Appendix C

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Mechanical Properties of an Austenitic Stainless Steel at Elevated Temperatures

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In the Laboratory of Steel Structures at Helsinki University of Technology, extensive experimental research has been carried out during the years 1994–1997 for investigating mechanical properties of various structural steels at elevated temperatures. The latest research was concentrated on an austenitic stainless steel grade named by Polarit 725 (AISI 304, EN 1.4301). The purpose of this research was to study the behaviour of this stainless steel material at fire temperatures. The experimental part of this project was carried out using a mainly transient state tensile test method. The more common test method, the steady state test method, was also used to have a comparison with the test results obtained with another kind of test method.

The tests were carried out for both base material taken from a virgin cold-rolled steel sheet and for strongly cold-formed material taken from a small rectangular hollow section. The test results were used to determine the temperature dependencies of the mechanical properties, i.e. yield strength, elasticity modulus and thermal elongation of stainless steel grade EN 1.4301(AISI 304) at temperatures up to 900°C.

KEYWORDS

Elevated temperatures, fire temperatures, fire design, high-temperature properties, material properties, mechanical properties, steady-state, steel structures, transient-state.

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ABSTRACT

In the Laboratory of Steel Structures at Helsinki University of Technology, an extensive experimental research has been carried out during the years 1994-1997 for investigating mechanical properties of various structural steels at elevated temperatures. The latest research was concentrated on an austenitic stainless steel grade named by Polarit 725 (AISI 304, EN 1.4301). The purpose of this research was to study the behaviour of this stainless steel material at fire temperatures using mainly transient state tensile test method. The material was also tested with using steady state test method. The tests were carried out for both base material taken from a virgin cold-rolled steel sheet and for strongly cold-formed material taken from a small rectangular hollow section. The test results were used to determine the temperature dependencies of the mechanical properties i.e. yield strength, elasticity modulus and thermal elongation of stainless steel grade EN 1.4301(AISI 304) at temperatures up to 900°C.

KEYWORDS

Elevated temperatures • Fire temperatures • Fire design • High-temperature properties • Material properties • Mechanical properties • Steady-state • Steel structures • Transient-state

INTRODUCTION

Fire resistance of austenitic stainless steels is known to be considerably better than that of low carbon structural steels. The use of stainless steels in load-bearing structures is still very little and one of the main reasons to that is the lack of experimental data of mechanical properties of stainless steels at elevated temperatures. The purpose of this research was to examine these mechanical properties at elevated temperatures for an austenitic stainless steel grade named by Polarit 725 (AISI 304, EN 1.403) using both transient state and steady state test methods.

Two similar test series were carried out. One series for the base material and the other for strongly cold-formed material. Increase of strength caused by cold-forming is significant for the studied material and one main objective of this research was to study the remaining of the increased strength at elevated temperatures. In the first series, the test pieces were cut out from a rectangular hollow section 40×40×4mm manufactured by the company Stala Oy and in the second series the test pieces were cut out from a virgin sheet of a cold rolled steel sheet manufactured by the company Outokumpu Polarit Oy. The test results were used to define the temperature dependencies of the mechanical properties i.e. thermal elongation, modulus of elasticity and yield strength of the studied austenitic stainless steel Polarit 725. The mechanical properties were determined from both transient and steady state test results.

TEST METHODS

The experimental part of this project was carried out using mainly transient state tensile test method. The more common test method, the steady state test method was also used to have a comparison with the test results obtained with an other kind of test method.

Transient State Test Method

In transient state tests the test specimen is under a constant load and under a constant temperature rise. Temperature and strain are measured during the test. As a result, a temperature-strain curve is recorded during the test. Thermal elongation is subtracted from the total strain. The transient state test method gives a quite realistic basis in predicting the material behaviour under fire conditions.

The transient state tests (Outinen , Mäkeläinen 1997) were conducted with two identical tests at each stress level. The stress levels for cold-formed material were 3, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, and 600 N/mm^2 and for base material 3, 30, 60, 90, 120, 150, 180, 210, 240, and 270 N/mm^2. Thermal elongation was determined at stress level of $3N/mm^2$. Deviation between the tests was very little. Heating rate in the transient state tests was 10°C min^{-1}. The steel temperature was measured from the test specimen using temperature-detecting element fastened to the specimen.

Steady State Test Method

In the steady state tests the test piece is heated up to a specific temperature. After that a tensile test is carried out. In the steady state tests, stress and strain values are first recorded and from the stress-strain curves the mechanical material properties can be determined. The steady state tests can be carried out either as strain- or as load-controlled. In the strain-controlled tests, the strain rate is kept constant and in the load-controlled tests the loading rate is kept constant.

TESTING FACILITIES

Test Specimen

In the first series, the test pieces were cut out longitudinally from the middle face opposite to the weld seam of a rectangular hollow section 40×40×4mm. In the second series the test pieces were cut out from a virgin cold-rolled steel sheet having thickness of 4mm. The test pieces were cut out longitudinally to rolling direction.

The test specimen having rectangular cross-section was in accordance with the standard EN 10 002-5 1992. Strain was measured from the middle of the test piece. The gauge length was 25mm. The test specimen is shown in Figure 2.

Testing Device

The tensile testing machine used in the research projects is verified in accordance with the standard EN 10 002-2 1992. The extensometer is in accordance with the standard EN 10 002-4

1992. The oven in which the test specimen is situated during the tests was heated by using three separately controlled resistor elements. The air temperature in the oven was measured with three separate temperature-detecting elements. The steel temperature was measured accurately from the test specimen using temperature-detecting element that was fastened to the specimen during the heating. The testing device is shown in Figure 2.

MATERIAL PROPERTIES AT ROOM TEMPERATURE

Mechanical Properties

Mechanical properties of the studied stainless steel Polarit 725 at room temperature were determined with four tensile tests for both cold-formed and base material. The increase of strength caused by cold-forming can be clearly seen from the test results. Yield strength of the cold-formed material was about double compared to that of the base material. In Table 2, $R_{p0.2}$ is the yield strength based on 0.2% non-proportional strain and $R_{t2.0}$ is the yield strength based on 2 % total strain. The average values of the measured properties are given in Table 2.

TRANSIENT STATE TEST RESULTS

Thermal Elongation

Thermal expansion coefficient of stainless steels is normally about 30% bigger than that of structural steels. Thermal elongation of the studied material was determined with transient state tests at stress level of $3 N/mm^2$. There was no significant difference between the test results and those in literature (Peckner *et al.* 1977). The thermal expansion coefficient at temperatures up to 200°C for both cold-formed material and base material determined from the transient state tests was about $1{,}8\times10^{-5}$ 1/°C. The value grows so that at temperature 900°C it is about $2{,}0\times10^{-5}$ 1/°C. The test results compared to those in literature (Peckner *et al.* 1977), are presented in Figure 3.

Modulus of Elasticity

Modulus of elasticity of stainless steel Polarit 725 was determined from the stress-strain curves which were converted from the transient state test results. Elasticity modulus was also determined from the steady state test results.

The modulus of elasticity was determined as an initial slope of the stress-strain curves. It is difficult to determine the exact value for the modulus of elasticity at elevated temperatures because the stress-strain curves of stainless steels do not have any exact proportional limit, especially at elevated temperatures. The values for elasticity modulus at elevated temperatures determined from the transient state test results are smaller than values for stainless steel AISI 304 given in literature, (Peckner *et al.* 1977). Elasticity modulus values for structural steels given in Eurocode 3: Part 1.2 (ENV 1993-1.2 1993), are smaller than the values based on the test results.

The deviation of the test results from different kind of tests is very large. Comparison between the transient state and steady state test results and the values given in the literature are presented in Figure 4.

Yield Strength

Yield strength of stainless steels is usually given as a $R_{p0.2}$ stress value, which is based upon

0,2% non-proportional strain. In Eurocode 3 the yield strength is given as a $R_{t2.0}$ stress value, which is based upon 2% total strain. Yield strength of the tested materials at elevated temperatures was determined as yield stress $R_{p0.2}$, and as yield stress $R_{t2.0}$. Yield strength was determined from the stress-strain curves based on the transient state test results.

Cold-forming process causes a significant strength increase in a metallic material. Yield strength of the base material of Polarit 725 was only about half of that of the cold-formed material at room temperature. The remaining of this difference at elevated temperatures can be clearly seen from the test results. The difference seems to remain as about the same as at room temperature up to 600°C. The test results for both materials are presented in Figure 5.

The nominal yield strength at room temperature for the base material is 230N/mm^2 and for cold-formed material 350N/mm^2. The measured yield strength values for Polarit 725 at elevated temperatures seem to remain very well compared to their nominal values. The yield strength of the cold-formed material at temperature 600°C is still above the nominal value. The test results are scaled to the nominal yield strength values in Figure 6.

STEADY STATE TEST RESULTS

The steady state tests for stainless steel Polarit 725 were carried out as strain-rate controlled with two different strain rates 0,002min^{-1} and 0,006min^{-1}. Steady state tests were carried out for cold-formed material at temperatures 400°C, 500°C and 600°C and for base material at temperatures 400°C, 500°C, 600°C and 700°C. Difference between the stress-strain curves from transient state and steady state tests was very little at the studied temperature range. Figure 7 shows clearly the uniformity of the results obtained from different tests. The difference is bigger for low carbon steels (Outinen , Mäkeläinen 1995).

Modulus of Elasticity

Mechanical properties of the studied materials were also determined from the steady state test results. The modulus of elasticity was the only measured property that varied significantly from the transient state test results. The determination of elasticity modulus was difficult because stainless steels do not have any clear proportional limit, especially at elevated temperatures. The test results of the elasticity modulus determined from the steady state tests are presented earlier in this paper in Figure 4.

CONCLUSIONS

An experimental research was carried out to study the mechanical properties of an austenitic stainless steel Polarit 725 (EN 1.4031 and AISI 304) at elevated temperatures. Two test series were carried out, one for the base material and another for the cold-formed material.

Thermal elongation was determined with transient state tests at stress level of 3N/mm^2. There was no significant difference between the test results and the values given for similar material in the literature.

The elasticity modulus was determined from the stress-strain curves converted from the transient state tests. It is difficult to determine the exact value for the modulus of elasticity at a high temperature because the stress-strain curve of stainless steel do not have any exact proportional limit, especially at elevated temperatures. There was a notable difference between the test results of both materials and the values given in the literature for AISI 304. The measured elasticity modulus reduction factor was still above the reduction factor given for structural steels in Eurocode 3. The elasticity modulus reduction factor determined from the steady state tests was near the values given in the literature, although the deviation of the test results was very large.

Yield strength ratio of the base material was a little above the yield strength ratio given in the literature for the whole temperature range. The yield strength reduction factor of the cold-formed material is clearly higher than the yield strength reduction factor given in the literature for AISI 304 until the temperature exceeds about 670°C. When the yield strength values of the studied materials at elevated temperatures are scaled to their nominal values at room temperatures, the difference between the test results and the yield stress reduction factor for structural steels given in Eurocode 3 is significant. The measured yield strength values for cold-formed material, for example, are still above the nominal values when the temperature exceeds 600°C.

The steady state tests for stainless steel Polarit 725 were carried out as strain-rate controlled with two different strain rates. Elasticity modulus values determined from the steady state tests differed considerably from the values determined from the transient state test results. The steady state test results for yield strength did not differ considerably from the transient state test results at the studied temperature range. The difference begins to appear at temperatures above 700°C, so that the tests with a higher strain rate give higher results. The results are also very near the values given in the literature. This is very promising when concerning the constructional fire design of austenitic stainless steels. In an other research project (Ala-Outinen 1996), that was linked to the transient state test project, the possibility to use the austenitic stainless steel Polarit 725 in some load-bearing structures up to 30 minutes fire resistance time without fire protection was studied. This possibility seems to be very realistic on the basis of the transient state test results.

FIGURES

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Paper 101, Figure 1: The test specimen

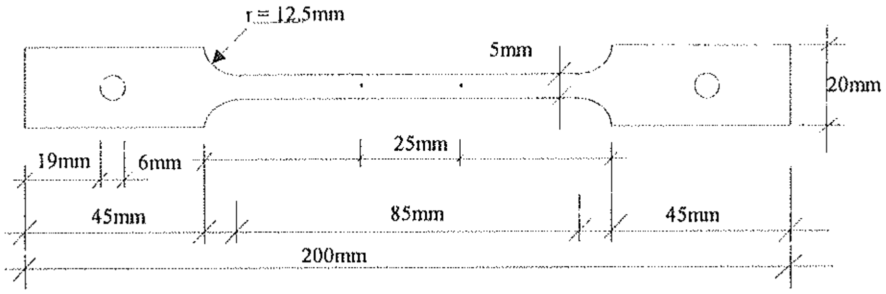

Figure 1: The test specimen

Paper 101, Figure 2: The transient state tensile testing device

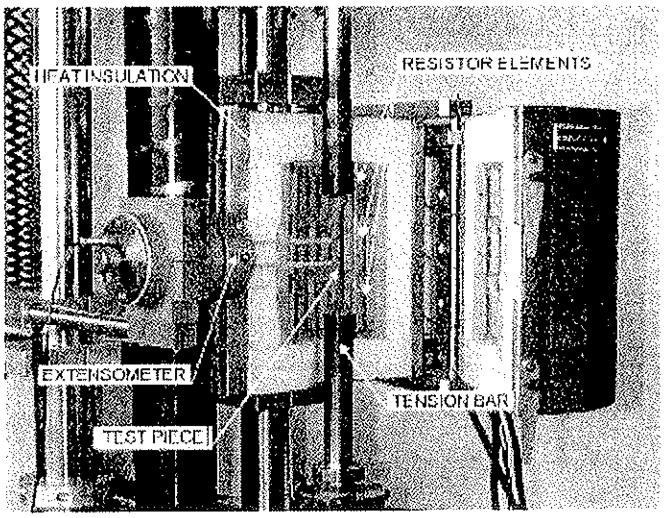

Figure 2: The transient state tensile testing device

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Paper 101, Figure 3: Thermal elongation of stainless steel Polarit 725 at el

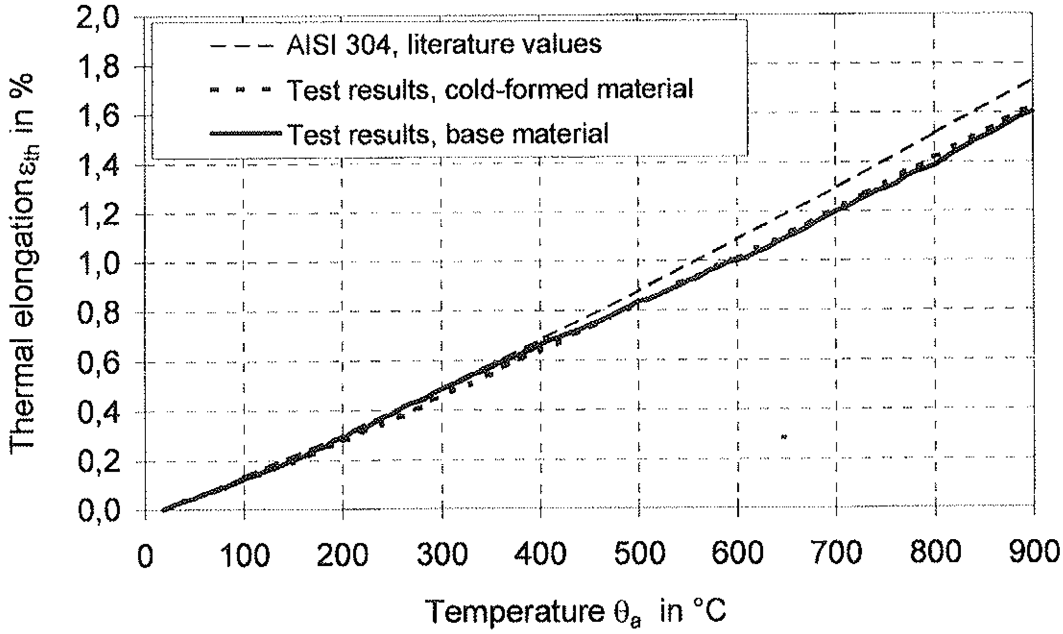

Figure 3: Thermal elongation of stainless steel Polarit 725 at elevated temperatures

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Paper 101, Figure 4: Temperature dependence of the modulus of elasticity

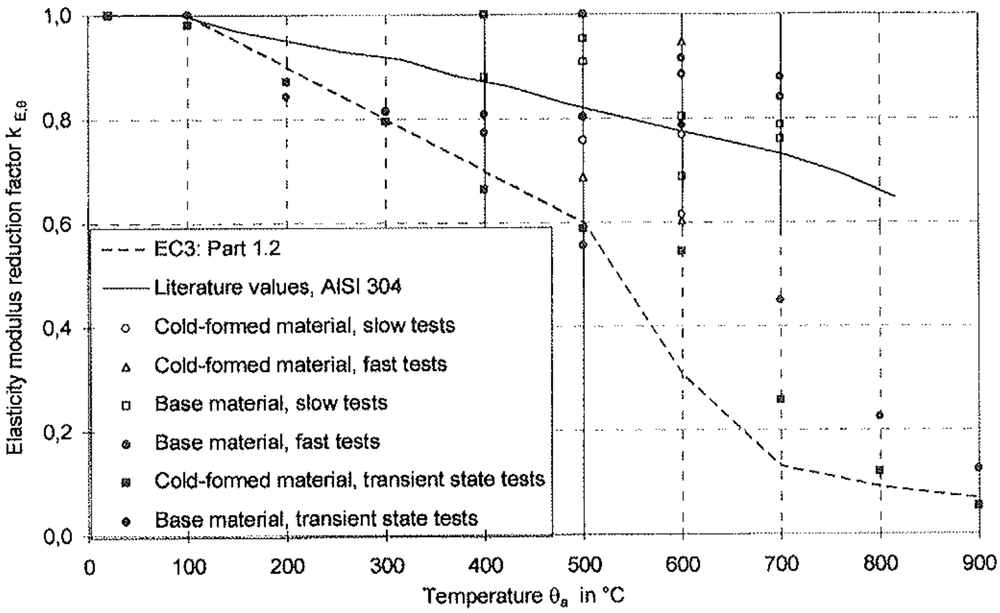

Figure 4: Temperature dependence of the modulus of elasticity for stainless steel Polarit 725 (EN 1.4301, AISI 304) at elevated temperatures

Paper 101, Figure 5: Temperature dependence of yield stresses Rp0.2 and

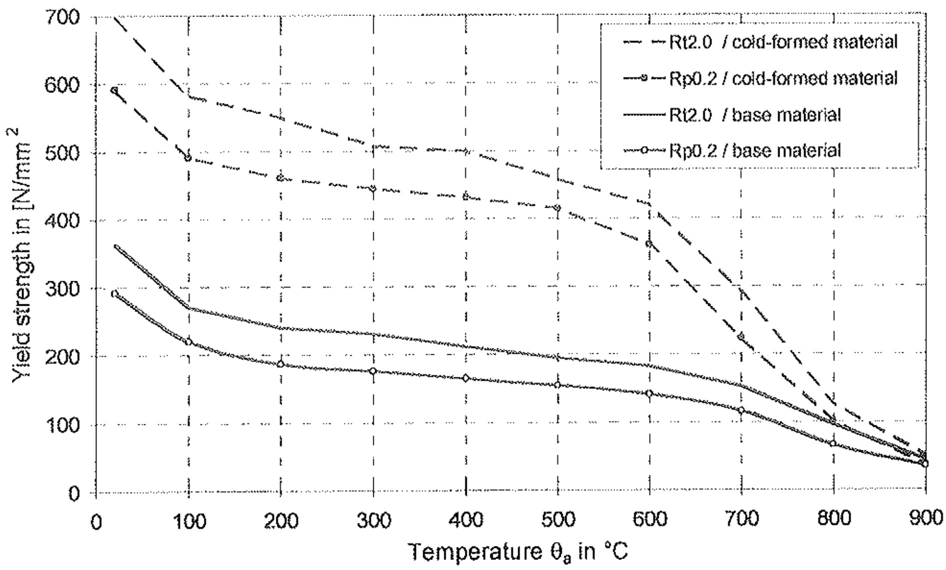

Figure 5: Temperature dependence of yield stresses $R_{p0.2}$ and $R_{t2.0}$ of stainless steel Polarit 725

according to the transient state tensile test results

Paper 101, Figure 6: Temperature dependence of yield strength Rp0.2 for

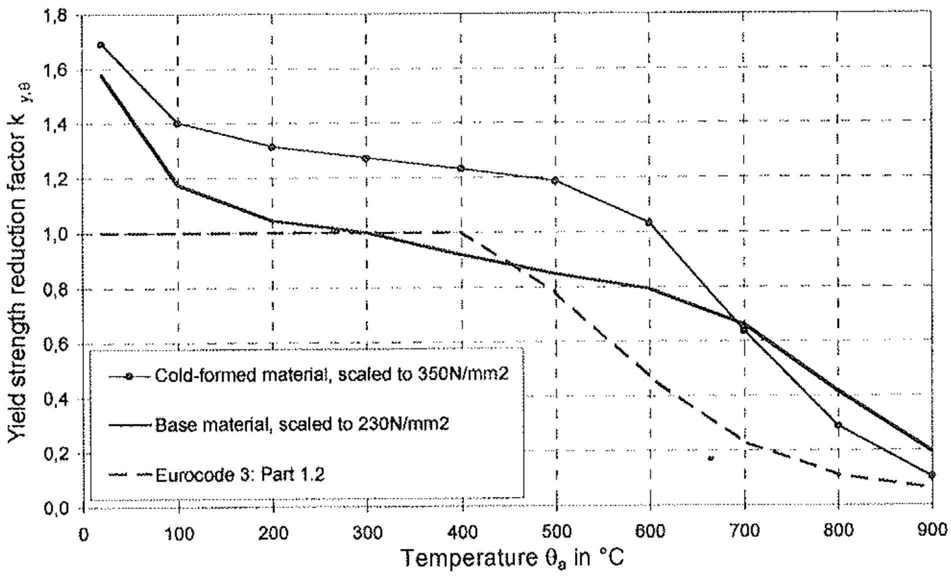

Figure 6: Temperature dependence of yield strength $R_{p0.2}$ for stainless steel Polarit 725

Paper 101, Figure 7: Stress-strain curves for base material of stainless stee

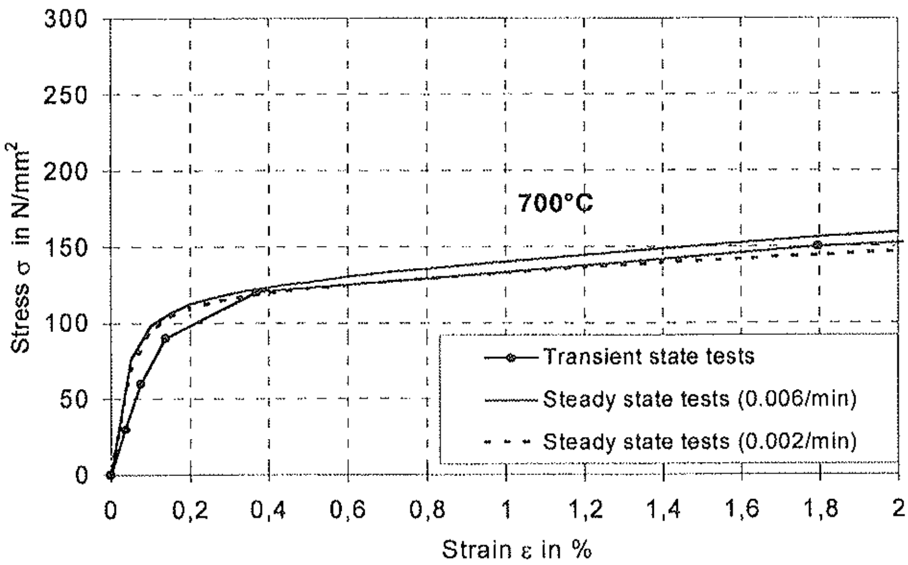

Figure 7: Stress-strain curves for base material of stainless steel Polarit 725 at temperature 700°C

TABLES

Paper 101, Table 2 MECHANICAL PROPERTIES OF STAINLESS STE

Measured property	**Symbol**	**Unit**	**Base material**	**Cold-formed material**
Modulus of elasticity	E	N/mm^2	177844	197980
Yield stress (0,2 % non-proportional strain)	$R_{p0.2}$	N/mm^2	291	592
Yield stress (1,0 % non-proportional strain)	$R_{p1.0}$	N/mm^2	333	676
Yield stress (1,0 % total strain)	$R_{t1.0}$	N/mm^2	326	667
Yield stress (2,0 % total strain)	$R_{t2.0}$	N/mm^2	363	695
Ultimate stress	R_m	N/mm^2	640	736
Percentage elongation after fracture	A_{25}	%	53	27.4

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