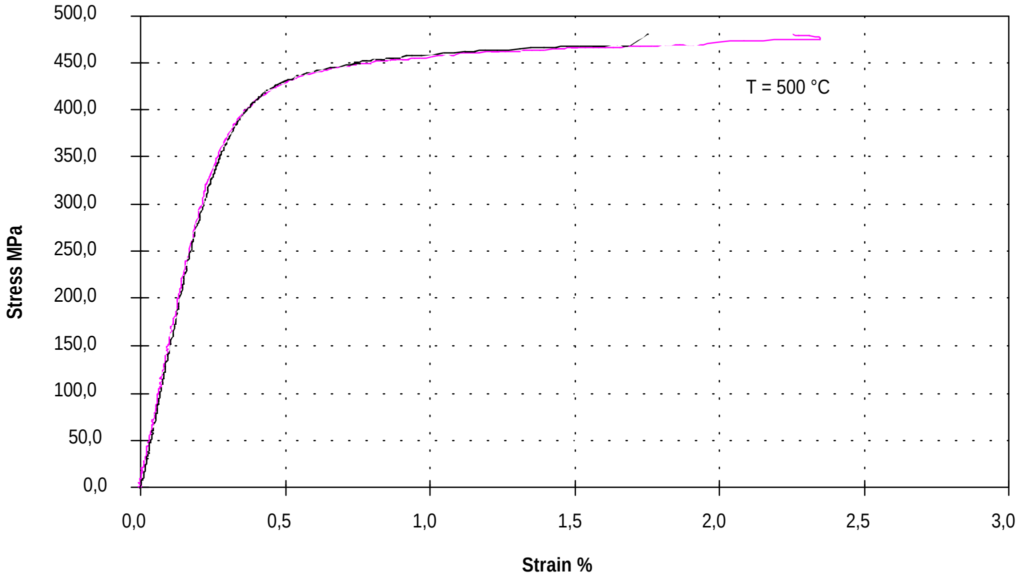
500,0
400,0
300,0
200,0
100,0
0,0
Stress MPa
0,000
0,500
1,000
1,500
2,000
2,500
3,000
Strain %
T = 400 °C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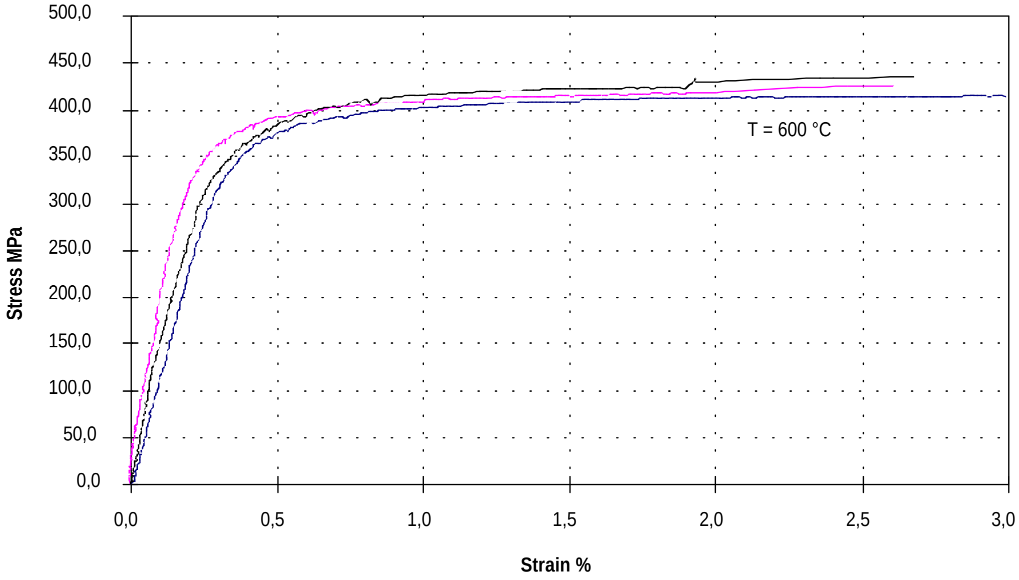
450,0
400,0
350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
T = 500 °C
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %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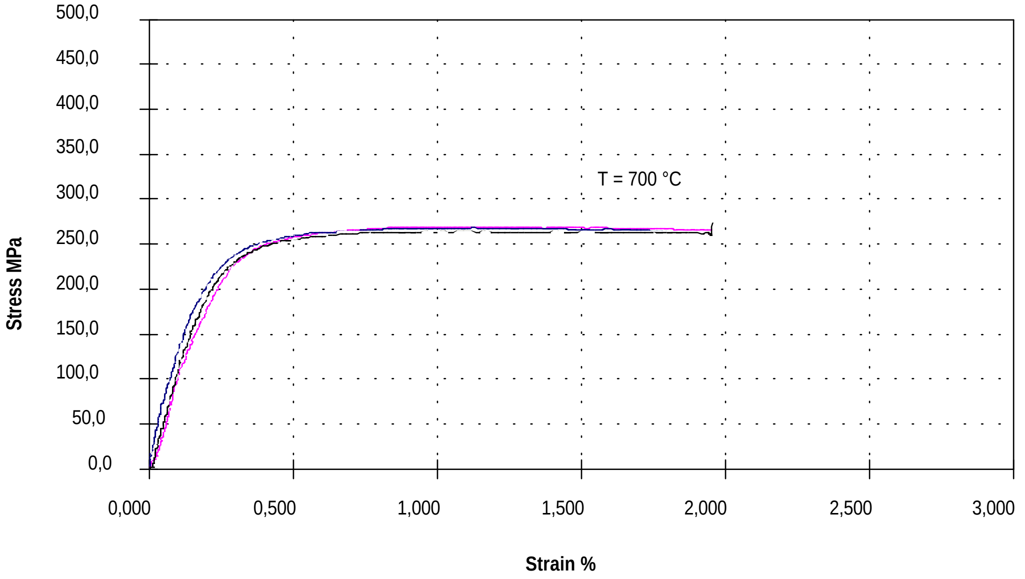
400,0
350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
T = 600 °C
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %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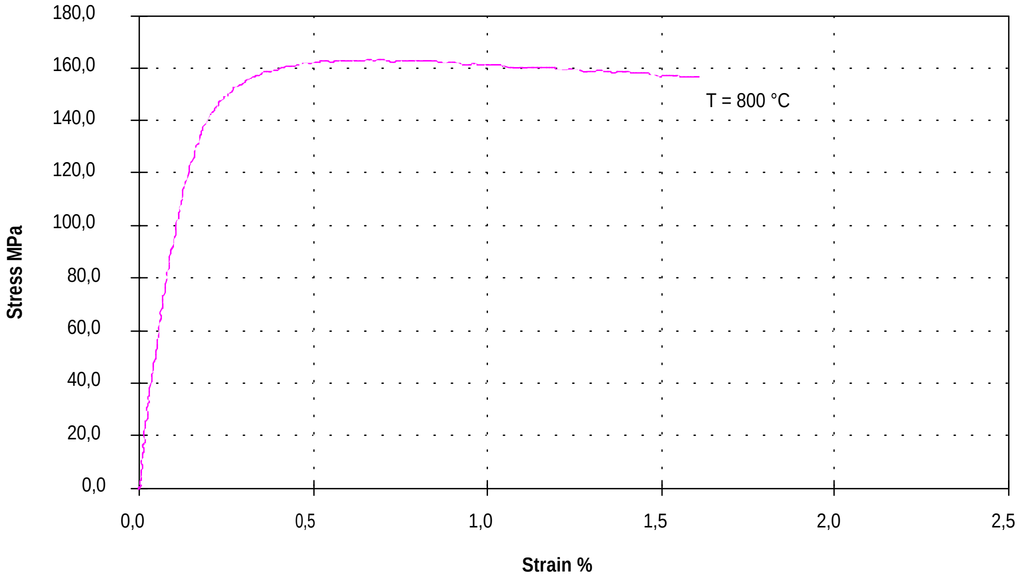
450,0
400,0
350,0
300,0
250,0
200,0
150,0
100,0
50,0
0,0
Stress MPa
T = 700 °C
0,000
0,500
1,000
1,500
2,000
2,500
3,000
Strain %


Stress MPa
180,0
160,0
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
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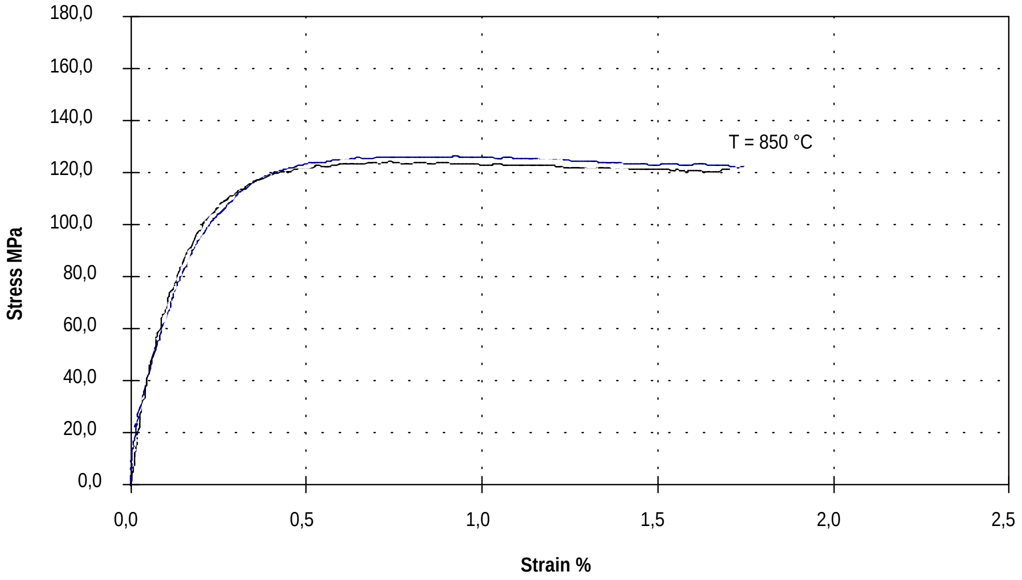
0,5
1,0
1,5
2,0
2,5
Strain %
T = 800 °C


Stress MPa
180,0
160,0
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 850 °C

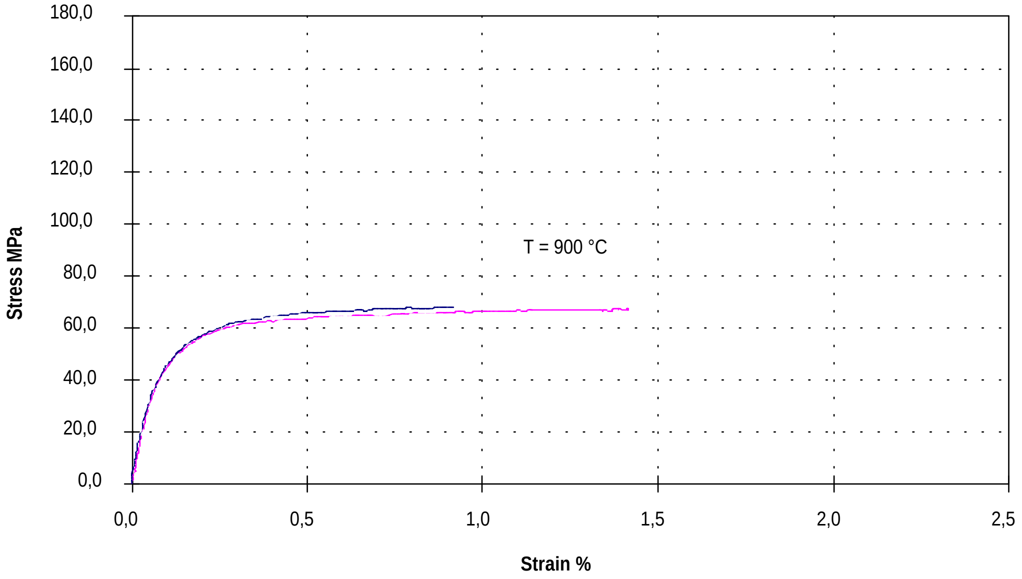
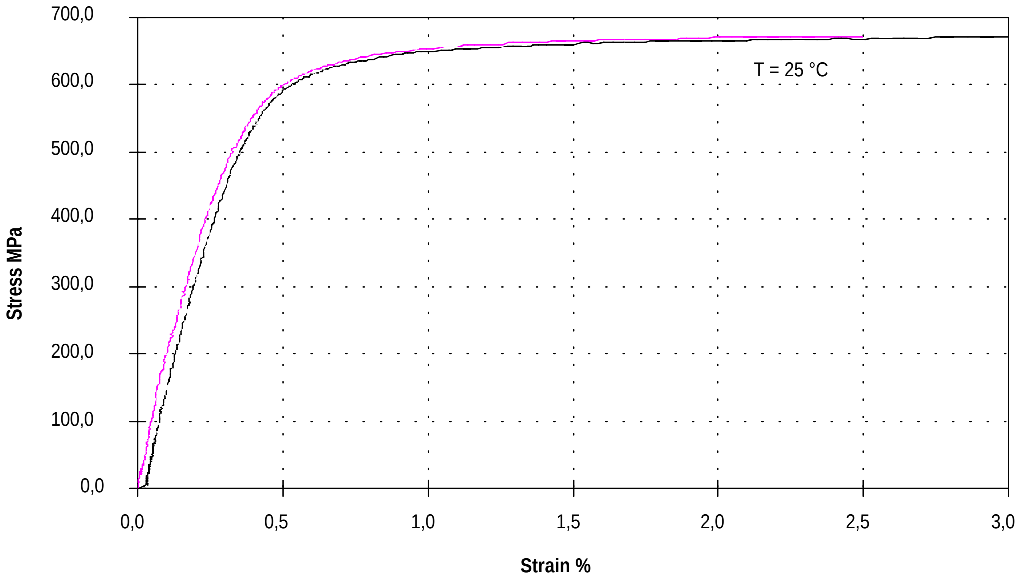
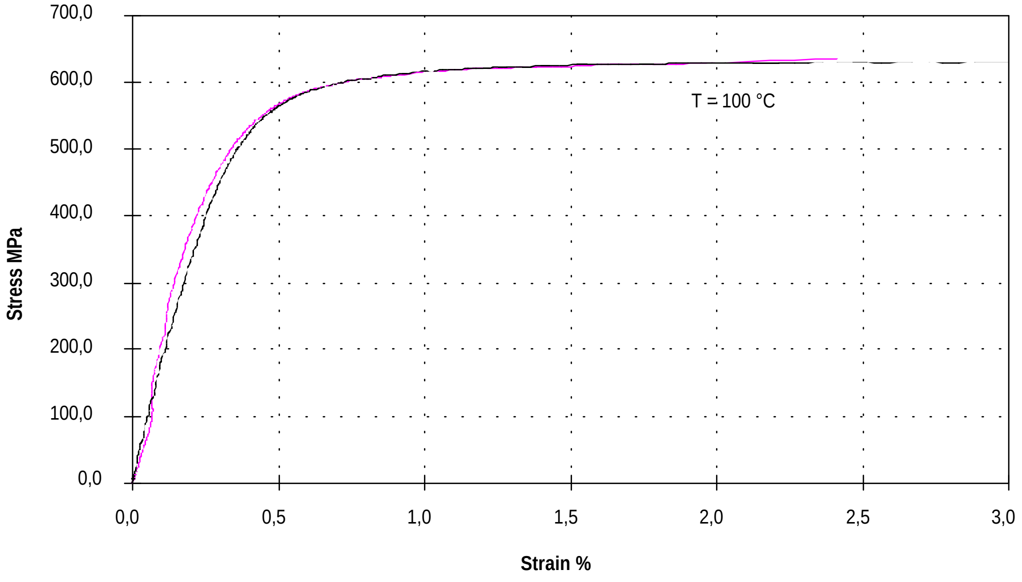

Stress MPa
180,0
160,0
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
Strain %
T = 900 °C

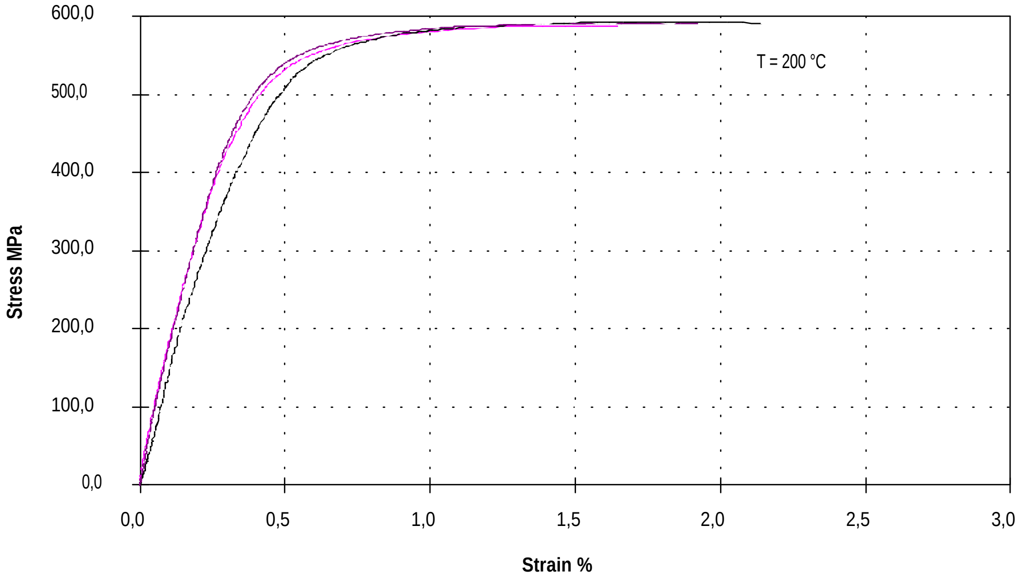
Table 1. The mechanical material properties of cold-formed material of Polarit 725.

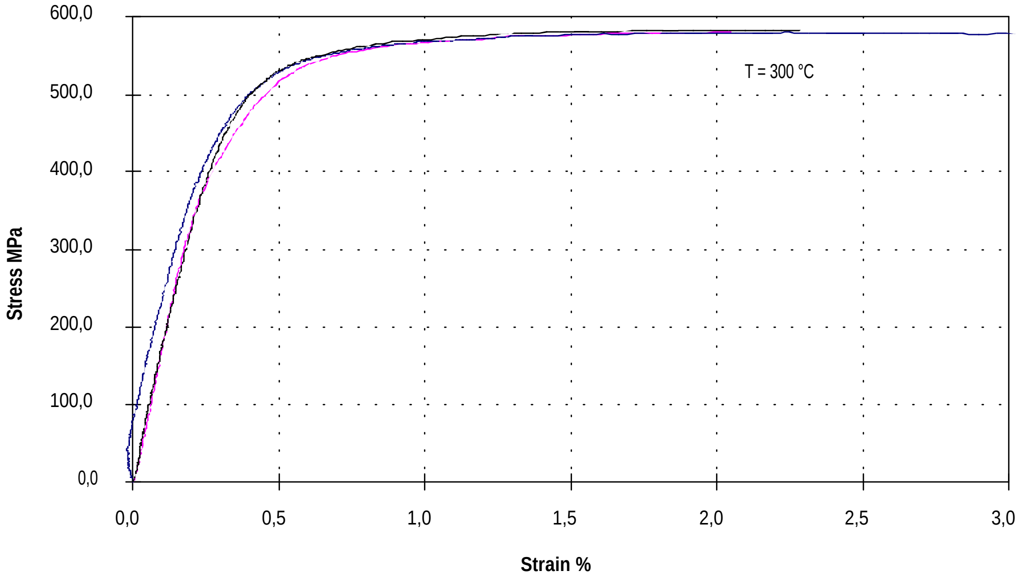
Specimen	Temperature [°C]	The modulus of elasticity [N/mm^2]	0.2%-proof stress $R_{p0.2}$ [N/mm^2]	1.0%-proof stress $R_{p1.0}$ [N/mm^2]	Tensile strength R_m [N/mm^2]	Elongation after fracture A_5
NR 1	25	198	594	666	753	40
NR 2	25	196	595	668	757	41
NR 5	100	205	548	618	646	25
NR 6	100	196	534	619	645	26
NR 7	100	167	548	619	648	27
NR 9	200	181	537	591	597	17
NR 10	200	174	510	580	589	16
NR 11	200	188	531	588	599	15
NR 13	300	194	485	556	569	14
NR 14	300	194	495	555	575	16
NR 16	300	189	499	564	572	13
NR 17	400	161	476	536	557	17
NR 18	400	160	472	536	557	16
NR 21	500	160	425	464	485	18
NR 22	500	177	410	462	486	18
NR 23	500	155	431	479	485	17
NR 25	600	172	381	423	441	16
NR 26	600	127	379	409	426	16
NR 27	600	169	386	415	433	16
NR 29	700	132	251	266	298	37
NR 30	700	146	252	268	303	38
NR 31	700	138	253	270	303	37
NR 33	800	-	166	-	190	70
NR 34	800	127	160	162	198	69
NR 35	800	-	163	167	205	65
NR 36	800	-	173	173	211	63
NR 45	850	108	113	123	159	67
NR 46	850	104	120	125	162	65
NR 37	900	-	59	63	103	84
NR 38	900	69	62	69	106	83
NR 40	900	78	60	67	103	90

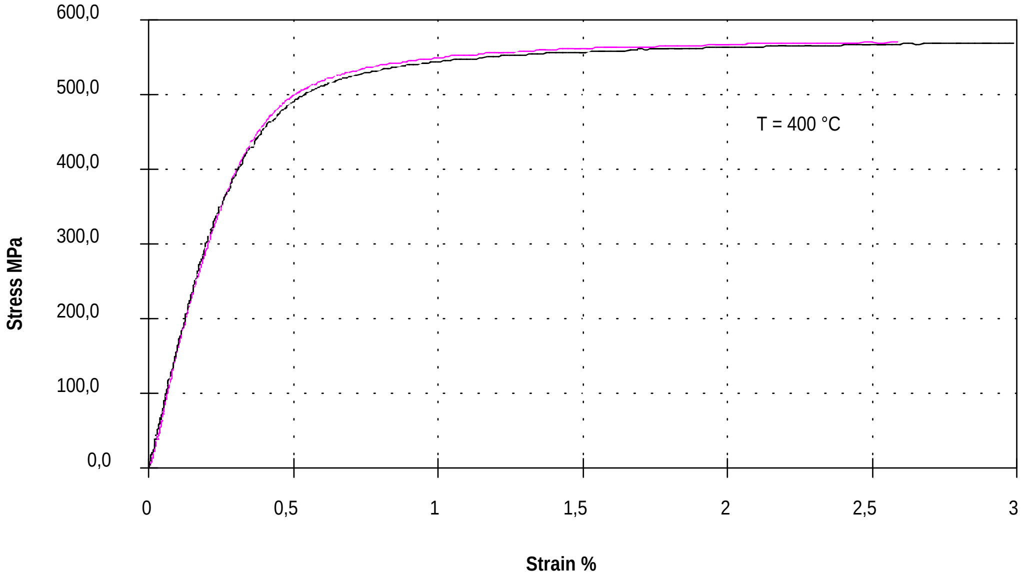
STRESS-STRAIN CURVES AND MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES OF COLD-FORMED MATERIAL OF POLARIT 761

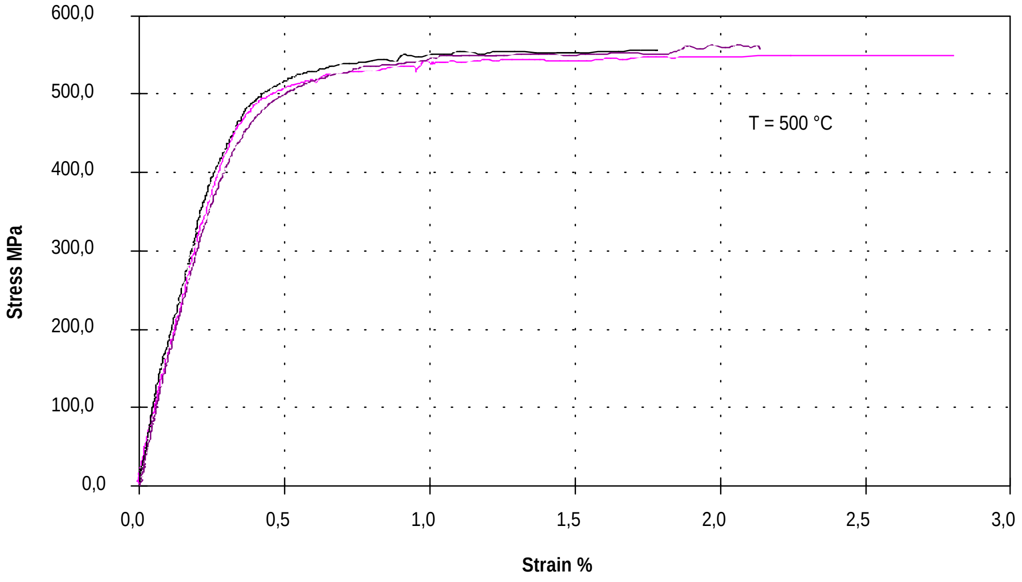


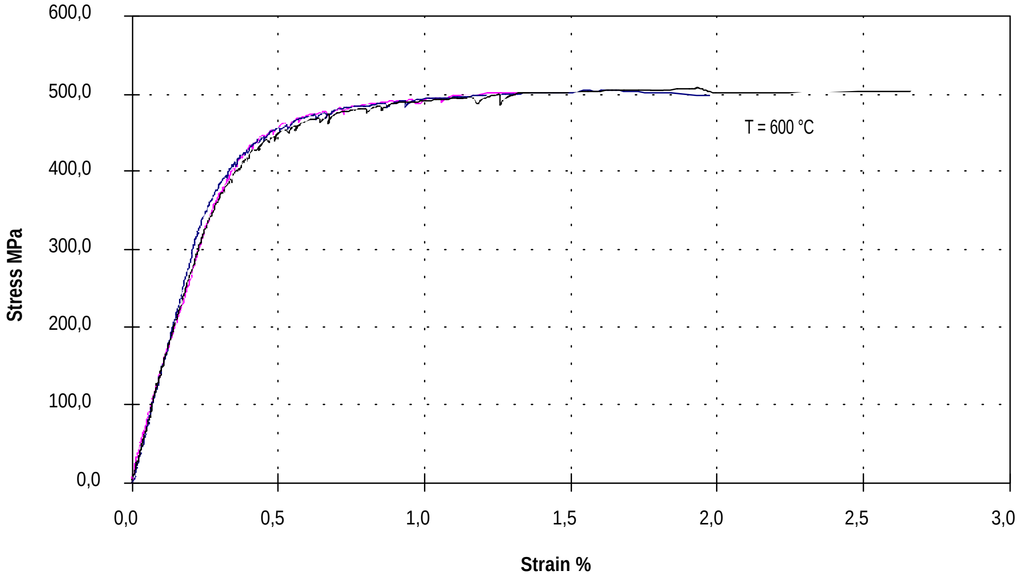


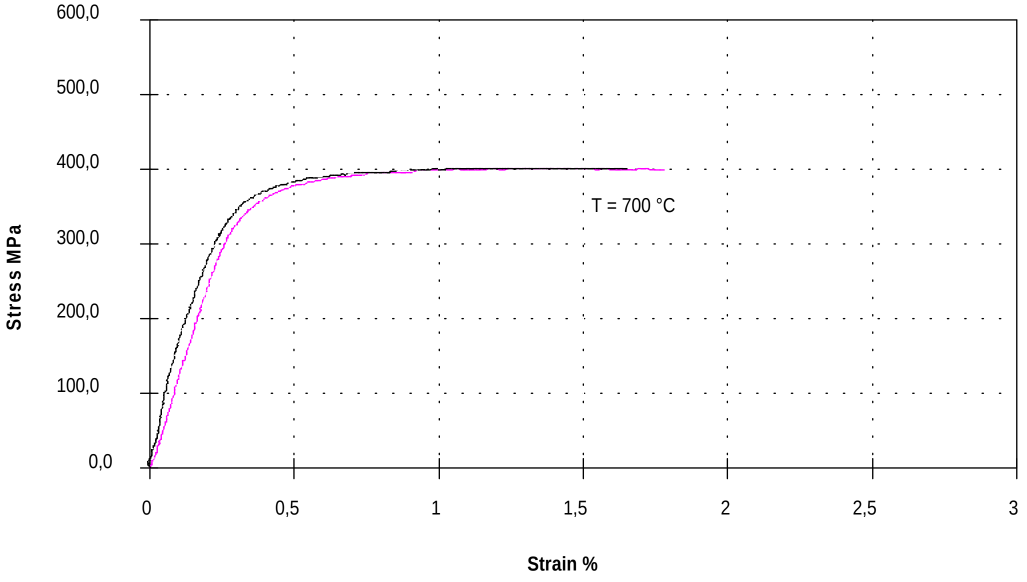

600,0
500,0
400,0
300,0
200,0
100,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 200 °C

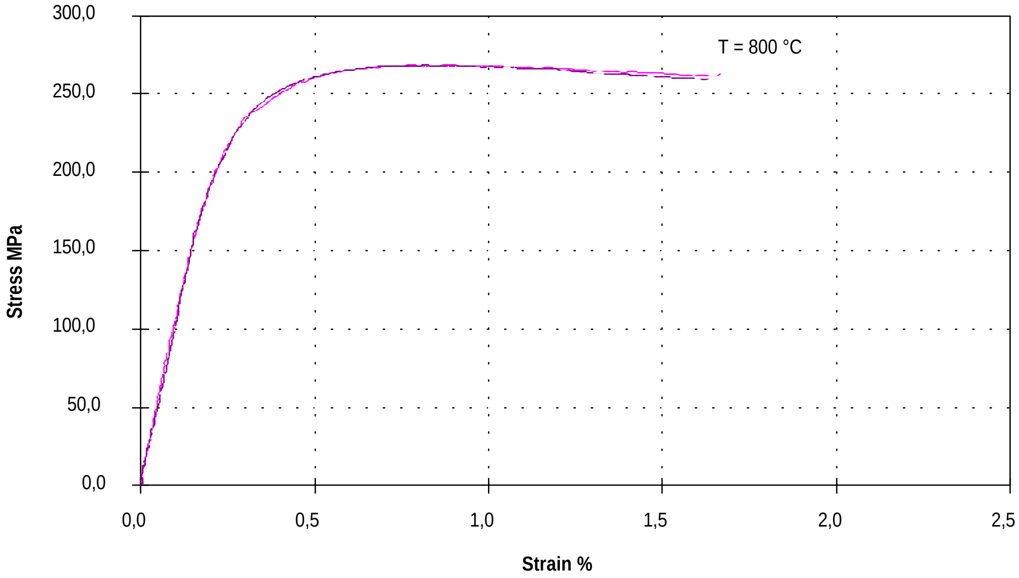

600,0
500,0
400,0
300,0
200,0
100,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 300 °C


600,0
500,0
400,0
300,0
200,0
100,0
0,0
Stress MPa
0
0,5
1
1,5
2
2,5
3
Strain %
T = 400 °C

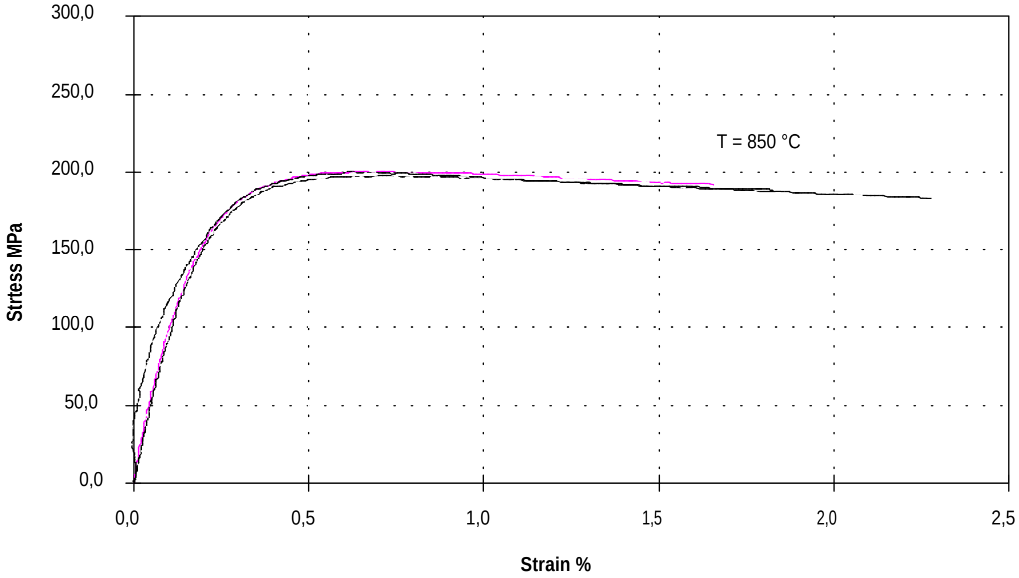

600,0
500,0
400,0
300,0
200,0
100,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 500 °C


600,0
500,0
400,0
300,0
200,0
100,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
2,5
3,0
Strain %
T = 600 °C

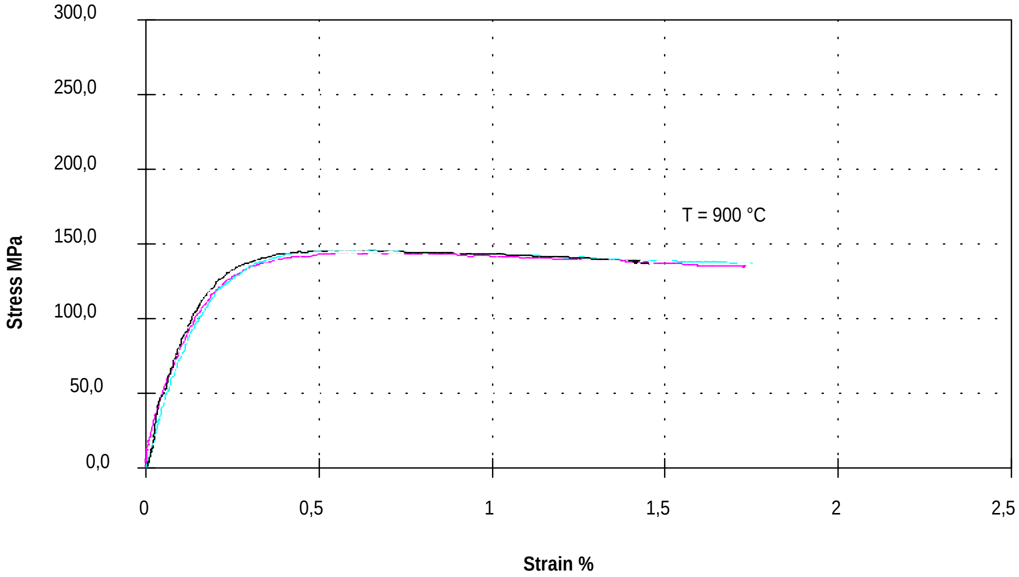

600,0
500,0
400,0
300,0
200,0
100,0
0,0
Stress MPa
0
0,5
1
1,5
2
2,5
3
Strain %
T = 700 °C



T = 800 °C
Stress MPa
300,0
250,0
200,0
150,0
100,0
50,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
Strain %



T = 850 °C
Strtess MPa
300,0
250,0
200,0
150,0
100,0
50,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
Strain %



T = 900 °C
Stress MPa
300,0
250,0
200,0
150,0
100,0
50,0
0,0
0
0,5
1
1,5
2
2,5
Strain %

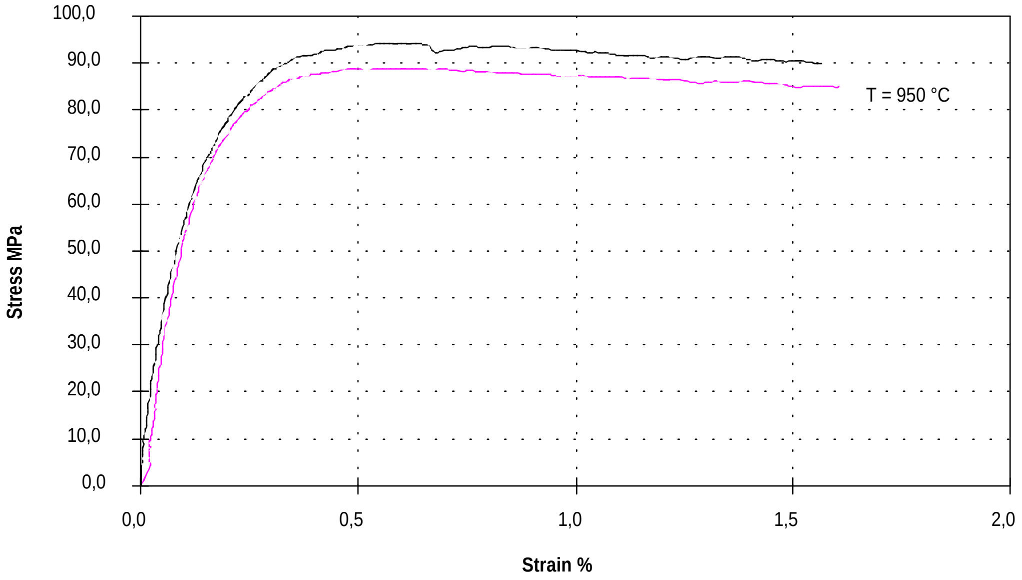

100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
Stress MPa
0,0
0,5
1,0
1,5
2,0
Strain %
T = 950 °C

Table 1. The mechanical material properties of cold-formed material of Polarit 761.

Specimen	Temperature [°C]	The modulus of elasticity [N/mm^2]	0.2%-proof stress $R_{p0.2}$ [N/mm^2]	1.0%-proof stress $R_{p1.0}$ [N/mm^2]	Tensile strength R_m [N/mm^2]	Elongation after fracture A_5
NT 1	25	205	615	663	703	29
NT 2	25	203	619	661	703	31
NT 5	100	190	577	627	633	17
NT 6	100	191	569	624	639	16
NT 9	200	179	539	589	589	13
NT 10	200	182	554	592	592	12
NT 11	200	160	552	593	594	13
NT 13	300	176	534	580	585	11
NT 14	300	183	516	577	582	10
NT 15	300	164	526	577	582	11
NT 17	400	174	500	560	575	11
NT 18	400	163	497	556	570	12
NT 21	500	152	513	546	552	12
NT 22	500	175	515	554	565	10
NT 23	500	174	523	558	567	10
NT 25	600	148	451	504	515	13
NT 26	600	151	471	504	511	11
NT 27	600	148	463	502	514	12
NT 29	700	131	381	403	437	19
NT 30	700	162	383	403	438	21
NT 33	800	111	257	266	309	24
NT 34	800	106	254	266	309	26
NT 45	850	123	183	195	225	33
NT 46	850	109	189	194	228	42
NT 48	850	116	194	197	233	39
NT 37	900	92	140	142	173	69
NT 38	900	100	137	141	169	56
NT 39	900	102	141	142	151	63
NT 41	950	79	86	87	115	75
NT 42	950	88	90	92	121	81

AN EXAMPLE OF FIRE RESISTANCE OF THE COLUMN

Here is given a calculation example, where the critical temperature is determined for a carbon steel column and for a stainless steel column. On the basis of critical temperature, the fire resistance time is determined where the gas temperature is assumed to rise according to the relationship specified in ISO 834.

In normal temperature design the action is 3050 kN and the required cross-section is 300 x 300 x 12.5, when the buckling length is 3.5 m. The reduction factor for the design load level for a fire situation is 0.5. The calculations are made for the carbon steel S235 (Fe360) and for the stainless steels Polarit 725 and Polarit 761. The yield strengths of all materials at room temperature are assumed to be 235 N/mm^2.

The critical temperature of the column in the beginning will be determined without taking into account the slenderness of the column and assuming that the whole cross-section is effective.

Carbon steel

The load level 0.5 (the load relation of the normal temperature design and fire design) is corresponding the critical temperature 585 °C on the basis of the Eurocode 3, Part 1.2.

$f_{y,585°C}$ = 121.4 N/mm^2

$E_{y,585°C}$ = 74 235 N/mm^2

The cross-section class will be checked also at elevated temperatures:

$$\frac{b}{t} \le 1.10\sqrt{\frac{E_t}{f_{yT}}} = 1.10\sqrt{\frac{74235}{121.4}} = 27.20 > \frac{b}{t} = 19$$

=> Class 1 cross-section

The buckling strength of the column at temperature 585 °C

$$\bar{\lambda}_{kT} = \frac{L_{cT}}{i\pi}\sqrt{\frac{f_{yT}}{E_T}} = 0.388$$

$$\beta = \frac{1 + 0.49\left(\bar{\lambda}_{kt} - 0.2\right) + \bar{\lambda}^2_{kT}}{2\bar{\lambda}^2_{kT}} = 4.126$$

$$f_{cT} = f_{yT}\left(\beta - \sqrt{\beta^2 - \frac{1}{\bar{\lambda}^2_{kT}}}\right) = 109.7 \text{ N/mm}^2$$

$$N_{PT} = f_{cT}A = 1518 \text{ kN}$$

The load in fire situation is 1 525 kN, so the critical temperature must be decreased.

T_{cri} = 580 °C

$f_{y,580°C}$ = 125 N/mm^2

$E_{y,580°C}$ = 77 280 N/mm^2

The cross-section class will be checked also at elevated temperatures:

$$\frac{b}{t} \leq 1.10\sqrt{\frac{E_t}{f_{yT}}} = 1.10\sqrt{\frac{77280}{125}} = 27.4 > \frac{b}{t} = 19$$

=> Class 1 cross-section

The buckling strength of the column at temperature 580 °C

$$\bar{\lambda}_{kT} = \frac{L_{cT}}{i\pi}\sqrt{\frac{f_{yT}}{E_T}} = 0.386$$

$$\beta = \frac{1 + 0.49\left(\bar{\lambda}_{kt} - 0.2\right) + \bar{\lambda}_{kT}^2}{2\bar{\lambda}_{kT}^2} = 4.163$$

$$f_{cT} = f_{yT}\left(\beta - \sqrt{\beta^2 - \frac{1}{\bar{\lambda}_{kT}^2}}\right) = 113 \text{ N/mm}^2$$

$N_{PT} = f_{cT}A$ = 1565 kN => OK

Austenitic stainless steels

Polarit 725

The load level 0.5 (the load relation of the normal temperature design and fire design) is corresponding the critical temperature 650 °C on the basis of the performed steady-state tests of Polarit 725 (virgin sheet).

$f_{y,650°C}$ = 112 N/mm^2

$E_{y,650°C}$ = 158 000 N/mm^2

The cross-section class will be checked also at elevated temperatures:

$$\frac{b}{t} \leq 1.10\sqrt{\frac{E_t}{f_{yT}}} = 1.10\sqrt{\frac{158000}{112}} = 41.3 > \frac{b}{t} = 19$$

=> Class 1 cross-section

The buckling strength of the column at temperature 650 °C

$$\bar{\lambda}_{kT} = \frac{L_{cT}}{i\pi}\sqrt{\frac{f_{yT}}{E_T}} = 0.255$$

For stainless steel the limiting slenderness is 0.4, so

$f_{cT} = f_{y,T} = 112$ N/mm^2

$N_{PT} = f_{cT}A = 1550$ kN

Polarit 761

The load level 0.5 (the load relation of the normal temperature design and fire design) is corresponding the critical temperature 825 °C on the basis of the performed steady-state tests of Polarit 761 (virgin sheet).

$f_{y,\,825°C} = 112$ N/mm^2

$E_{y,825°C} = 116\,000$ N/mm^2

The cross-section class will be checked also at elevated temperatures:

$$\frac{b}{t} \leq 1.10\sqrt{\frac{E_t}{f_{yT}}} = 1.10\sqrt{\frac{116000}{112}} = 35.4 > \frac{b}{t} = 19$$

=> Class 1 cross-section

The buckling strength of the column at temperature 825 °C

$$\overline{\lambda}_{kT} = \frac{L_{cT}}{i\pi}\sqrt{\frac{f_{yT}}{E_T}} = 0.298$$

For stainless steel the limiting slenderness is 0.4, so

$f_{cT} = f_{y,T} = 112$ N/mm^2

$N_{PT} = f_{cT}A = 1550$ kN

Fire resistance time

The critical temperature of carbon steel corresponds to the fire resistance time of 19 minutes and the critical temperature of stainless steel Polarit 725 corresponds to the fire resistance time of 25 minutes and the critical temperature of stainless steel Polarit 761 corresponds to the fire resistance time 41 minutes in standard fire.