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Petri Tojkander

TENSILE TESTS AT ELEVATED TEMPERATURES TO STEEL GRADES S960QC AND S700QL

Diplomityö, joka on jätetty opinnäytteenä tarkastettavaksi
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Valvoja: Professori Jari Puttonen Aalto-yliopisto

Ohjaaja: TkT Wei Lu Aalto-yliopisto

TkT Jyri Outinen Ramboll

Aalto-yliopisto
Insinööritieteiden korkeakoulu

Aalto-yliopisto, PL 12100, 00076 AALTO
www.aalto.fi

Diplomityön tiivistelmä

Tekijä Petri Tojkander

Työn nimi Kuumavetokokeet teräslaaduille S960QC ja S700QL

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Tiivistelmä

Työn tavoitteena oli tutkia S960QC ja S700QL teräslaatujen lujuusominaisuuksia korkeissa lämpötiloissa. Työn aihe tuli Rautaruukilta (nyk. SSAB) keväällä 2013. Kyseisille lujuusluokille ei ole tehty vastaavaa tutkimusta. Kokeellisen tutkimuksen suoritus tapahtui Aalto-yliopiston laboratoriossa keväällä 2013 ja testaus kesti noin 1,5 kk. Laitteistona vetokokeissa käytettiin Roell+Korthaus merkkistä vetolaitteistoa sekä kappaleiden lämmityksessä käytettiin Maytecin valmistamaa uunia.

Kokeellisessa osuudessa teräskappaletta lämmitettiin, kunnes kappale alkoi myötäämään. Lisäksi tehtiin muutamia tarkistuskokeita kuten kuumavetokokeita vakiolämpötilassa sekä normaaleja vetokokeita huoneen lämpötilassa. Kokeiden lisäksi saatuja tuloksia verrattiin aikaisempiin tutkimustuloksiin pienemmillä lujuusluokilla. Tutkimustuloksia verrattiin lisäksi Eurokoodin (1993-1-2) mukaiseen mitoitustilanteeseen. Saadut tulokset poikkesivat Eurokoodiin verraten hieman epävarmalle puolelle korkeissa lämpötiloissa.

Tutkimuksessa oli käytettävissä 35 kappaletta kumpaakin teräslaatua. Tutkimusaineisto oli liian pieni, jotta siitä olisi voinut määritellä epävarmuustekijät kyseisille teräslaaduille. Epävarmuustekijät ovat materiaalista riippuvaisia ja koska vastaavia tutkimuksia ei ollut tehty, ei kunnollista arvioita tulosten epävarmuudesta pystytty muodostamaan.

Avainsanat korkea lämpötila, kuumavetokoe, S960QC, S700QL

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Abstract

Main purpose of this research was to determine mechanical properties of high-strength steels S960QC and S700QL at elevated temperatures. Topic for the research came from Rautaruukki (nowadays SSAB) in Spring 2013. Actual physical testing was performed in Spring 2013 at laboratory of Aalto-university. Used test equipment were tensile test device manufactured by Roell+Korthaus and a furnace manufactured by Maytec.

Testing method in research was transient state testing where tension is kept constant and temperature is raised until yielding happens. Also few checkup tests were performed by steady state method. Steel grades were also tested in room temperature to check actual yield stresses. The test results were compared to earlier researches and to Eurocode (1993-1-2) calculating preferences. Results were slightly at the critical side when compared to Eurocode measurement.

There were 35 test pieces of both steel grades available to test in this research. Amount of the test pieces were too small to determine uncertainty contributors. Most significant contributors are temperature and strain rate and their different variations. These contributors are material dependant and therefore should be determined experimentally. In lack of any previous studies on these steel grades a proper assessment of uncertainty of the results could not be done.

Keywords transient state test, elevated temperature, S960QC, S700QL

Acknowledgements

This Master's thesis ends my long lasting studying experience which started in 2007 at Lappeenranta Saimaa university of applied sciences and ends in Aalto University. In all this time my professional life and family has raised to next level. To professional life I have got many great instructions from various people at department of civil and structural engineering which deepened my professional level got originally from Lappeenranta.

First of all, I would like to thank my instructors D.Sc Wei Lu and D.Sc Jyri Outinen. Wei Lu helped me at theory, timing of thesis and in academic writing and Jyri Outinen was main character in testing phase.

I want to thank my supervisor Professor Jari Puttonen for constructive critics, encouraging comments and patience in long lasting Master's thesis and questions during study time.

Specially I want to thank my family and friends, your support got me to this point. Kati, you supported me and raised our children while our family grew from two to five in this time. Our children's smiles keeps me going.

Petri Tojkander
Kouvola 10.10.2015

CONTENTS

SYMBOLS

Chapter 3

α	thermal elongation factor
ε	strain
σ	stress
θ_a	steel temperature
ΔL	change of length
ΔT	steel temperature difference
a_0	original thickness
b_0	original width
d	original diameter
f_y	yield strength at 20°C
$f_{y,\theta}$	effective yield strength at elevated temperature θ_a
$f_{p,\theta}$	proportional limit at elevated temperature θ_a
r	radius
E	modulus of elasticity
$E_{a,\theta}$	slope of the linear elastic range for steel at elevated temperature θ_a
E_a	modulus of elasticity of steel for normal temperature
L_0	original length
L_c	parallel length
L_t	total length
R_{eH}	yield stress
R_m	ultimate stress
T_{100}	stress-strain curve at temperature of 100°C

Chapter 5

S_0	original cross-sectional area
S_u	minimum cross-sectional area after fracture

FIGURES

TABLES

1 INTRODUCTION

1.1 Background

Topic for research came from Rautaruukki (nowadays SSAB) in Spring 2013 mainly because there were only few previous studies on higher yield strengths at elevated temperatures. Secondly EN 1993-1-1 design rules have been restricted to lower yield strengths. EN 1993-1-1 gives applicable methods to steel grade as high as 460 MPa. Main purpose of this research was to determine mechanical properties of high-strength steels at elevated temperatures. 20 years ago steel grade 355 MPa was called high strength steel but today nominal yield strength has been raised to 500-700 MPa of high strength steel and yield strength of ultra high strength steel nominal is 900-1100 MPa. Test specimen's nominal yield strengths were 700 MPa and 960 MPa. Tests were carried out during March and April 2013 in the laboratory of Department of Civil and Structural Engineering at Aalto University. Funding for this research came from Foundation for Aalto University Science and Technology.

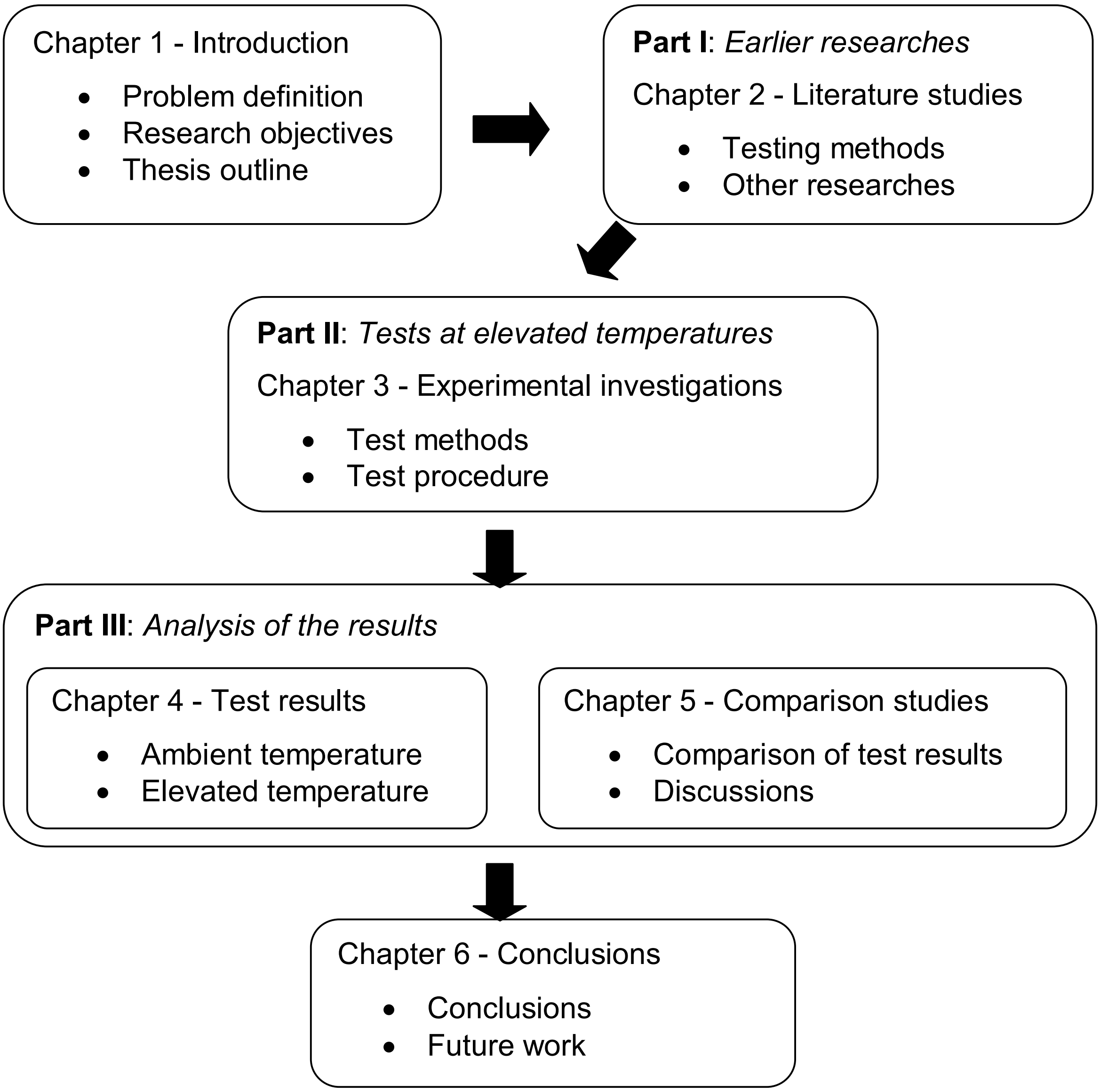
High strength steels are mainly used for vehicles or lifting equipment. Applications are not expected to resist fire. Benefits of using high strength steels are smaller dimensions and lighter structures. To get all the benefits of high yielding strength the steels stress should be at tension which leads to composite structures. Concrete could be the material compressed to protect the steel against fire.

1.2 Aim and scope of the thesis

The scope of this work was to study if the given steel grades behave the same way as milder steel grades. This was done by comparing these tests to earlier researches and the EN 1993-1-2 reduction curves. Results were expected to be higher than the EN 1993-1-2 reduction curves. Changes in material metallurgy and other high-strength steel grades were outlined from this thesis. This thesis covers the research of mechanical properties of steel grades S700QL and S960QC at elevated temperature.

1.3 Structure of the thesis

This thesis consists of three parts: the first part *Earlier researches*, second part *Tests at elevated temperatures* and final part *Analysis of the results*. First part covers earlier researches based on literature and mechanical properties of steel structures used in this research. Second part covers actual tensile testing with different methods at elevated temperatures. Third part covers analysis of the results.



2 LITERATURE STUDIES

2.1 High and ultra high structural steels

Nominal yield strength of high strength steels is equal or above 420 MPa based on EN 1993-1-1. Steels which nominal yield strength is 700-1100 MPa are called ultra high steels. Heat treatment techniques are the key to make high strength steels. Thermomechanical-treatment leads to high strength and very good toughness with weldability better than normalized steels. Quenching produces very high strength.(Qiang, 2013)

Examples for each category (Ruukki catalog) are Multisteel N (S355N) normalized steels, Optim 700MC of thermomechanically rolled steels and Optim 960QC of quenched and tempered steels (Ruukki, 2015). Normalized steels are heated to approximately 900°C and cooled by air. In thermomechanical-technique the steels are rolled at 800-900°C temperature and accelerated-cooled to below 600°C. Quenched steels are heated to approximately 900°C and then quickly cooled by water.(Voestalpine, 2015)

2.2 Methods to study the mechanical properties of structural steel in fire

In transient tensile test the stress level is kept at the same and temperature rises until the specimen fractures. Transient state tests give Temperature-Strain curves at intended stress level as a result. The results are more realistic because loading is kept unchanged and only temperature rises like in actual case of fire. The transient state test takes more time due to a slow heating rate. In the transient state test results have lower values than those of steady state tests results because of the creep. (Maljaars, Twilt, Fellinger, Snijder, & Soetens, 2010)

In steady state tensile test the temperature stays at the same level and stress rises until fracture happens. The steady state tests gives Stress-Strain curves at intended temperature as a result. The steady state test is more sensitive to strain rate than transient state test. Steady state tests are more commonly used in research as they are easier to perform and results are received immediately. (Outinen, Jyri, 2007)

The strength reduction factors are from Temperature-Strain curves. Reduction factor from EN 1993-1-2 for effective yield strength ($f_{y,\theta}$) is 2%-strain level at different temperatures. Reduction factor for proportional limit ($f_{p,\theta}$) can be read from curves. It is the point where the strain begins to grow first time. Below proportional point only thermal expansion affect strain curve. Temperature-Strain curve is shown in Figure 2.1 and example of strength reduction factor is shown in Figure 2.2.

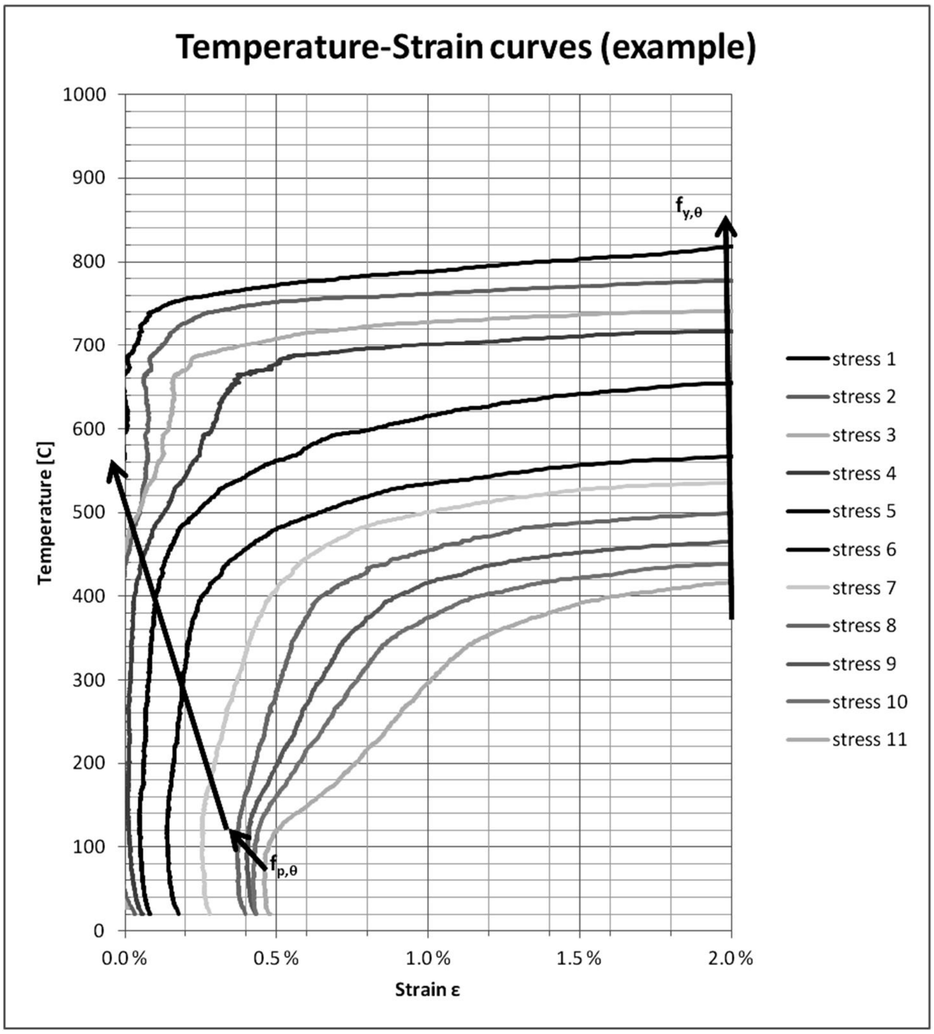


Figure 2.1 Temperature-Strain curve (example)

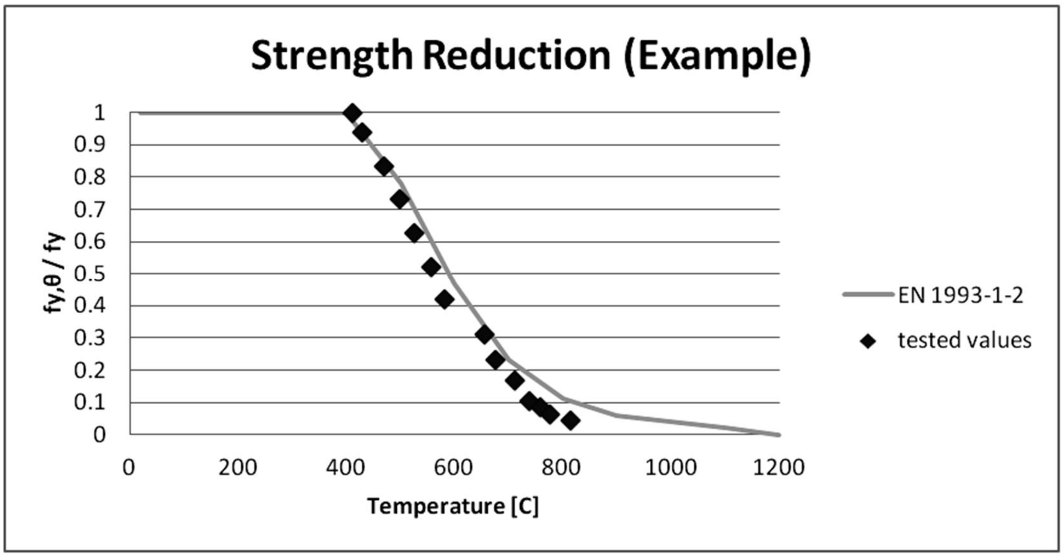


Figure 2.2 Yield strength reduction factor (example)

Transient state tensile tests gives Temperature-Strain curves as a result which can be converted to Stress-Strain curves. Conversion is possible only when there is enough measured stress levels. Temperature curve can be made from points on stress curves. One temperature-curve needs points from every stress levels at indented temperature level. For example, stress curve at 100 degrees (T_{100}) needs points (stress, strain) from every stress level at temperature 100 degree (Figure 2.3).

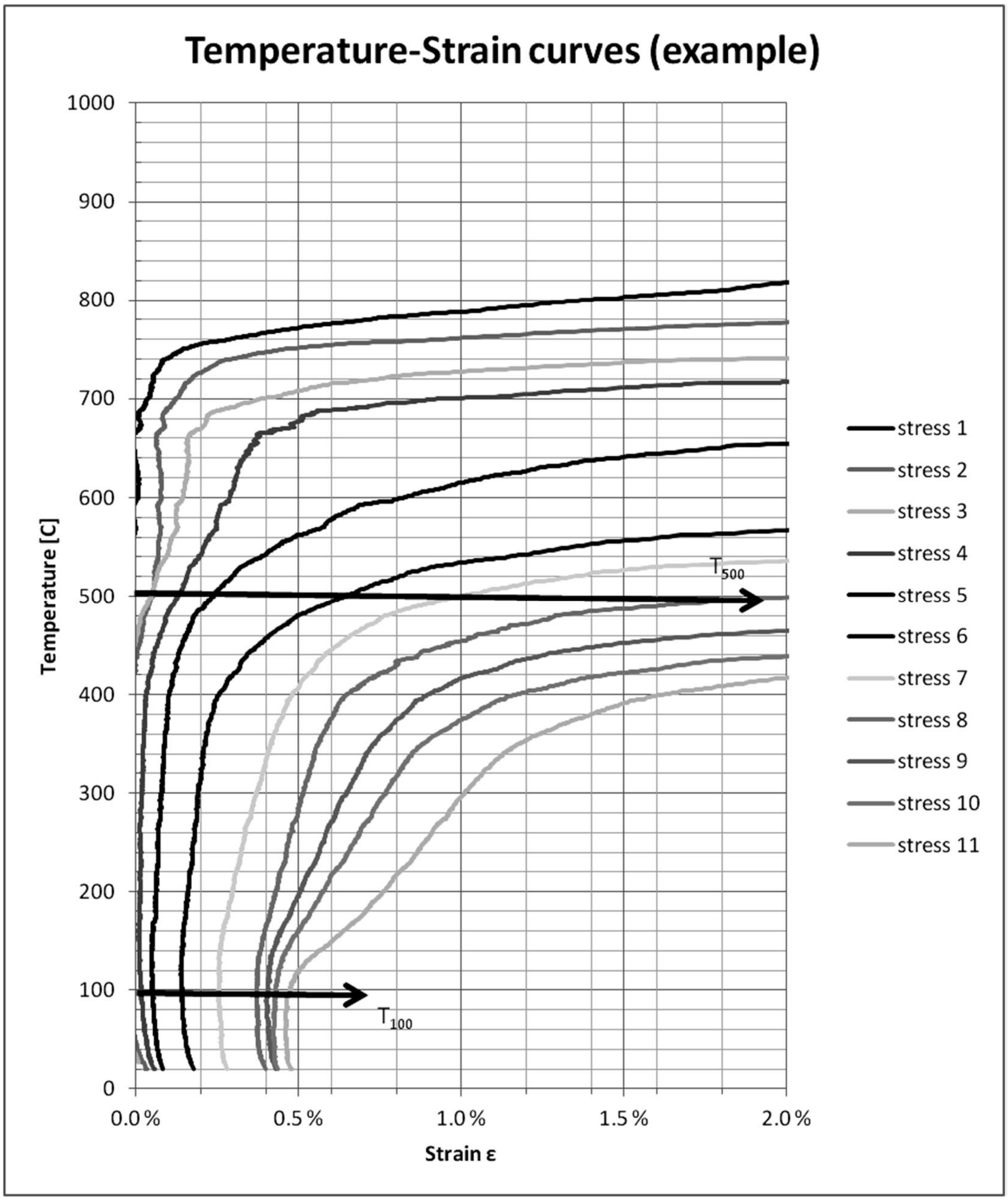


Figure 2.3 Temperature-Strain curve to Stress-Strain curve (example)

Stress curve can be made when all points are taken. Curve is made by plotting these points on the same line. In Figure 2.4 is shown example stress curves T_{100} and T_{500}.

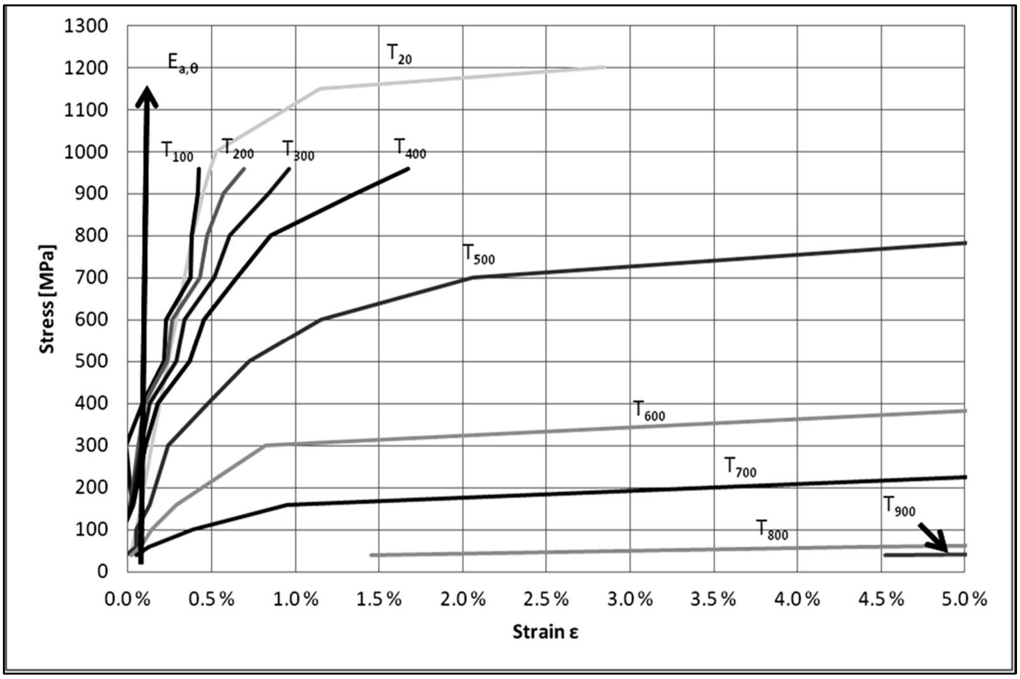


Figure 2.4 Converted Stress-Strain curves (example)

Steady state tests gives straight stress-strain curves without conversions. Stress-strain curves needed to get reduction factor to modulus of elasticity ($E_{a,\theta}$) at different temperatures. When stress-strain curves are known at different temperatures the modulus of elasticity can be calculated by Hook's Law. In Figure 2.5 is shown reduction factor for modulus of elasticity.

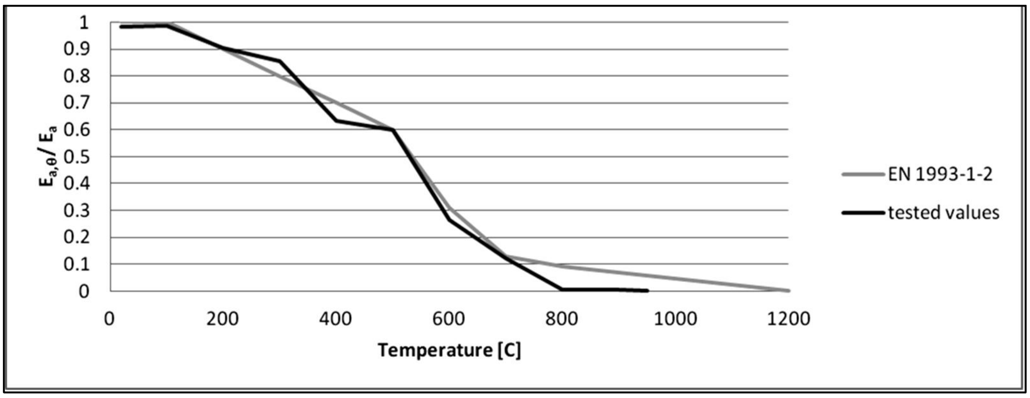


Figure 2.5 Reduction curve for modulus of elasticity (example)

2.3 Current researches on mechanical properties of structural steel in fire

Qiang, Bijlaard and Kolstein have tested the structural steel of a type of S460N at elevated temperatures by both testing methods, namely the steady state and the transient state tests. At the steady state tests the heating rate was 50 °C/min and the strain rate 0.005/min. After heating the steel to a wanted temperature, a waiting time of 10 min was used to stabilize temperature in the steel before starting the tension test. Results are shown in Figure 2.6 and Figure 2.7. (Qiang, Bijlaard, & Kolstein, 2012)

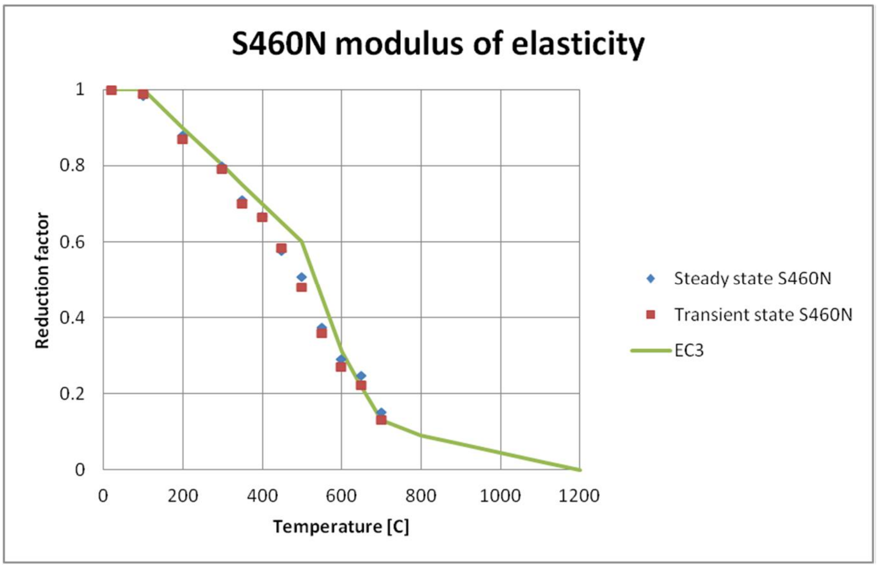


Figure 2.6 Reduction factor for modulus of elasticity (Qiang, Bijlaard, & Kolstein, 2012)

In Figure 2.6 the steady state values are higher than the transient values and lower in Figure 2.7. The transient state values should be lower than the steady state values because testing time is longer.

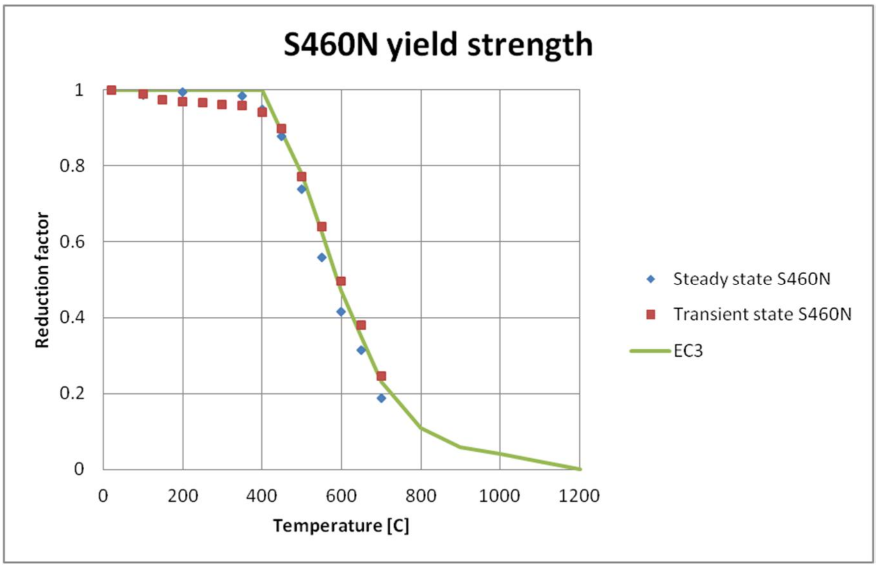


Figure 2.7 Reduction factor for yield strength (Qiang, Bijlaard, & Kolstein, 2012)

W. Chen, J. H. Ye, X. L. Zhao and Y. Bai investigated Q345 cold-formed steel at elevated temperatures. The testing method was steady state tests with heating rate of 20 °C/min and 15 min stabilizing time after reaching the designed temperature. Strain rate at the tension test was approximately 0.0025/min. Two different kind of testing samples were used: a corner sample and a flat sample. Results are shown in Figure 2.8 and Figure 2.9. (Chen, Ye, Zhao, & Bai, 2012)

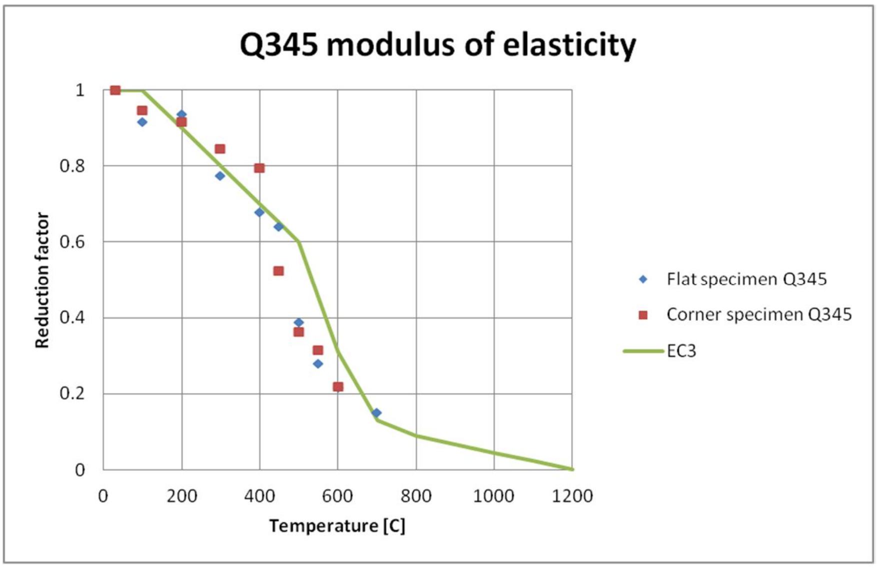


Figure 2.8 Reduction factor for modulus of elasticity (Chen, Ye, Zhao, & Bai, 2012)

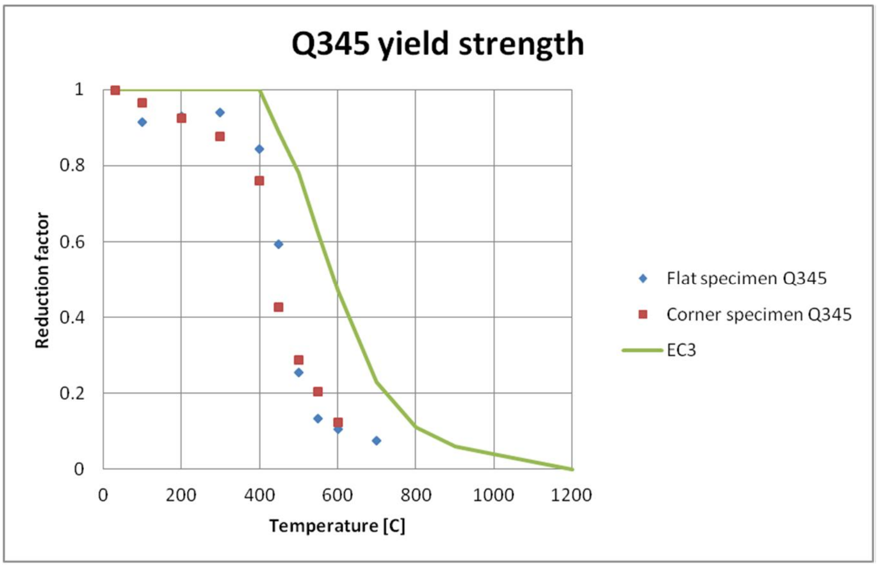


Figure 2.9 Reduction factor for yield strength (Chen, Ye, Zhao, & Bai, 2012)

In both researches the EN 1993-1-2 overestimated the material properties at elevated temperatures. Thus, in the both of the cases new reduction factors to get conservative estimations at elevated temperatures were to be defined.

Jyri Outinen has researched mechanical properties of structural steels at elevated temperatures in his doctoral dissertation. Few remarks are reviewed next. There is difference in different testing methods at elevated temperatures. In the steady state test the strain rate has significant effect on results. Figure 2.10 shows comparison of results. High strain rate at a steady state test gets too positive results. (Outinen, Jyri, 2007)

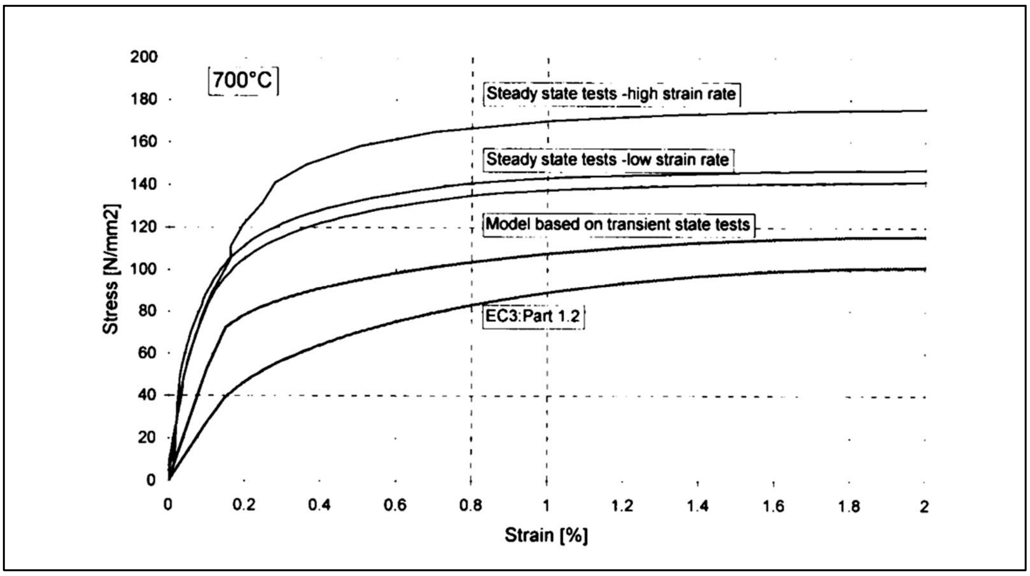


Figure 2.10 Affect of strain rate to results (Outinen, Jyri, 2007)

High temperature affects negatively strength of structural steels even if material is not loaded. Outinen has in his investigations heated structural steel up to 950 °C and after cooling performed tension tests. Results of one of these tests is shown in Figure 2.11. Strength has been dropped to 90 % of the original strength. However in these tests the strength values were still over nominal yield strength. (Outinen, Jyri, 2007)

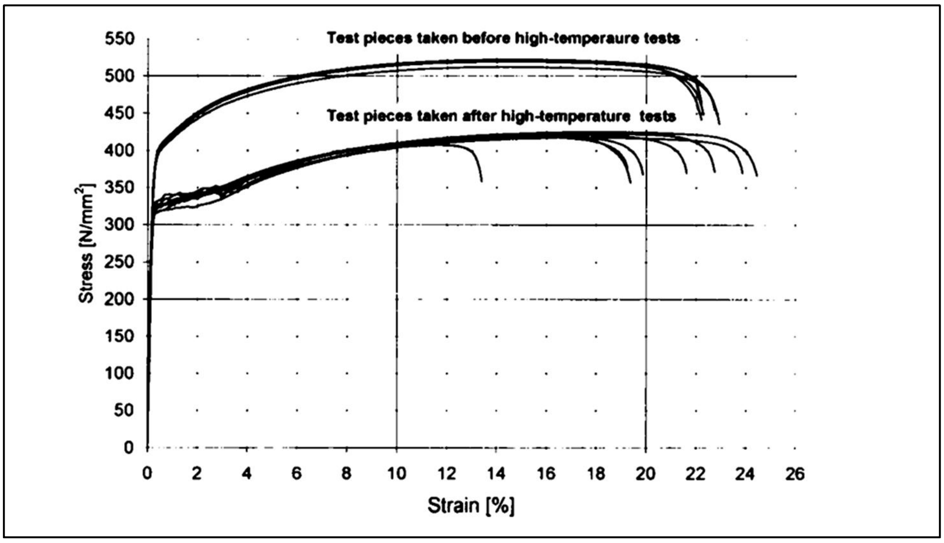


Figure 2.11 Strength loss after heating (Outinen, Jyri, 2007)

Possibility of re-using the structural steel after fire is dependent on temperature and distortions. Strength might be adequate but distortions that the fire has caused for shape and straightness of the structural steel might be too large. If the structural steel is hot-dip galvanized the usability is easy to evaluate. If zinc coating has been smelted (419.6 °C) the damage is in most cases too expensive to repair on site. (Outinen, Jyri, 2007)

2.4 Current researches on ultra high steel S960

S960QC has been researched more than S700QL by Rautaruukki because in EN 1993-1-1 design rules have been restricted to yield strength lower than 700 MPa. Currently produced high strength structural steels have yield strengths up to 1200 MPa. Research results were found at Rautaruukki's website and summary of those results were reviewed in this chapter. (Porter, 2010)

Design rules of EN 1993-1-1 give non-conservative local buckling capacities when yield strength is higher than 700 MPa. Non-conservative values start at slenderness below 0.9 and at higher values capacities are clearly overestimated. New reduction factors for buckling have been researched in Lappeenranta University of Technology based on tests of 12 pieces of steel grades S900 and S960. (Halmea, Huusko, Marquis, & Björk, 2010)

Welding of high strength steels has been researched at Lappeenranta University of Technology. Research consists tension tests to S960 steel grade and nonlinear finite element analysis. Results confirm EN 1993-1-8 design rules for joint design. Deformation capacity was lower than mild structural steels which yield strengths are lower than 460 MPa. (Björk, Toivonen, & Nykänen, 2010)

Fracture was researched at Lappeenranta University of Technology. Conclusion of research was that S960 steel fracture tests indicated ductile behavior. Both small-scale and large-scale tests showed that brittle cleavage fracture will not become the dominant fracture mode. (Nevasmaa, et al., 2010)

S960QC belongs to Optim product family. This product family has been designed to have good welding and flanging abilities and to be suitable for laser processing. S960QC is also cold formable and hot-dip galvanizing does not affect yield strength negatively. (Hemmilä, Laitinen, Liimatainen, & Porter, 2010)

3 EXPERIMENTAL INVESTIGATIONS

3.1 Test methods

Two different kinds of methods were used to determine mechanical properties of given steel grades. Transient state test method was mainly used to get mechanical properties at elevated temperature. Steady state test method was used to verify the transient state test results. The transient state test results were used to get reduction factors for effective yield strength, proportional yield limit and modulus of elasticity.

After all the test pieces were tested the data was exported from the testing program. Data received from the testing program was checked manually and transformed into a readable form. Hand calculations are explained in this chapter. All data have been imported to Microsoft Excel and all calculations have been made in Excel.

First thing in manual check is Hook's Law (Formula 3.1). Hook's Law shows that when stress is below yield level the strain is linear. Linear coefficient is called modulus of elasticity.

$$\sigma = \varepsilon E \tag{3.1}$$

Before starting the tension test the Hook's Law is used to check that program in the tensile test device and sensors work and register right values for strain when the force is known. Hook's Law is also used to calculate modulus of elasticity at different temperatures.

Thermal elongation needs to be taken into consideration when elongation is measured quantity. Formula 3.2 shows parameters in thermal elongation calculation.

$$\Delta L/L_0 = \alpha \Delta T \tag{3.2}$$

In this research thermal elongation is taken into consideration by EN1993-1-2. Where ($\alpha\Delta T$) gets values form Table 3.1.

Table 3.1 Thermal elongation of steel (SFS-EN 1993-1-2, 2005)

Steel temperature, θ_a	Thermal elongation, $\Delta L/L_0$
20 °C ≤ θ_a ≤ 750 °C	$1.2 * 10^{-5}\theta_a + 0.4 * 10^{-8}{\theta_a}^2 - 2.416 * 10^{-4}$
750 °C ≤ θ_a ≤ 860 °C	$1.1 * 10^{-2}$
860 °C ≤ θ_a ≤ 1200 °C	$2 * 10^{-5}\theta_a - 6.2 * 10^{-3}$

Minor adjustments were made for the results measured so that the results are comparable with earlier researches. Correction does not mean “data manipulation” it means that unclear data results are taken off or changed to better results. It does not matter if their effect is positive or negative on the final evaluation. An example of this kind of a result is a too big difference between manual check and data received from the testing program. These corrections are discussed in this section. Data manipulation means that only negative results are taken off or changed.

3.2 Test materials, specimens and program

Both testing materials S700QL and S960QC are hot-rolled steels and were manufactured by the Finnish company Rautaruukki Corporation (nowadays SSAB). Test specimens are graded as high-strength steels. There were 35 test pieces of both steel grades. Before any testing all the test pieces were measured and verified that they are in accordance with standard SFS-EN 6892-1 and -2. Results of the measurements are in Appendix A and test programs are in Appendix B. (SFS-EN 6892-1, 2009)

S700QL is quenched (Q) and low-temperature tough (L) steel which meets the requirements of S690QL EN 10025-6 standard. Test specimens are cut out from thicker hot-rolled steel sheet with a nominal thickness of 20 mm. Test specimen dimensions are given in Figure 3.1 and in Table 3.2 (S700QL properties, 2013) respectively.

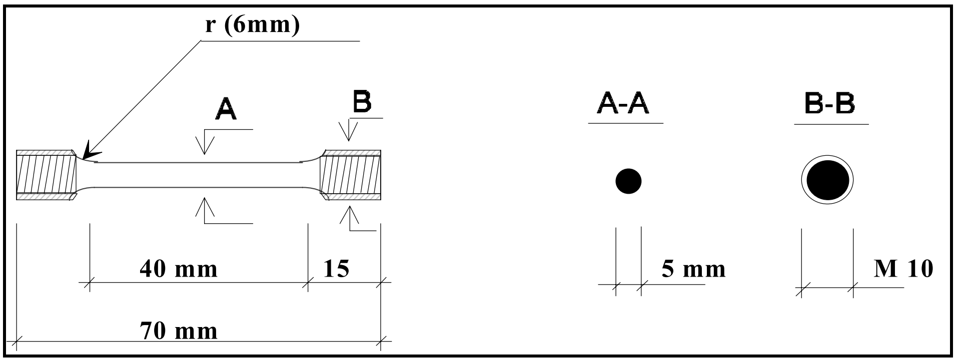


Figure 3.1 S700QL -test specimen

Table 3.2 S700QL Dimensions of the specimen

Total length	L_t	70 mm
Parallel length	L_c	40 mm
Original gauge length	L_0	25 ± 0.005 mm
Original diameter of the parallel length	d	5 ± 0.040 mm
Diameter of the worm end		M10
Transition radius	r	6 mm

Chemical compositions of the steel material S700QL are shown in Table 3.3. Chemical compositions are provided by the manufacturer.

Table 3.3 S700QL Chemical compositions

NAME		CONCENTRATION
Aluminium	Al	0.044
Boron	B	0.0014
Calsium	Ca	0.002
Carbon	C	0.169
Chromium	Cr	0.59
Manganese	Mn	1.01
Molybdenum	Mo	0.194
Nickel	Ni	0.19
Niobium	Nb	0.001
Nitrogen	N	0.0043
Phosphorus	P	0.011
Silicon	Si	0.316
Sulfur	S	0.0001
Titanium	Ti	0.02
Vanadium	V	0.01

S960QC is quenched (Q) and cold-formable (C) steel which meets the requirements of S960MC EN 10149-2 standard. Test specimens are cut out from a hot-rolled steel sheet with a nominal thickness of 8 mm. Test specimen dimensions are given in Figure 3.2 and in Table 3.4 (Nevasmaa, et al., 2010) respectively.

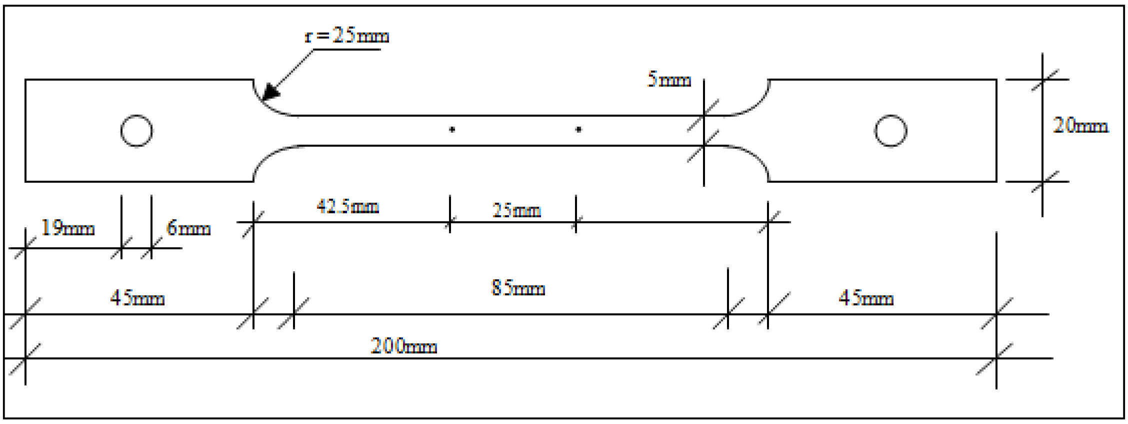


Figure 3.2 S960QC -test specimen

Table 3.4 S960QC Dimensions of the specimen

Total length	L_t	200 mm
Parallel length	L_c	85 mm
Original gauge length	L_0	25 mm
Original thickness	a_0	4.00 ± 0.05 mm
Original width of the parallel length	b_0	5.00 ± 0.05 mm

Chemical compositions of the steel material S960QC are shown in Table 3.5. Chemical composition are provided by the manufacturer.

Table 3.5 S960QC Chemical compositions

NAME		CONCENTRATION
Aluminium	Al	0.034
Boron	B	0.0019
Calsium	Ca	0.0025
Carbon	C	0.096
Chromium	Cr	1.1
Manganese	Mn	1.1
Molybdenum	Mo	0.201
Nickel	Ni	0.404
Niobium	Nb	0.003
Nitrogen	N	0.0047
Phosphorus	P	0.009
Silicon	Si	0.249
Sulfur	S	0.0004
Titanium	Ti	0.03
Vanadium	V	0.011

3.3 Test setup and procedure

All testing equipment are calibrated in accordance with the standard SFS-EN ISO 6892-1. The testing equipment are shown in Figure 3.3. Tensile testing machine used in this research was manufactured by the German company Roell+Korthaus. The machine has two loading ranges 0-50 kN and 0-250 kN. In these tests the loading range of 0-50 kN was chosen because the maximum load in the tests is about 25 kN. Maximum error of the load cell is ±0.05 kN by the use of maximum loading capacity of 250 kN. Gauge length of the extensometer used in this research was 25 mm with an elongation range of 0-4 mm. Extensometer has an accuracy of ±0.003 mm. (SFS-EN 6892-1, 2009)

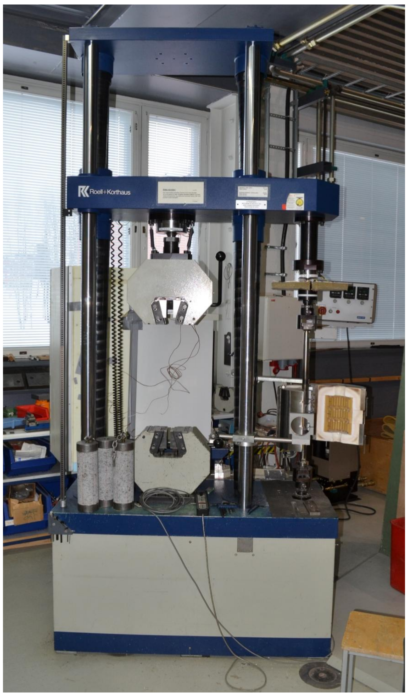


Figure 3.3 Test equipment

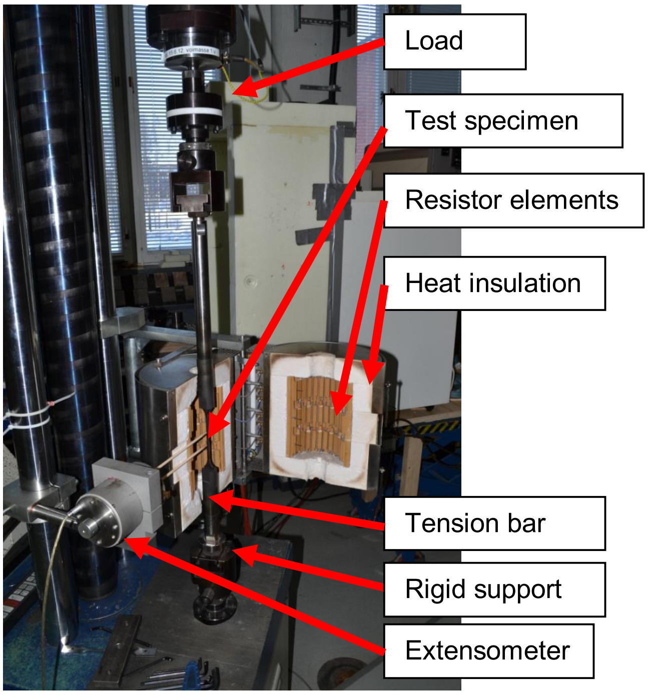


Figure 3.4 Furnace and tensile testing device

Heating device manufactured by the German company Maytec GmbH is shown in Figure 3.4. In the furnace there were three separately controlled resistor elements which ensure stable air temperature. The resistors are controlled by temperature-controlling unit which is manufactured by the British company Eurotherm Ltd. The air temperature in the furnace is measured with three separate temperature-detecting elements.

Even though the heating rate of the furnace is quite slow, the temperature of the steel is not rising at the same rate as temperature of the air. The difference of the temperatures are measured at one test without tension on the test sample. The steel temperature is measured accurately from the test specimen using temperature-detecting element that was fastened to the specimen during the heating process. The differences between the air temperatures and the steel temperatures are shown in Figure 3.5. The steel temperature can be calculated from the air temperature without measuring steel temperature in every test by using this temperature curve.

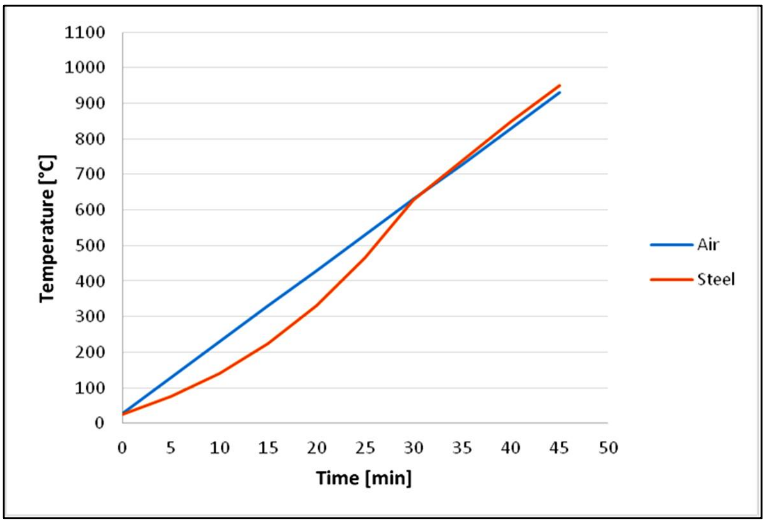


Figure 3.5 Furnace temperature compared to steel temperature

Before starting to make any tests, all of the test pieces were measured to make sure that results are reliable and dimensions of samples are correct. In Appendix A the results of measurements on both steel grades are represented. From S960QC-sample the thickness and width were measured from three points (both ends and middle). At S700QL-sample the diameter was measured same way from three points (both ends and middle). Because of the shape of the cylinder each point needed two measurements and the measurements needed to be placed perpendicularly to each other. Measuring device is shown in Figure 3.6.

Figure 3.6 Measuring device

After measuring every piece results were checked and unclear samples were taken away from the test program. Test programs are in Appendix B for both steel grades. Furnace and tensile test machine were checked so that they work as intended. Two pretests were made before real tests. Rising speed of the temperature in the furnace is set to 20 degrees per minute. Jyri Outinen has done many researches with different heating rate (10 degree/minute, 20 degree/minute) and the results are reliable at 20 degree/minute. Furnace controlling unit is shown in Figure 3.7.(Outinen, Jyri, 2007)

Figure 3.7 Controlling unit of furnace

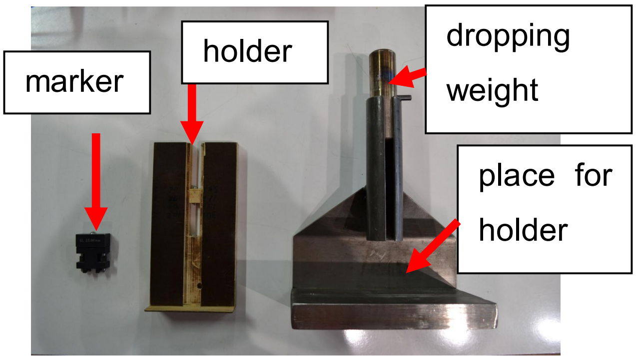


Figure 3.8 Marking tools

At the beginning the measurement points have to hit to the sample. Figure 3.8 shows equipment to make measurement points. Measuring gauge length is 25 mm and that is hit to sample by the marker. In the middle there is a holder which keeps the marker at the middle of the sample. Object at the right is the hammering unit. Holder is placed at under the weight which is dropped to make measuring points to the sample. With these tools all measuring points are at the same place.

For safety reasons before connecting sample to tensile test device the furnace is turned OFF. Another reason is that furnace has been programmed to start heating when turned ON. Tensile test can be started when sample is connected. Next the full procedure is explained by one phase at the time. First phase is that the tensile test device takes loose space out from connections by stressing sample to 20% of the yield strength and then loosens the tension to zero. Figure 3.9 shows sample connected to the tensile test device.

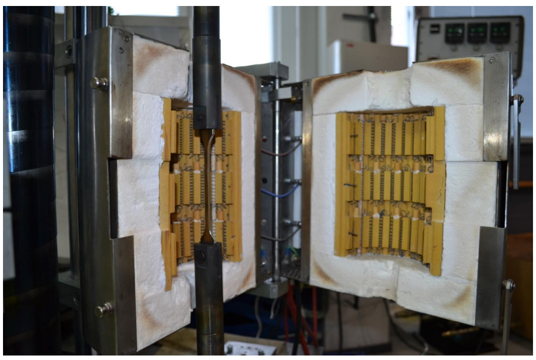


Figure 3.9 Sample connected to test device

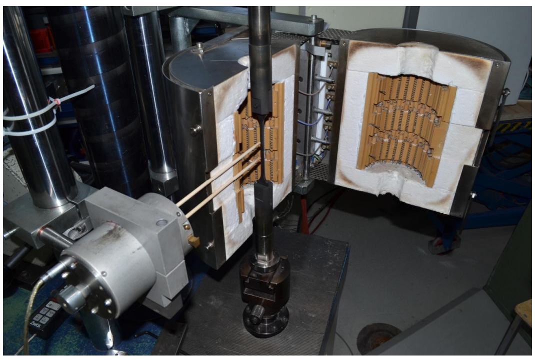


Figure 3.10 Strain measuring device connected

The tensile test machine could measure/calculate strain by given attributes but in these tests external measuring device is used for higher reliability. At the second phase of the tensile test an external measuring device is connected. Extreme caution has to be taken to connect external measuring device to the right place because of its sensitivity. Figure 3.10 shows connected external measuring device.

Third phase at the tensile test is to close the furnace and to make sure that the measuring device is not touching anything or nothing is not in the way of measuring devices. Fourth phase is to continue the tensile test so that the tensile test device pulls intended stress level. Fifth phase is turning the furnace ON and marking the starting time when turning the furnace ON. Sixth phase is to wait until the program stops (strain level 16%) or manually stop the program. Seventh phase is to release tension from the sample and start cooling the furnace for the next tension test. The next tension test can be started when furnace inner temperature is lower than 30 degrees when the furnace doors are closed.

At steady state tensile test the startup procedures are quite the same as transient state tests. Differences come from intended temperature of the furnace and actual tensile test. Changes start at fourth phase when the oven is set to keep the temperature at intended temperature by the same heating rate as in the transient state tests. Fifth phase is turning the furnace ON and waiting for temperature to rise to intended temperature. Sixth phase is starting the tensile test after the furnace has held the intended temperature for five minutes. Parameters for the tensile test are the same as in standard tensile test at room temperature. The tensile test ends when the sample breaks. Seventh phase is the same as in the transient state tests.

4 TEST RESULTS

4.1 Mechanical properties at ambient temperature

To verify properties reported by the manufacturer the tensile tests were carried out according to SFS-EN ISO 6892-1. Tensile tests were carried out as strain rate-controlled loading with strain rate being 0.006 s^{-1}. The results are shown in Figure 4.1 and Table 4.1 with standard EN 10025-6. Two test pieces of both steel grades were used in room temperature tests.

Table 4.1 Material properties of both steel grades in room temperature

	S960QC			**S700QL**		
	Measured	Reported	EN10025-6	Measured	Reported	EN10025-6
Modulus of elasticity E (MPa)	208600	Not measured	-	205200	Not measured	-
Yield stress R_{eH} (MPa)	1098	1060	960	833	820	690
Ultimate stress R_m (MPa)	1189	1150	980 - 1150	880	870	770 - 940

Results confirm manufacturer's reported properties and are accepted by standard EN10025-6. S960QC-steel grades yield stress (R_{eH}) differences 3.6% from reported value and ultimate stress (R_m) 3.4% from reported value. S700QL-steel grades yield stress differences 1.6% and ultimate stress 1.1% from reported values. According to SFS-EN ISO 6892-1 Appendix K, the reproducibility of the tensile test between testing laboratories is ±2.0% to high strength -steels yield strength and ±1.5% to ultimate strength. Because of the small amount of tests in room temperature the results are acceptable.

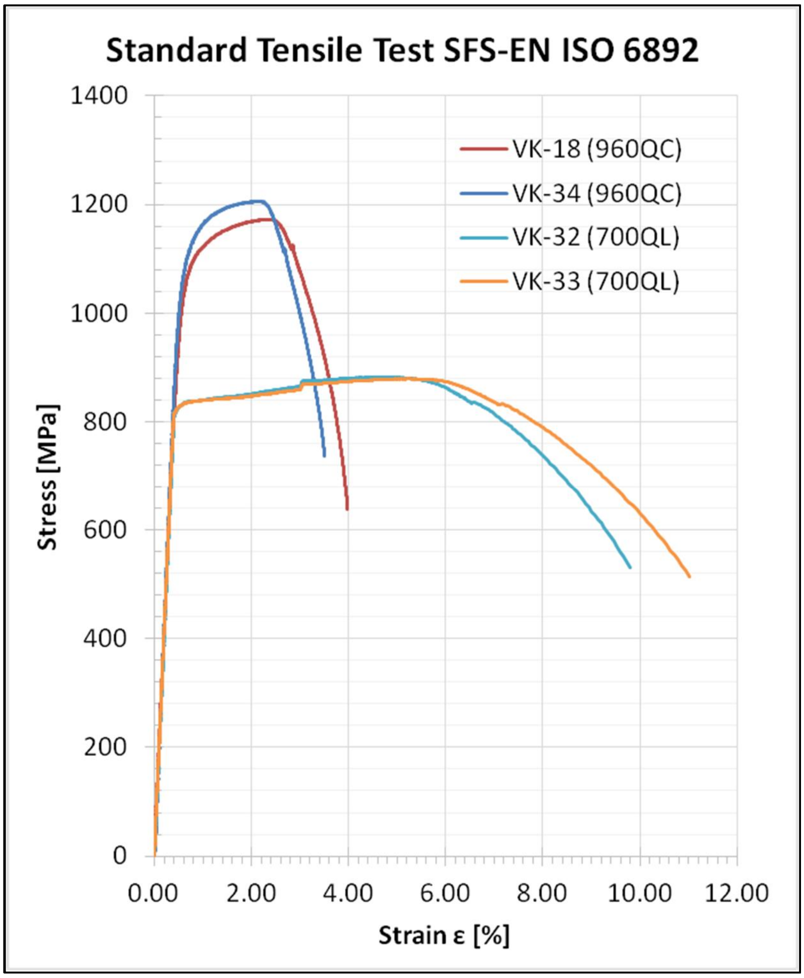


Figure 4.1 S960QC and S700QL, Standard tensile tests

4.2 Mechanical properties at elevated temperatures

4.2.1 Transient state tests S960QC

Transient state tensile tests were carried out with two repeated tests at each load level. Thermal elongation of the structural steel was taken into consideration according to EN1993-1-2. In temperature-strain relationship thermal elongation was subtracted from the total strain. Heating rate in the transient tests was 20 °C/min. Test specimen was heated until the temperature was 950 °C or until the yielding of the test specimen.

There were 14 stress levels in transient state tests at S960QC (28 pieces). Figure 4.2 and Figure 4.3 show results from transient tests respectively. Temperature-Strain curves are shown in Figure 4.2 and Stress-Temperature curves in Figure

4.3. In Appendix C results from each stress level are shown one by one. Colors in Appendix C mark if the result is used on conversion or not. Green means "used" and red means "not-used". All results were used to get 2%-yield reduction factor.

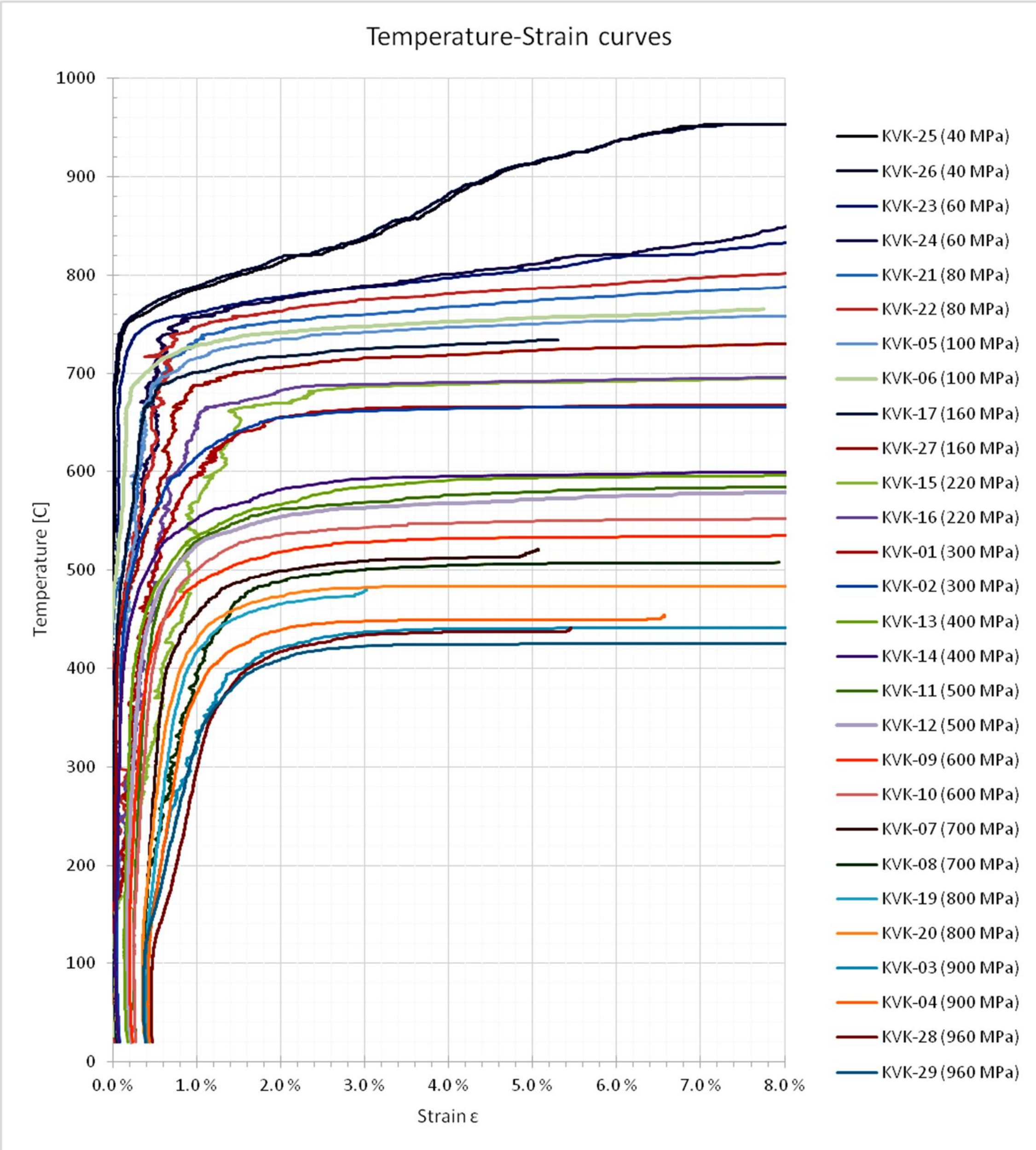


Figure 4.2 S960QC, Temperature-Strain curves

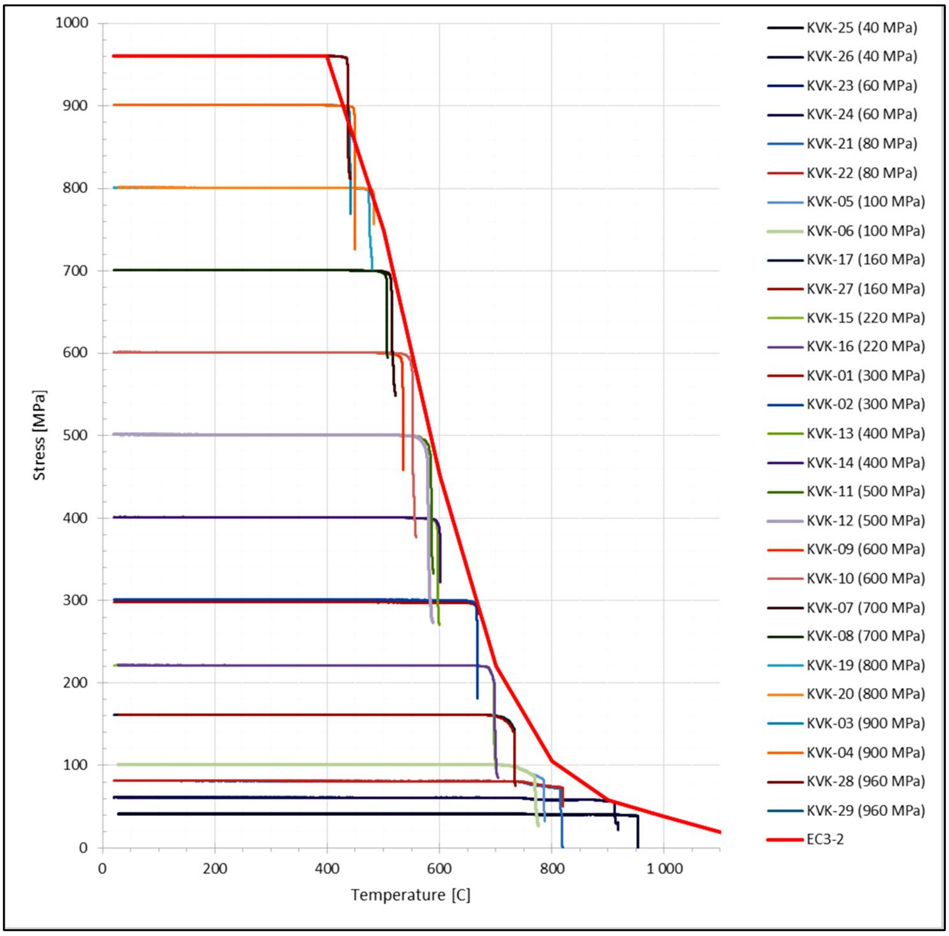


Figure 4.3 S960QC, Stress-temperature curves

Temperature-strain results were converted to stress-strain figures to get reduction factor for modulus of elasticity. This is also explained in Chapter 2.2. In Figure 5.1 is shown Stress-Strain curves.

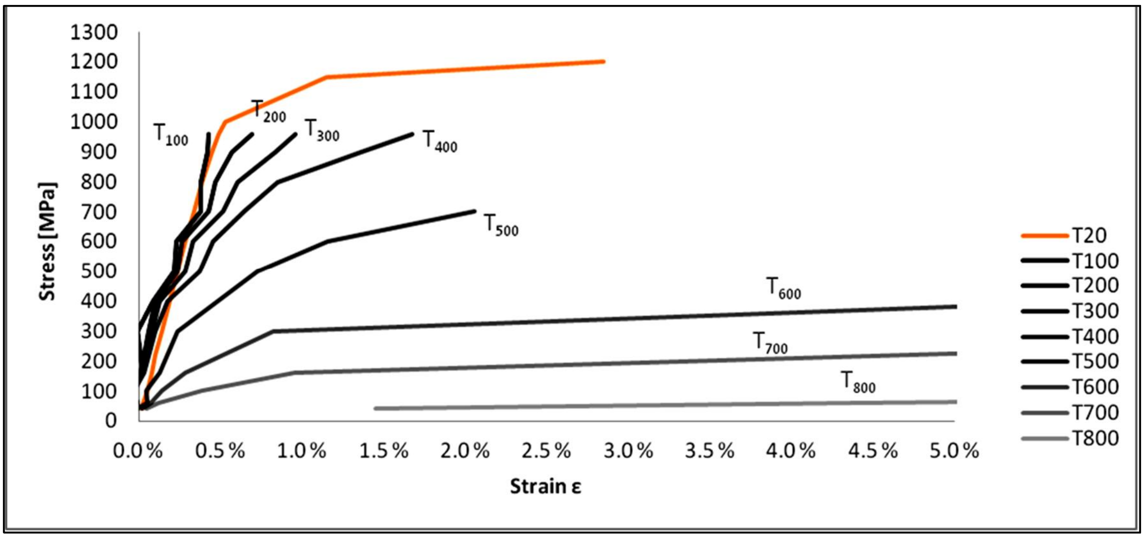


Figure 4.4 S960QC, Stress-Strain figure

4.2.2 Transient state tests S700QL

There were 14 stress levels in transient state tests at S700QL (28 pieces). Figure 4.5 and Figure 4.6 show results from transient tests respectively. Temperature-strain curves are shown in Figure 4.5 and stress-temperature curves in Figure 4.6. In Appendix D are shown results from each stress level one by one. Colors in Appendix D mark if the result is used on conversion or not. Green means "used" and red means "not-used". All results were used to get 2%-yield reduction factor.

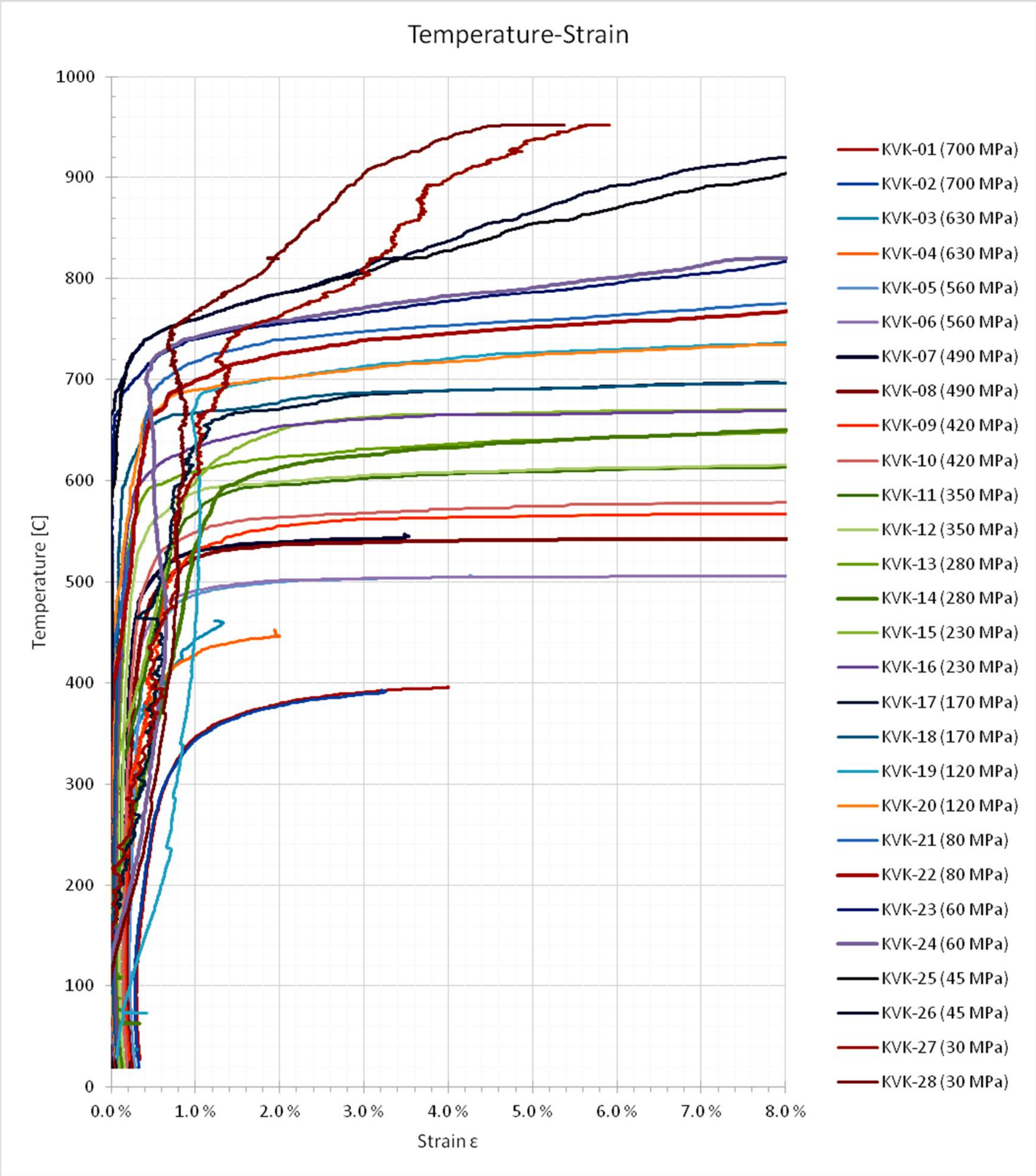


Figure 4.5 S700QL, Temperature-Strain curves

As can be seen from Figure 4.5 all high-tensioned tests failed. The samples begin to yield outside the measuring area. It seems that round samples were harder to get results than flat sample of S960QC.

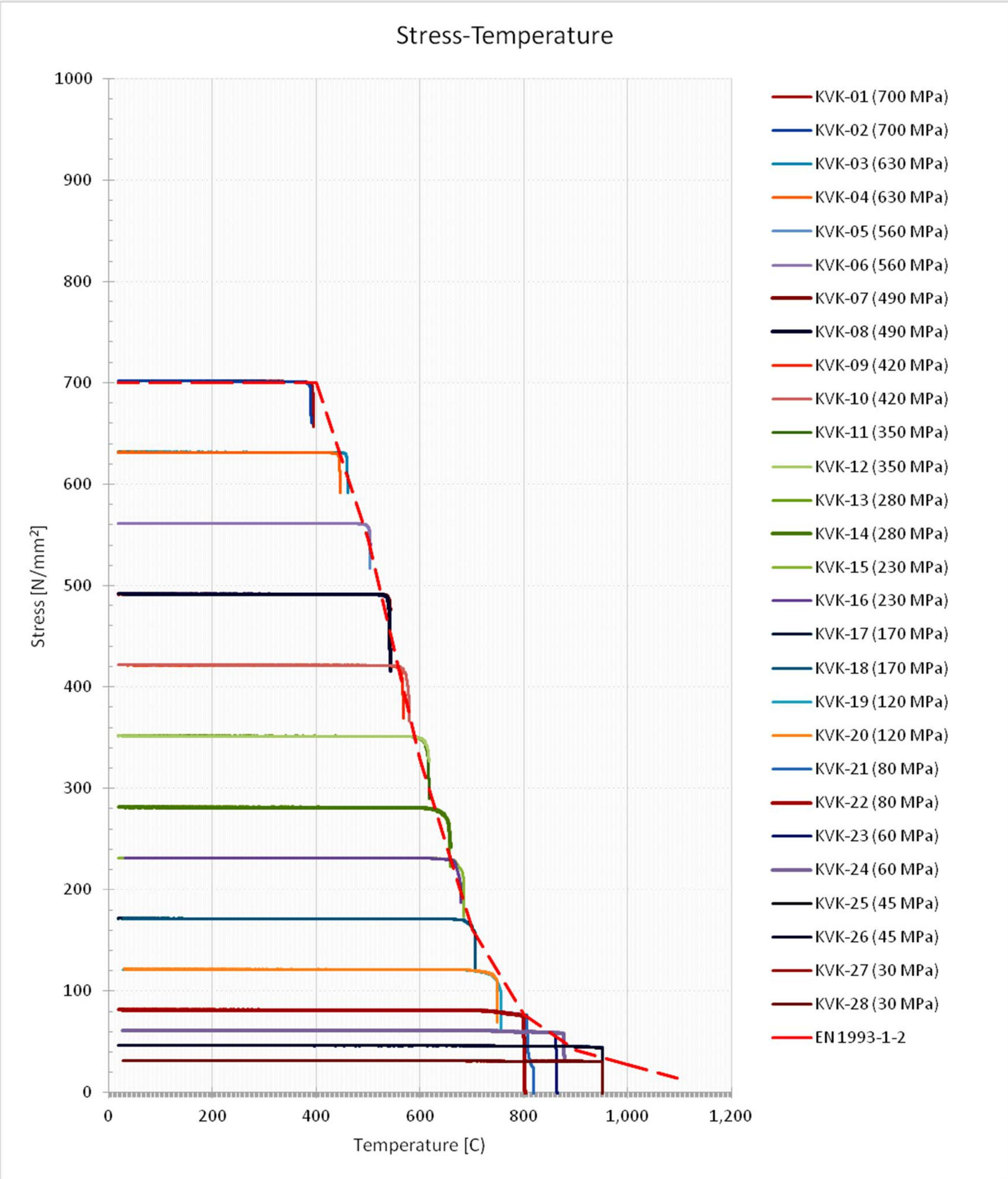


Figure 4.6 S700QL, Stress-Temperature curves

The temperature-strain results are converted to stress-strain figures and shown in Figure 4.7. Modulus of elasticity can be obtained from this figure as earlier with steel grade S960QC.

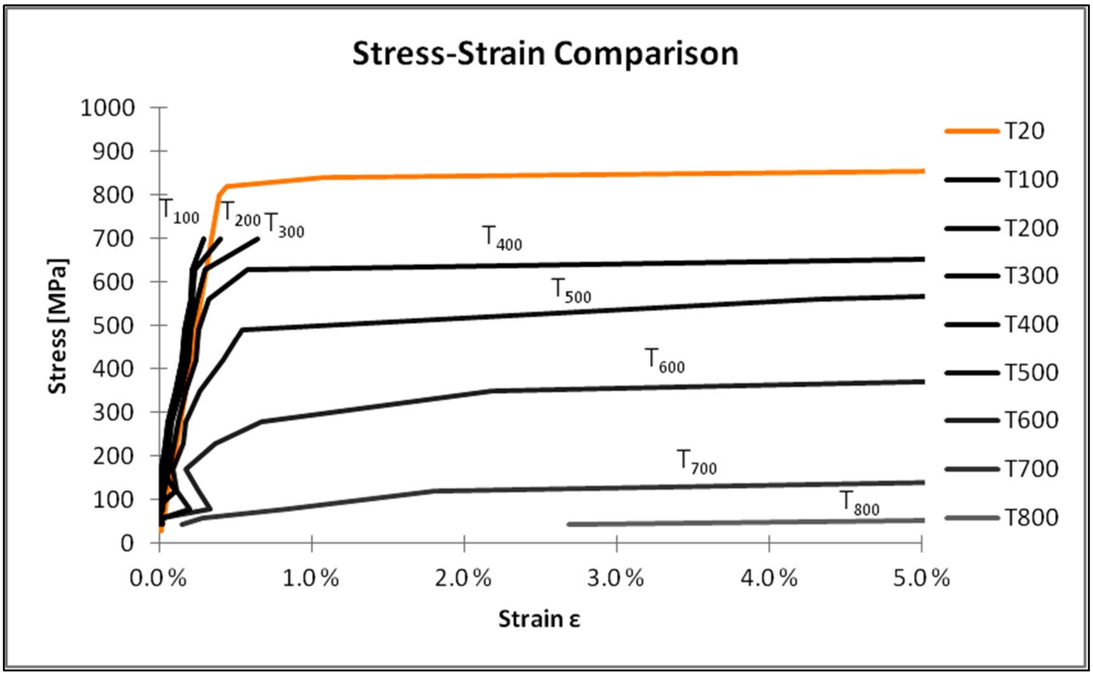


Figure 4.7 S700QL, Stress-Strain figure

4.2.3 Steady state tensile tests

The steady state tensile tests were carried out for both materials with one test at each temperature. The steady state tests used the same heating rate as in the transient tests (20 °C/min) until the temperature rose to the specified value. After temperature had risen there was a two minute waiting time before the tensile test.

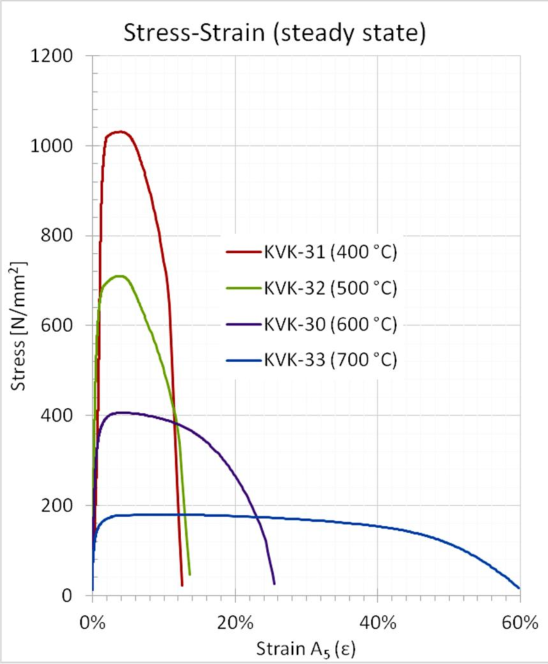


Figure 4.8 S960QC, Stress-Strain curves

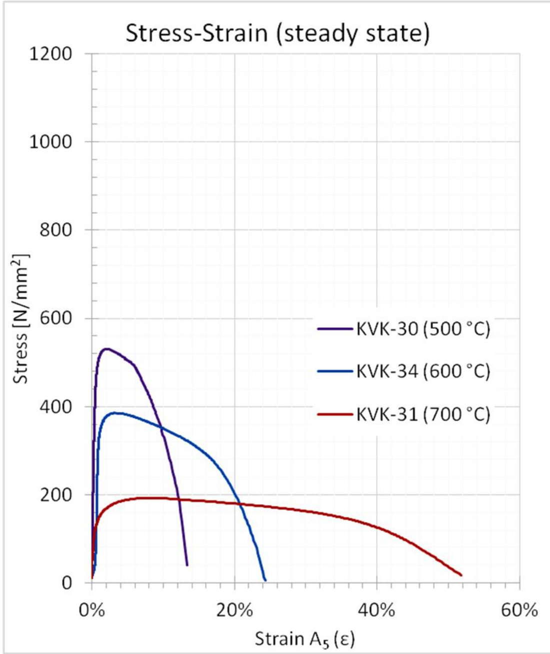


Figure 4.9 S700QL, Stress-Strain curves

Four steady state tests were carried out at temperatures of 400°C, 500°C, 600°C and 700°C for S960QC and 500°C, 600°C and 700°C for S700QL. The stress-strain curves from the steady state tests are shown in Figure 4.8 for S960QC and in Figure 4.9 for S700QL. What can be seen from these two figures is that the ductility of both steel grades rises when temperature rises. Fracture is not brittle at elevated temperatures with structural steels.

4.3 Failure modes of the specimens

Failure mode is hard to see from transient state tests in Figure 4.10 and Figure 4.11 because of the limits on test program. Strain was limited to 16 % in testing device which was the elongation range of extensometer used in transient state tests. At steady state tests the failure mode is more visible because there was not any strain limits because the extension was only measured to 3% by external extensometer and after that by tensile testing device.

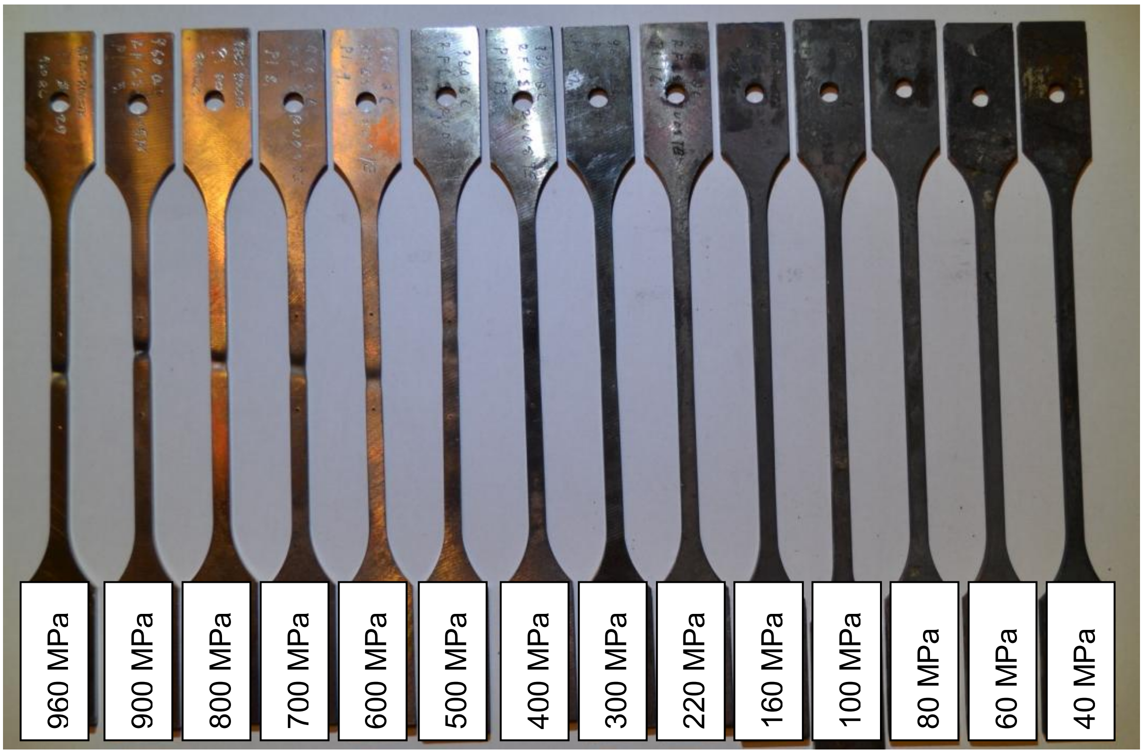


Figure 4.10 S960QC, transient state tests failure modes

Ductility is the most visible property and it rises while temperature rises. Necking is visible only at high stress levels (500-960 MPa). At lower stress levels (higher temperature) the failure mode is measurable but not so visible because the necking happens at longer length. Thus, the cross section area of the specimen is smaller after the test than at the beginning of the test.

Figure 4.11 S700QL, transient state tests failure modes

Figure 4.12 S960QC, steady state tests failure modes

At steady state tests, ductility can be seen in Figure 4.12 and Figure 4.13 as sharpening edges at breaking point. At 20 and 400 degree the breaking point is rough and starts to smooth when temperature rises. At 700 degree which was the highest temperature at steady state tests the breaking point is almost as sharp as a needle.

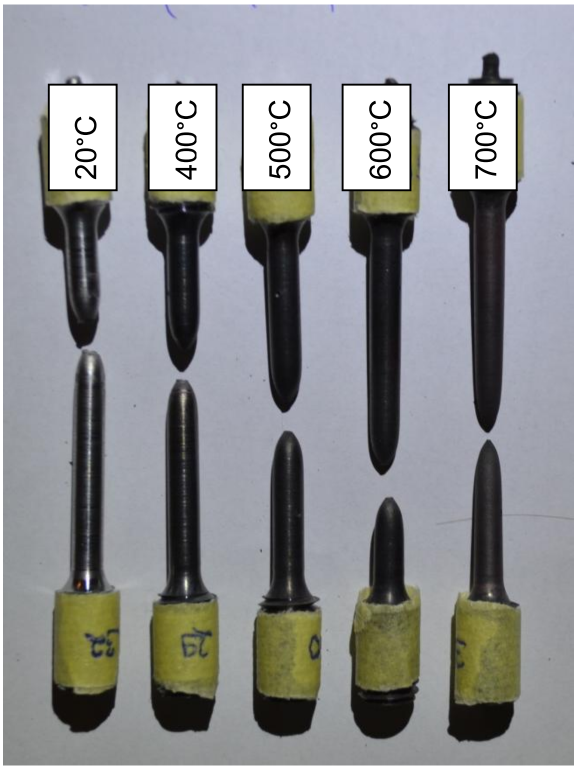


Figure 4.13 S700QL, steady state tests failure modes

4.4 Abandoned results

Some results have been abandoned from stress-strain figure and proportional limit calculations because of the principles of steel mechanics. Stress-strain figures were only used to determine reduction factor for modulus of elasticity. Reasons for abandoning:

- negative thermal elongation in the middle of the test
- manual calculations do not confirm results
- vacillation

Negative thermal elongation is assumed to be a measurement error. If negative thermal elongation existed it would be easy to verify by making tests in different laboratory. If manual calculation (Hook's law) difference to measured strain is greater than two percentage points the effect of differences on results has to be checked. Vacillations have been great in most of cases including negative thermal elongation so in most cases the results have been abandoned from the stress-strain calculation. All results have been used to determine reduction factors for effective yield strengths.

4.4.1 Yielding at unexpected locations

Unexpected yielding means that the test specimen has yielded outside of measurement point. Figure 4.14 shows sample of yielding or necking at unexpected point. Unexpected yielding has been taken care of by manually transferring yield strain to between the measurement points. This means that the strain from the necking is added to the strain measured from the measuring point. Time when the necking happens is easy to read from the data. It is the point where the density of the results recorded increases significantly. Outside the measurement points the yielding affects positively results because measured strain is smaller than actual strain. But these bad samples need to be taken into account somehow either taken whole sample off or done like mentioned above.

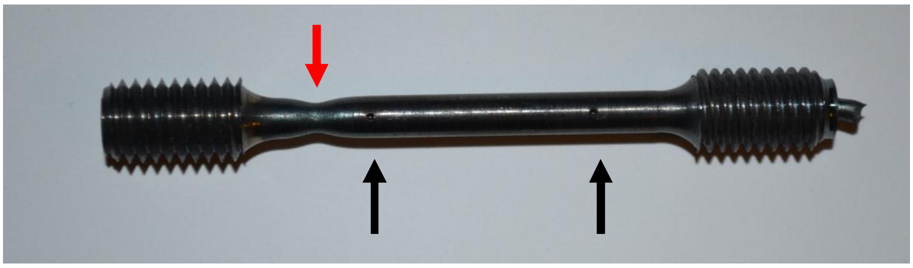


Figure 4.14 Unexpected yielding of sample

4.4.2 Unreasonable strain

Unreasonable strain might appear from multiple reasons (user error, testing software error, sensor/measurement device error etc). It is very easy to notice because usually the strain is 2-3 times bigger than expected or strain vacillates greatly and what manual calculations/measurements show. Sometimes strain is not growing when temperature rises. It is not possible that steels temperature elongation would be negative when temperature rises. It might also happen in the middle of test as shown in Appendix D-27. There is not much to do to change the results better. In almost every case the whole sample had to be rejected. Unreasonable strain almost always affects results negatively. Almost on every case the strain settles when yielding exceeds 2 %.

4.4.3 Lists of abandoned specimens

Some results need to be taken off from determination of proportional limit of steel grade S960QC. Abandoned results and the reasons for abandoning is shown in Table 4.2. All strains of the abandoned samples vary irregularly and in some cases the strain got smaller when the temperature rose.

Table 4.2 S960QC, Abandoned results

S960QC, Stress-Strain Figures		
Abandon result	Stress level	Reason for abandon
KVK-01	300MPa	Vacillate
KVK-05	100MPa	Unreasonable strain
KVK-08	700MPa	Vacillate
KVK-15	220MPa	Vacillate
KVK-16	220MPa	Vacillate
KVK-27	160MPa	Vacillate
KVK-21	80MPa	Vacillate
KVK-22	80MPa	Vacillate
KVK-24	60MPa	Vacillate

Like with S960QC also some of the results need to be taken off from determination of proportional limit of steel grade S700QL. Abandoned results and reasons for abandoning is shown in Table 4.3. In abandoned samples 17, 27 and 28 strain varies irregularly. In samples 03, 19 and 24 strains got smaller when temperature rose and the final strain was verified by manual measurement. In samples 09, 11, 14 and 15 occurred unreasonable strain which was not verified by manual measurement.

Table 4.3 S700QL, Abandoned results

S700QL, Stress-Strain Figures		
Abandon result	Stress level	Reason for abandon
KVK-03	630MPa	Vacillate
KVK-09	420MPa	Unreasonable strain
KVK-11	350MPa	Unreasonable strain
KVK-14	280MPa	Unreasonable strain
KVK-15	230MPa	Unreasonable strain
KVK-17	170MPa	Vacillate
KVK-19	120MPa	Vacillate
KVK-24	60MPa	Vacillate
KVK-27	30MPa	Vacillate
KVK-28	30MPa	Vacillate

5 COMPARISION STUDIES

5.1 Comparison of transient tests with steady tests

In Figure 5.1 the S960QC steady state test results are compared to transient state results. The steady state results are higher than transient state test results except in the case of the S400 with which it has happened some kind of slipping at start of the test. The last point of all transient curves is very difficult to determine because one transient curve is combined from separate tests.

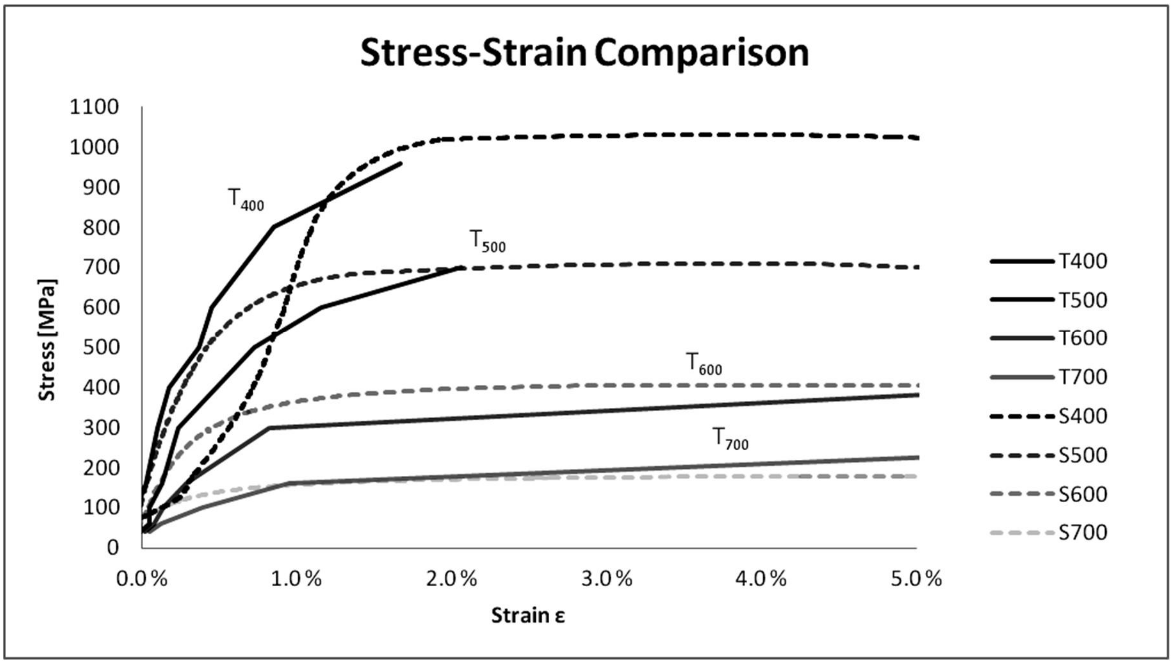


Figure 5.1 S960QC, comparison of transient and steady state tests Stress-Strain figures

In Figure 5.2 the S700QL steady state test results are compared to transient sate results. At S600 test the measurement device has been loosely connected to the test sample and some sliding has occurred. Steady state test results are higher than transient state test results. Same happened with the S960QC tests. This can be explained by faster loading and shorter loading time when compared to transient state tests.

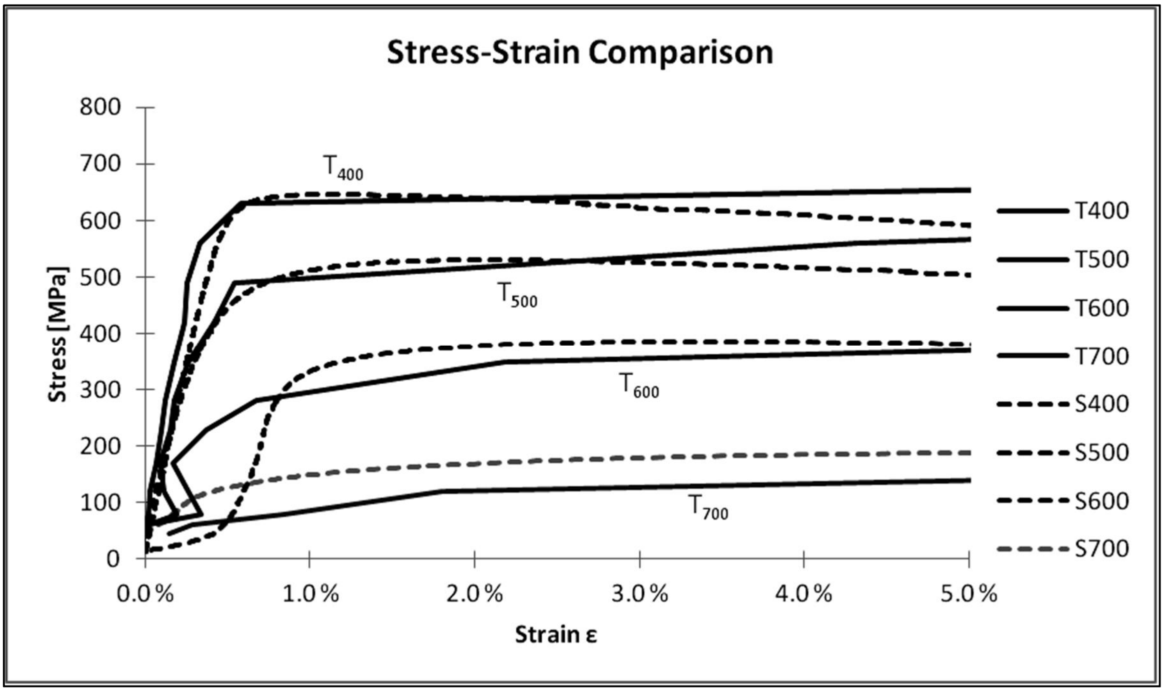


Figure 5.2 S700QL, comparison of transient and steady state tests Stress-Strain figures

5.2 Comparison of test results with EN 1993-1-2

In Figure 5.3 and Figure 5.4 the reduction factors of yield strength derived from transient test results of S960QC are compared with steady state test results and with the reduction curve given in EN1993-1-2. Nominal stress value (960 MPa) was used to get stress curve from the reduction curve. Steady state test results are higher than transient test results and so they verify the transient test results.

In Figure 5.3 the yield strength results are compared to EN 1993-1-2 effective yield strength values. Results are slightly below EN 1993-1-2 curve but overall the results are fine. The origin of these figures is explained in Chapter 2.2.

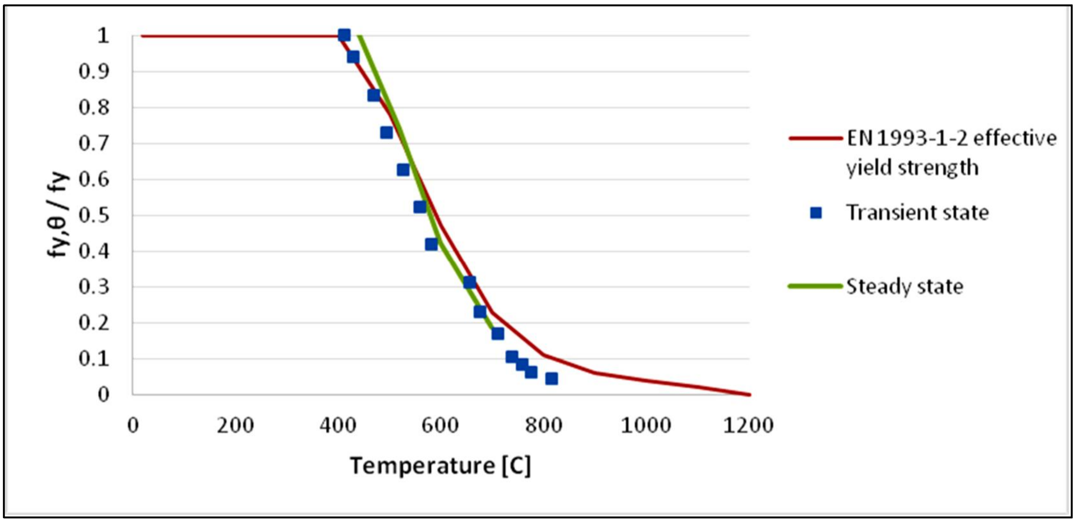


Figure 5.3 S960QC, Comparisons of effective yield strength derived from both transient and steady state tests with EN1993-1-2 effective yield strength

Figure 5.4 shows comparison of effective proportional limits results to EN 1993-1-2. The transient state results are good below 450 °C but after 500 °C they are not on conservative side when compared to EN 1993-1-2. Steady state results are conservative even at elevated temperatures.

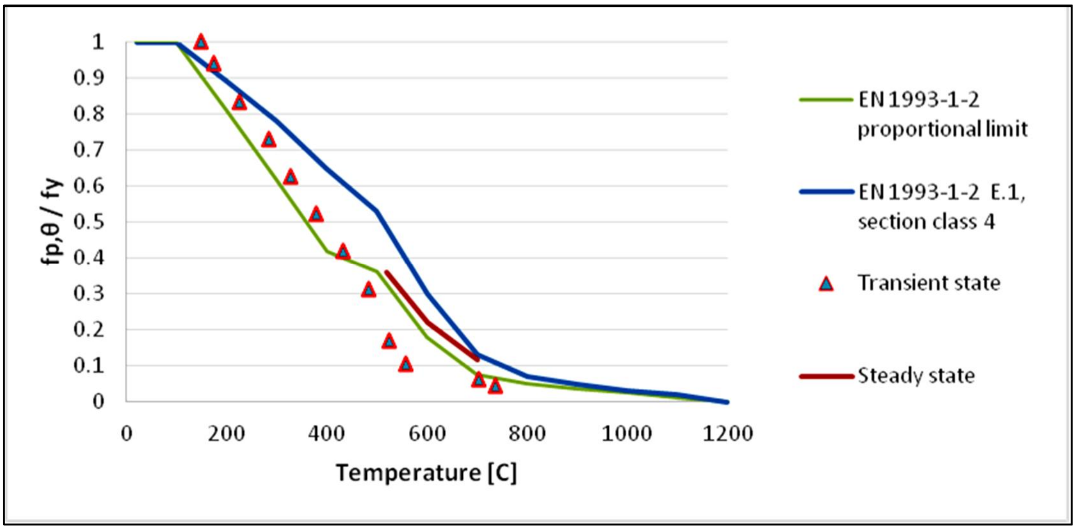


Figure 5.4 S960QC, Comparisons of effective proportional limits derived from both transient and steady state tests with EN1993-1-2 effective proportional limit

Reduction factor of steel grade S960QC for modulus of elasticity is shown in Figure 5.5. Overall results are fine when compared to EN 1993-1-2 values.

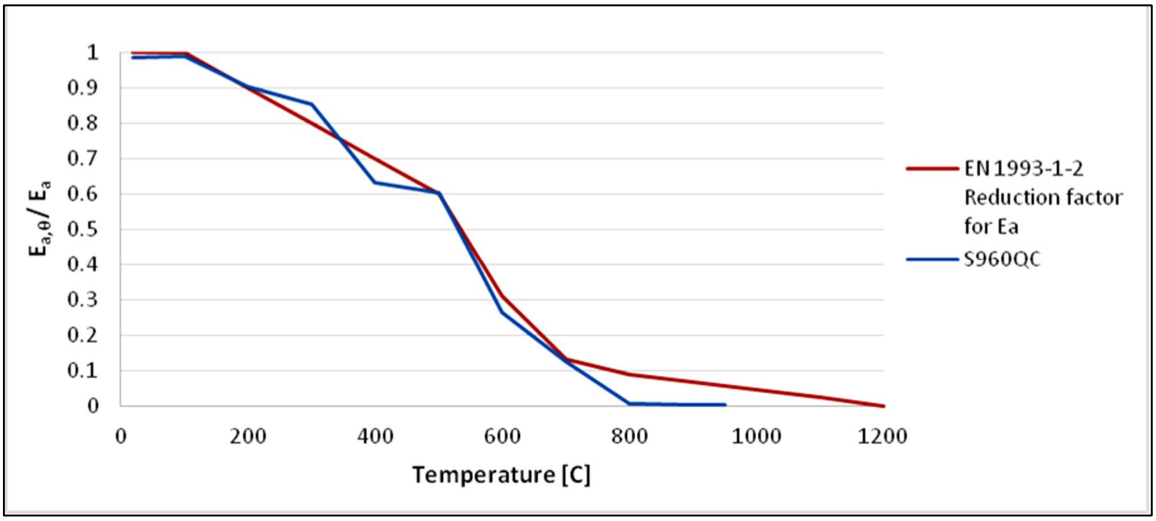


Figure 5.5 S960QC, Reduction factor of modulus of elasticity

In Figure 5.6 and Figure 5.7 transient test results of S700QL are compared with the steady state test results and with the reduction curve from EN1993-1-2. Nominal stress value (700 MPa) was used to get stress curve from the reduction curve. The steady state test results are higher than the transient test results and so they also verify the transient test results.

In Figure 5.6 the yield strength results are compared to EN 1993-1-2 effective yield strength values. Points fit fine to the EN 1993-1-2 effective yield strength curve. How these figures have been composed is explained in Chapter 2.2.

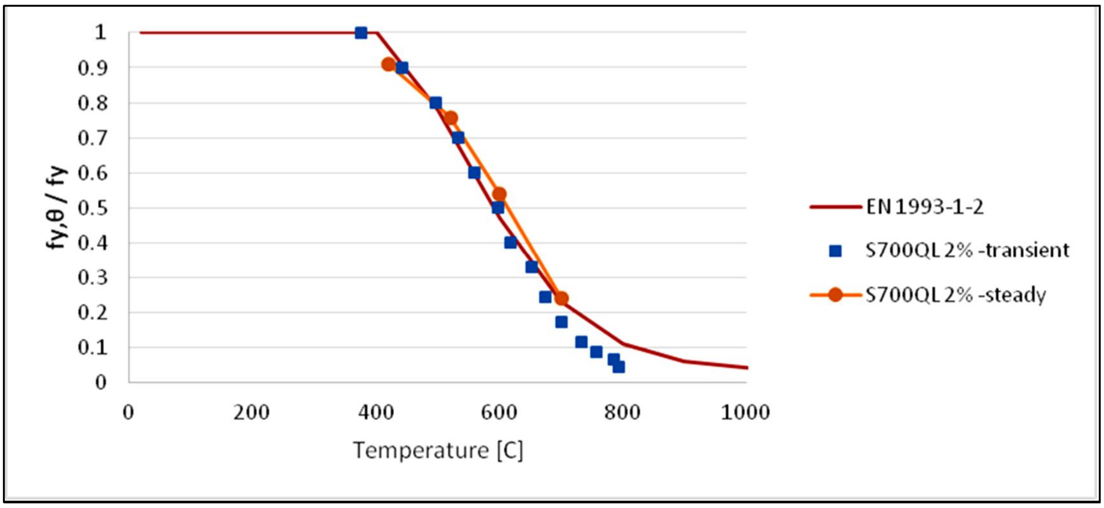


Figure 5.6 S700QL, Comparisons of effective yield strength from both transient and steady state tests with EN1993-1-2 effective yield strength

Figure 5.7 shows comparison of proportional limit results to EN 1993-1-2. Few points (0.7-0.9) are slightly too positive results. Actually there is a measurement mistake. When looking at Appendix D there is a negative strain which distorts the results. Same kind of negative impact is in few points at higher temperature results (0.1-0.2). Overall the results are fine. Steady state results are conservative at elevated temperatures when comparing to EN 1993-1-2.

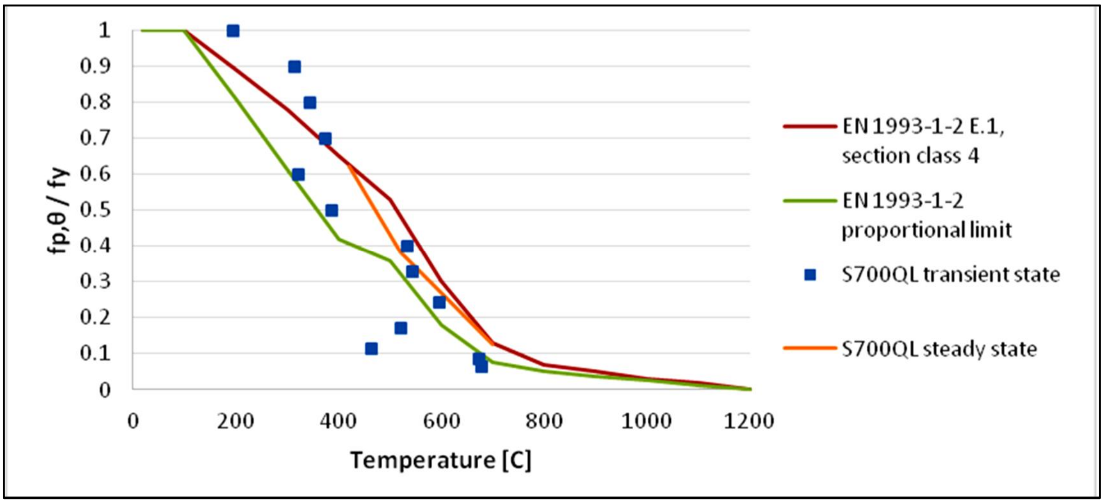


Figure 5.7 S700QL, Comparisons of effective proportional limit derived from both transient and steady state tests with EN1993-1-2 effective proportional limit

Figure 5.8 shows comparison of the reduction factor of modulus of elasticity and EN 1993-1-2. Reduction curve is little too positive between 0.7-0.9 as explained earlier.

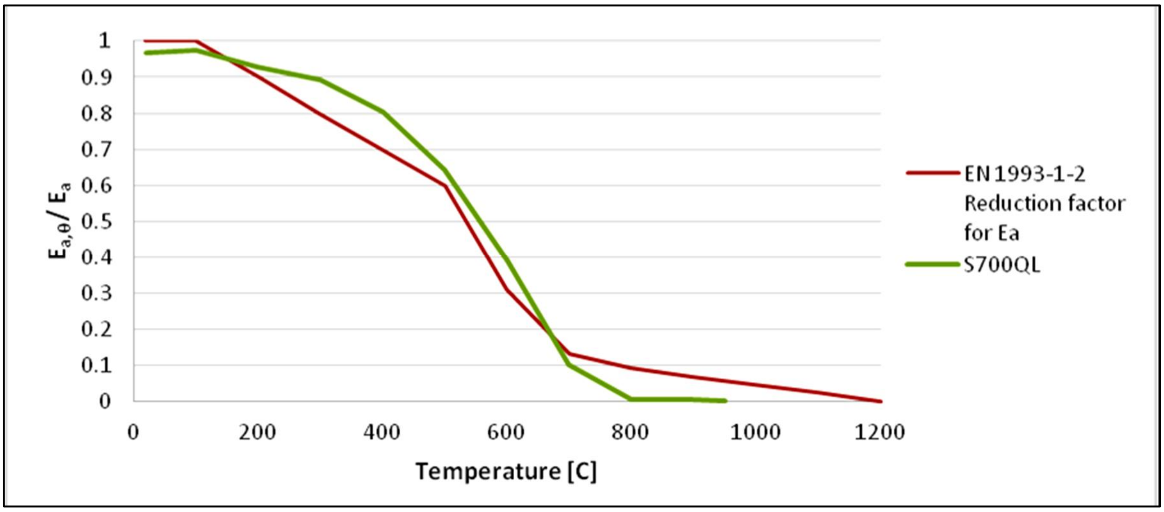


Figure 5.8 S700QL, Comparisons of reduction factor of modulus of elasticity from transient tests with EN 1993-1-2 modulus of elasticity

5.3 Comparison of test results with other researches

In Figure 5.9 is shown comparison of yield strength reduction factors from literature. In these tests actual yield stress was used to get reduction factor instead of nominal yield strength as in this research earlier. So test results of this research were changed to same way to make comparison. For tested steel grades S960QC and S700QL yield strengths were 1060 MPa and 820 MPa respectively. High strength steel results are slightly lower than on milder steels.

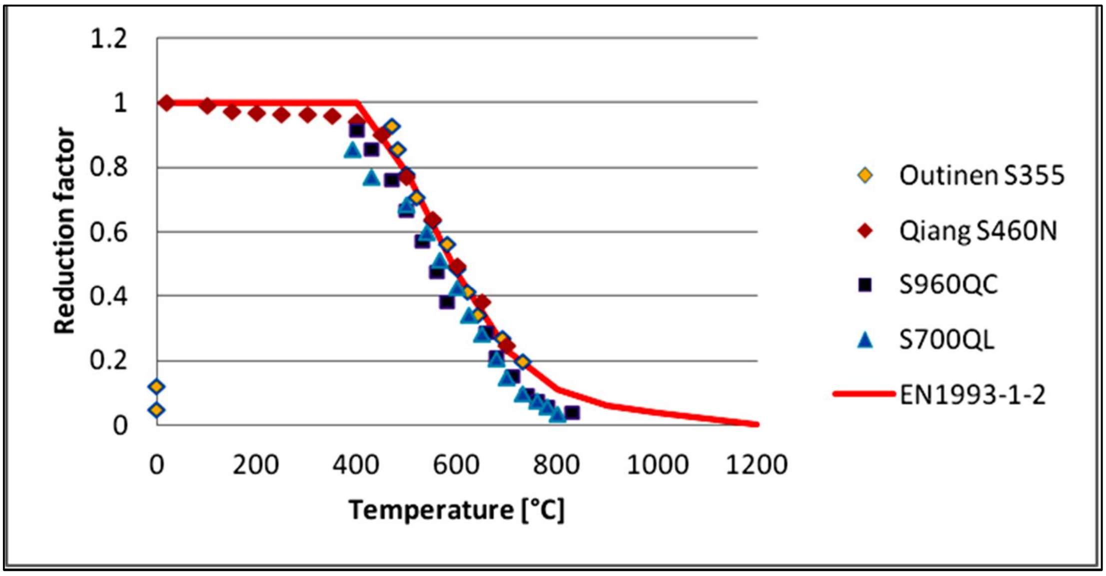


Figure 5.9 Comparison of yield strength reduction factors with literature (Outinen, Jyri; Mäkeläinen, Pentti, 1994), (Qiang, Bijlaard, & Kolstein, 2012)

5.4 Discussions

The test results seemed to be settling according to EN 1993-1-2 reduction curves. Due to a large amount of abandoned test pieces from the results there is a slight possibility that the results are not at the conservative side when compared to EN 1993-1-2 reduction curves. Many factors affect measurement uncertainty as can be seen from Table 5.1. All relevant contributors (parameters) are marked with X if it affects the test result.

Table 5.1 Uncertainty contributors of the test results (SFS-EN 6892-2, 2011)

Parameter	Test results					
	R_{eH}	R_{eL}	R_m	R_p	A	Z
Force	X	X	X	X	—	—
Extension	—	—	—	X	X	—
Gauge length	—	—	—	X	X	—
S_o	X	X	X	X	—	X
S_u	—	—	—	—	—	X
Temperature	X	X	X	X	X	X
Strain rate	X	X	X	X	X	X
NOTE X relevant — not relevant						

Most significant contributors are temperature and strain rate and their different variations. These contributors are material dependant and therefore should be determined experimentally. Test equipment affects uncertainty could be calculated from the calibration certificates of the devices used for measurement. (SFS-EN 6892-2, 2011)

Due to the small amount of the test specimens these uncertainty parameters could not been determined enough reliably enough. Uncertainty of testing can be reduced by making tests by different methods for example transient state and steady state tests.

6 CONCLUSIONS AND FUTURE WORK

There were 35 test pieces of both steel grades. Steady state tests verified transient test results. The steady state tests results were slightly higher than the transient tests. The results in this research verify that the results of both materials are settling to EN 1993-1-2 reduction curves when temperature is lower than 700°C. After 700°C the EN 1993-1-2 reduction factors overestimates the yield strength. In Table 6.1 are shown the reduction factors of the yield strength proposed for both steel grades S960QC and S700QL.

Table 6.1 Effective yield strength reduction factors for tested steel grades

Temperature	S960QC	S700QL	Eurocode 3
20	1	1	1
100	1	1	1
200	1	1	1
300	1	1	1
400	1	1	1
500	0.70	0.78	0.78
600	0.41	0.47	0.47
700	0.20	0.16	0.23
800	0.05	0.04	0.11
900	0	0	0.06
1000	0	0	0.04
1100	0	0	0.02
1200	0	0	0

At Figure 6.1 and Figure 6.2 is shown comparison of reduction curves. The results are not on the conservative side when temperature rises over 700°C when comparing to EN 1993-1-2 reduction curves. New factors drop the yield strength to 0 when temperature is 900 °C. Actually there is still some strength left but modulus of elasticity has dropped to such a low level at these temperatures that significant deformations happens to structural steel.

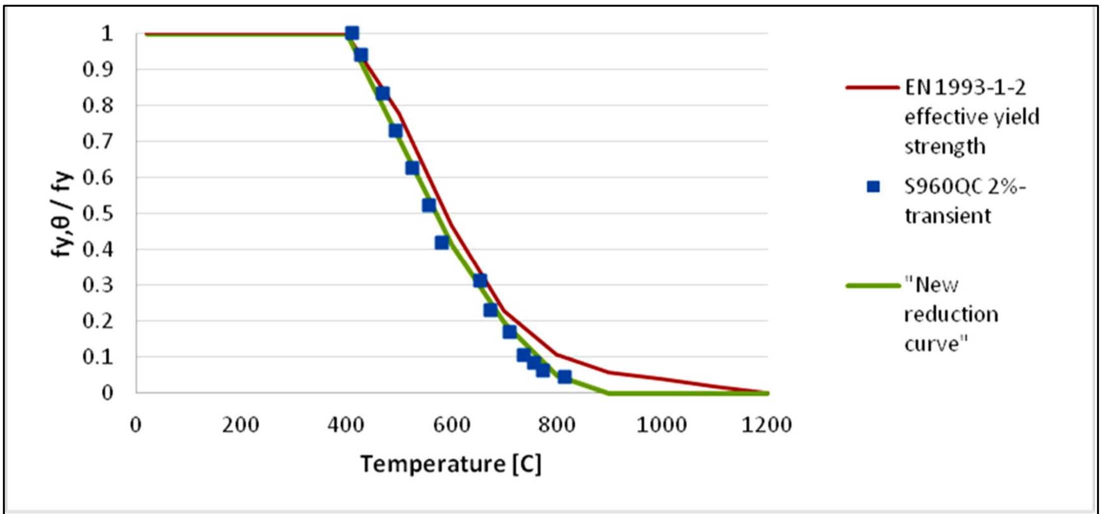


Figure 6.1 S960QC, Comparison of reduction factors for effective yield strength

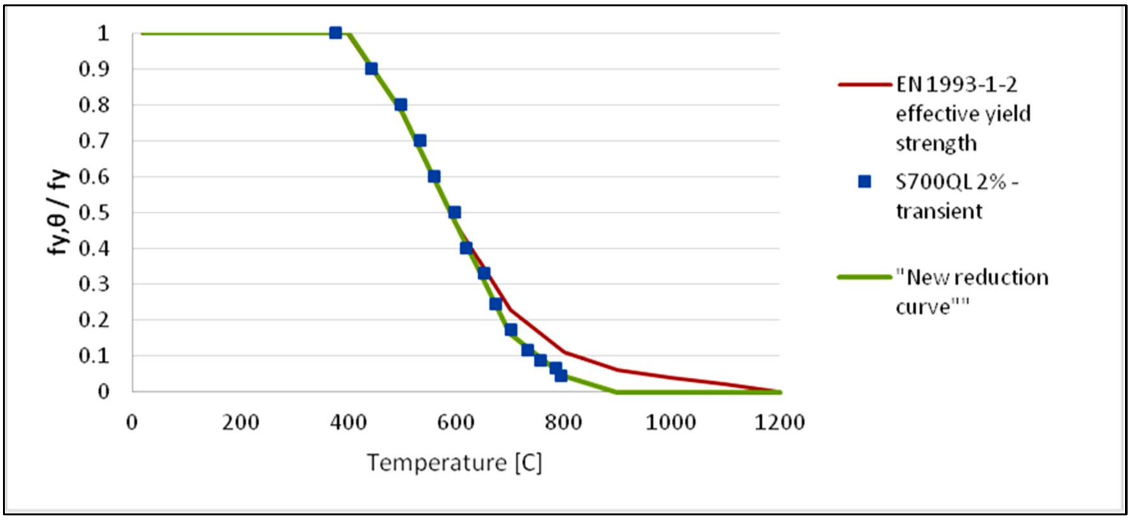


Figure 6.2 S700QL, Comparison of reduction factors for effective yield strength

This research verify the use of reduction factors given in Table 6.1 for S960QC and S700QL structural steels manufactured by Rautaruukki. This research does not verify that factors given in this research are usable to all steel grades which nominal yield strength is 960 or 700 MPa. This research also verifies that reduction factors of EN 1993-1-2 for modulus of elasticity and proportional limit are usable (Figure 5.4, Figure 5.5, Figure 5.7 and Figure 5.8).

Uncertainty parameters for these materials need further studies. Also these materials should be tested more to make sure that reason for abandoning results (abandon from proportional limit and modulus of elasticity factor determination) were a foul based on procedure or device. More testing is required to make general reduction factors to yield strengths 960 or 700 MPa. These factors should include all different kind of steel grades with specified nominal yield strengths.

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APPENDIX A: Geometric measurements

Table A.1 S960QC measurements

Specimen	width 1	width 2	width 3	thickness 1	thickness 2	thickness 3
1	5.054	5.048	5.040	4.006	3.996	4.013
2	5.079	5.060	5.061	3.991	3.970	3.976
3	5.086	5.052	5.060	4.009	3.989	3.998
4	5.086	5.080	5.081	4.017	4.006	3.998
5	5.068	5.060	5.054	3.999	3.999	4.006
6	5.043	5.045	5.040	3.986	4.004	4.013
7	5.027	5.033	5.027	4.001	3.970	3.976
8	5.050	5.046	5.050	4.003	4.000	4.004
9	4.973	4.980	4.970	4.000	3.980	3.983
10	4.988	5.004	5.004	4.024	4.013	4.005
11	4.989	4.994	4.978	3.990	3.977	4.003
12	5.044	5.020	5.006	3.997	3.999	4.016
13	5.038	5.025	5.018	4.015	4.016	4.032
14	5.039	5.010	4.988	4.022	4.003	4.009
15	5.022	5.014	5.001	3.998	3.988	4.017
16	5.015	5.026	5.020	4.010	4.017	4.025
17	5.037	5.005	4.998	4.029	4.020	4.020
18	5.074	5.059	5.079	4.030	4.041	4.039
19	5.042	5.042	5.047	3.989	3.986	4.004
20	5.071	5.037	4.997	4.013	3.979	4.021
21	5.045	4.985	4.997	4.014	4.011	4.007
22	5.026	5.009	5.005	4.008	3.984	3.995
23	5.031	5.007	5.014	4.019	3.998	4.006
24	4.991	4.978	4.971	4.014	4.027	4.024
25	5.002	5.018	5.034	4.016	4.027	4.025
26	4.960	4.954	4.955	4.023	4.005	4.014
27	5.049	5.040	5.045	3.998	3.988	4.016
28	5.007	5.019	5.012	4.014	4.015	4.021
29	4.980	4.995	5.006	4.010	3.990	3.998
30	4.989	4.993	4.973	3.983	3.980	4.003
31	5.058	5.074	5.112	3.994	3.988	3.988
32	5.175	5.151	5.148	3.994	3.990	3.995
33	5.051	5.059	5.061	3.997	3.994	3.997
34	5.122	5.168	5.069	4.019	4.011	4.011
35	4.866	4.972	4.851	4.007	4.006	4.001

Table A.2 S700QL measurements

Specimen	d1	d2	d3
1	5.004	4.997	4.986
2	5.010	5.027	5.030
3	5.031	5.025	5.014
4	5.037	5.023	5.010
5	5.040	5.021	5.010
6	5.029	5.019	5.005
7	5.029	5.017	5.005
8	5.073	5.058	5.047
9	5.061	5.048	5.036
10	5.065	5.054	5.049
11	5.060	5.040	5.033
12	5.049	5.040	5.030
13	5.041	5.033	5.023
14	5.047	5.038	5.020
15	5.058	5.042	5.027
16	5.025	5.033	5.040
17	5.022	5.036	5.040
18	5.052	5.038	5.025
19	5.062	5.047	5.038
20	5.080	5.070	5.053
21	5.019	5.007	4.995
22	5.064	5.049	5.034
23	5.064	5.050	5.031
24	5.053	5.047	5.033
25	5.051	5.035	5.025
26	5.046	5.041	5.025
27	5.057	5.057	5.027
28	5.049	5.046	5.031
29	5.077	5.061	5.058
30	5.067	5.054	5.044
31	5.032	5.018	5.010
32	5.021	5.032	5.035
33	5.044	5.032	5.027
34	5.024	5.038	5.042
35	5.022	5.033	5.041

APPENDIX B: Test program

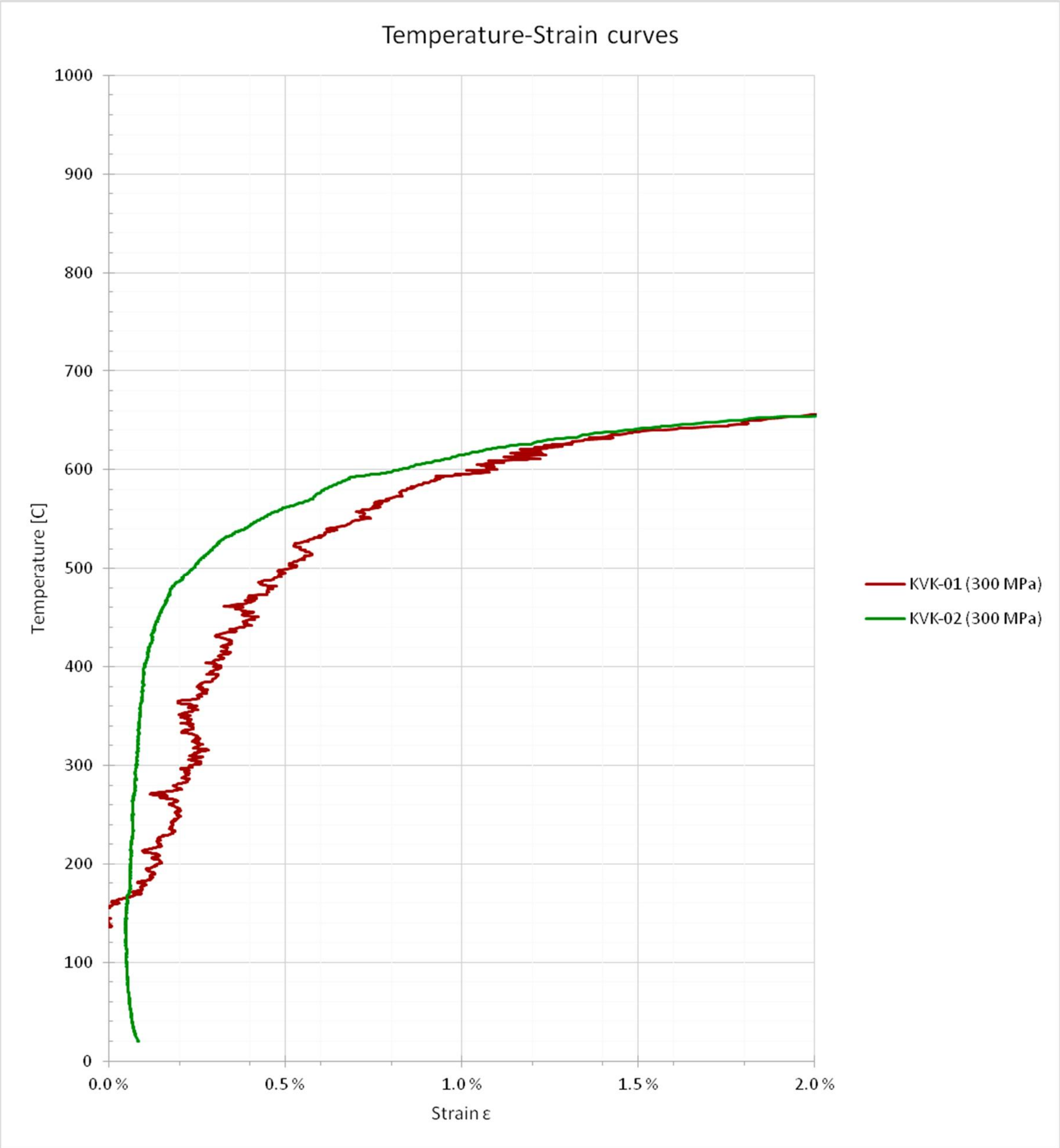
Specimen id	Specimen	width (mm)	thickness (mm)	Force (kN)	Stress (Mpa)	Strain Calculated	/ Measured	time s (heating ON)
KVK-01_130301	1	5.047	4.005	6.06	300	0.036	-	529
KVK-02_130304	2	5.067	3.979	6.05	300	0.036	0.021	127
KVK-03_130307	3	5.066	3.999	18.23	900	0.107	0.099	240
KVK-04_130307	4	5.082	4.007	18.33	900	0.107	0.108	496
KVK-05_130322	5	5.061	4.001	2.02	100	0.012	0.004	270
KVK-06_130325	6	5.043	4.001	2.02	100	0.012	0.004	175
KVK-07-130308	7	5.029	3.982	14.02	700	0.083	0.1	315
KVK-08-130308	8	5.049	4.002	14.14	700	0.083	0.103	535
KVK-09_130322	9	4.974	3.988	11.90	600	0.071	0.06	230
KVK-10_130325	10	4.999	4.014	12.04	600	0.071	0.07	225
KVK-11-130315	11	4.987	3.990	9.95	500	0.060	0.071	325
KVK-12_130325	12	5.023	4.004	10.06	500	0.060	0.055	380
KVK-13_130304	13	5.027	4.021	8.09	400	0.048	0.044	234
KVK-14_130306	14	5.012	4.011	8.04	400	0.048	0.018	680
KVK-15-130313	15	5.012	4.001	4.41	220	0.026	0.018	260
KVK-16-130313	16	5.020	4.017	4.44	220	0.026	0.022	320
KVK-17-130311	17	5.013	4.023	3.23	160	0.019	0.015	245
~~KVK-18~~	~~18~~	~~5.071~~	~~4.037~~	Normal tensile test				
KVK-19-130314	19	5.044	3.993	16.11	800	0.095	0.108	365
KVK-20-130314	20	5.035	4.004	16.13	800	0.095	0.096	560
KVK-21-130311	21	5.009	4.011	1.61	80	0.010	0.009	190
KVK-22-130312	22	5.013	3.996	1.60	80	0.010	0.007	195
KVK-23-130314	23	5.017	4.008	1.21	60	0.007	0.007	405
KVK-24-130318	24	4.980	4.022	1.20	60	0.007	0.009	170
KVK-25-130308	25	5.018	4.023	0.81	40	0.005	0.003	175
KVK-26-130307	26	4.956	4.014	0.80	40	0.005	0.001	215
KVK-27-130311	27	5.045	4.001	3.23	160	0.019	0.018	180
KVK-28-130315	28	5.013	4.017	19.33	960	0.114	0.12	280
KVK-29-130320	29	4.994	3.999	19.17	960	0.114	0.097	270
KVK-30-130424	30	4.985	3.989	Steady state test			600	600
KVK-31-130425	31	5.081	3.990	Steady state test			440	
KVK-32-130425	32	5.158	3.993	Steady state test			530	
KVK-33-130424	33	5.057	3.996	Steady state test			700	700
~~KVK-34~~	~~34~~	~~5.120~~	~~4.014~~	Normal tensile test				
KVK-35_130306_lämpö	35	4.896	4.005	Temperature test				

B.1 S960QC test program

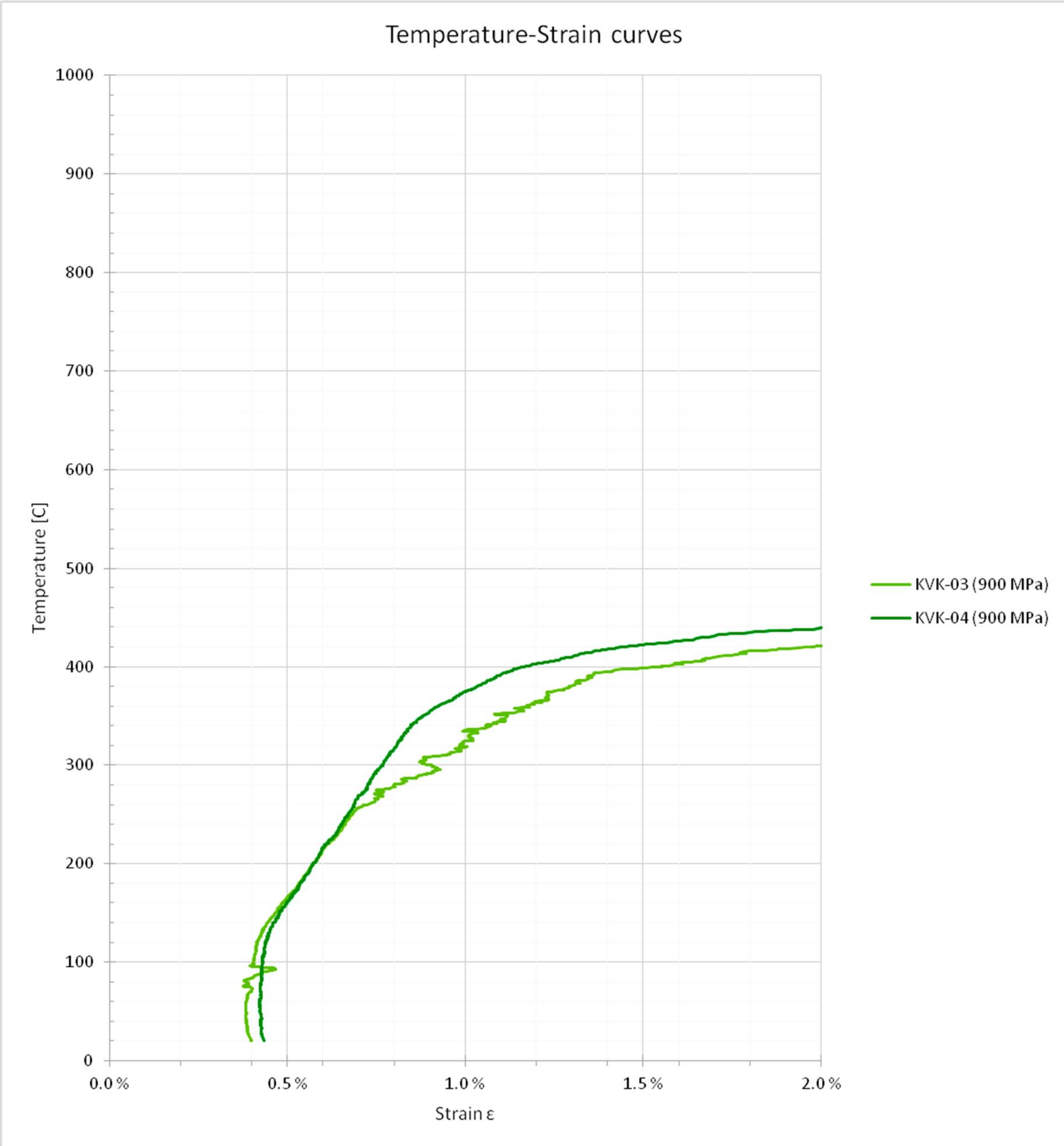
Specimen id	Specimen	d (mm)	Force (kN)	Stress (Mpa)	Strain Calculated / Measured		time s (heating ON)
KVK-S700-01_130328	1	4.996	13.72	700	0.083	0.087	240
KVK-S700-02_130328	2	5.022	13.87	700	0.083	0.082	230
KVK-S700-03_130403	3	5.023	12.49	630	0.075	0.066	230
KVK-S700-04_130408	4	5.023	12.49	630	0.075	0.069	250
KVK-S700-05_130412	5	5.024	11.10	560	0.067	0.07	240
KVK-S700-06_130416	6	5.018	11.07	560	0.067	0.059	350
KVK-S700-07_130417	7	5.017	9.69	490	0.058	0.052	250
KVK-S700-08_130423	8	5.059	9.85	490	0.058	0.06	185
KVK-S700-09_130326	9	5.048	8.41	420	0.050	0.056	180
KVK-S700-10_130326	10	5.056	8.43	420	0.050	0.05	255
KVK-S700-11_130409	11	5.044	6.99	350	0.042	0.039	255
KVK-S700-12_130411	12	5.040	6.98	350	0.042	0.04	255
KVK-S700-13_130408	13	5.032	5.57	280	0.033	0.029	410
KVK-S700-14_130419	14	5.035	5.58	280	0.033	0.03	310
KVK-S700-15_130402	15	5.042	4.59	230	0.027	0.023	215
KVK-S700-16_130405	16	5.033	4.58	230	0.027	0.025	230
KVK-S700-17_130327	17	5.033	3.38	170	0.020	0.017	240
KVK-S700-18_130327	18	5.038	3.39	170	0.020	0.017	160
KVK-S700-19_130408	19	5.049	2.40	120	0.014	0.02	245
KVK-S700-20_130411	20	5.068	2.42	120	0.014	0.012	140
KVK-S700-21_130409	21	5.007	1.58	80	0.010	0.009	145
KVK-S700-22_130419	22	5.049	1.60	80	0.010	0.007	215
KVK-S700-23_130411	23	5.048	1.20	60	0.007	0.005	125
KVK-S700-24_130417	24	5.044	1.20	60	0.007	0.005	200
KVK-S700-25_130412	25	5.037	0.90	45	0.005	0.002	175
KVK-S700-26_130415	26	5.037	0.90	45	0.005	0.003	125
KVK-S700-27_130327	27	5.047	0.60	30	0.004	0.001	180
KVK-S700-28_130402	28	5.042	0.60	30	0.004	0.001	230
KVK-S700-29_130424	29	5.065	Steady state test			400 C	170
KVK-S700-30_130423	30	5.055	Steady state test			500 C	210
KVK-S700-31_130410	31	5.020	Steady state test			700 C	180
VK-SFS-EN-32_130404	32	5.029	Tensile test				
VK-SFS-EN-33_130404	33	5.034	Tensile test				
KVK-S700-34_130410	34	5.035	Steady state test			600 C	375
KVK-S700-35_130410	35	5.032	Steady state test			600 C	75

B.2 S700QL test program

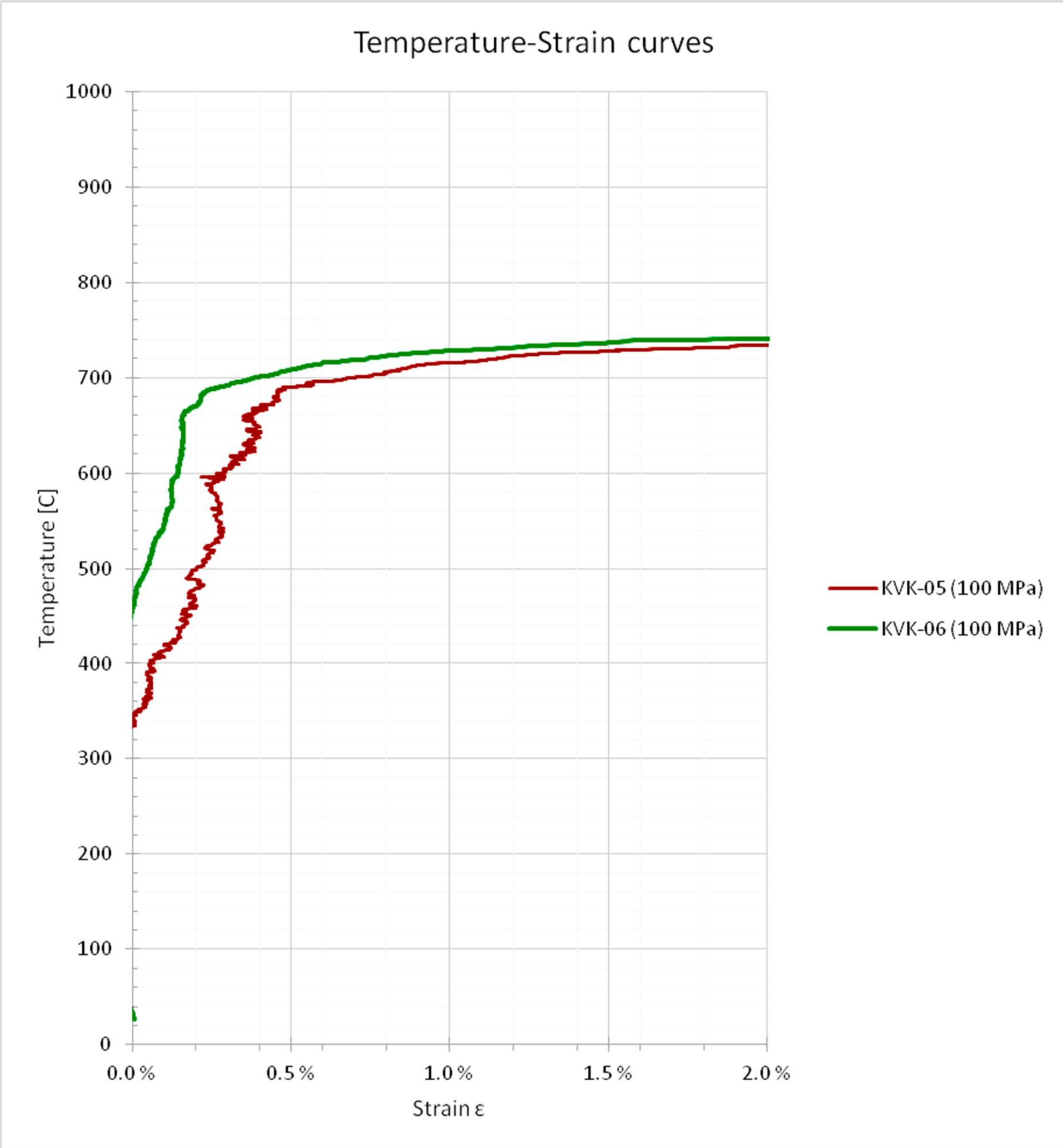
APPENDIX C: S960QC Transient state tests



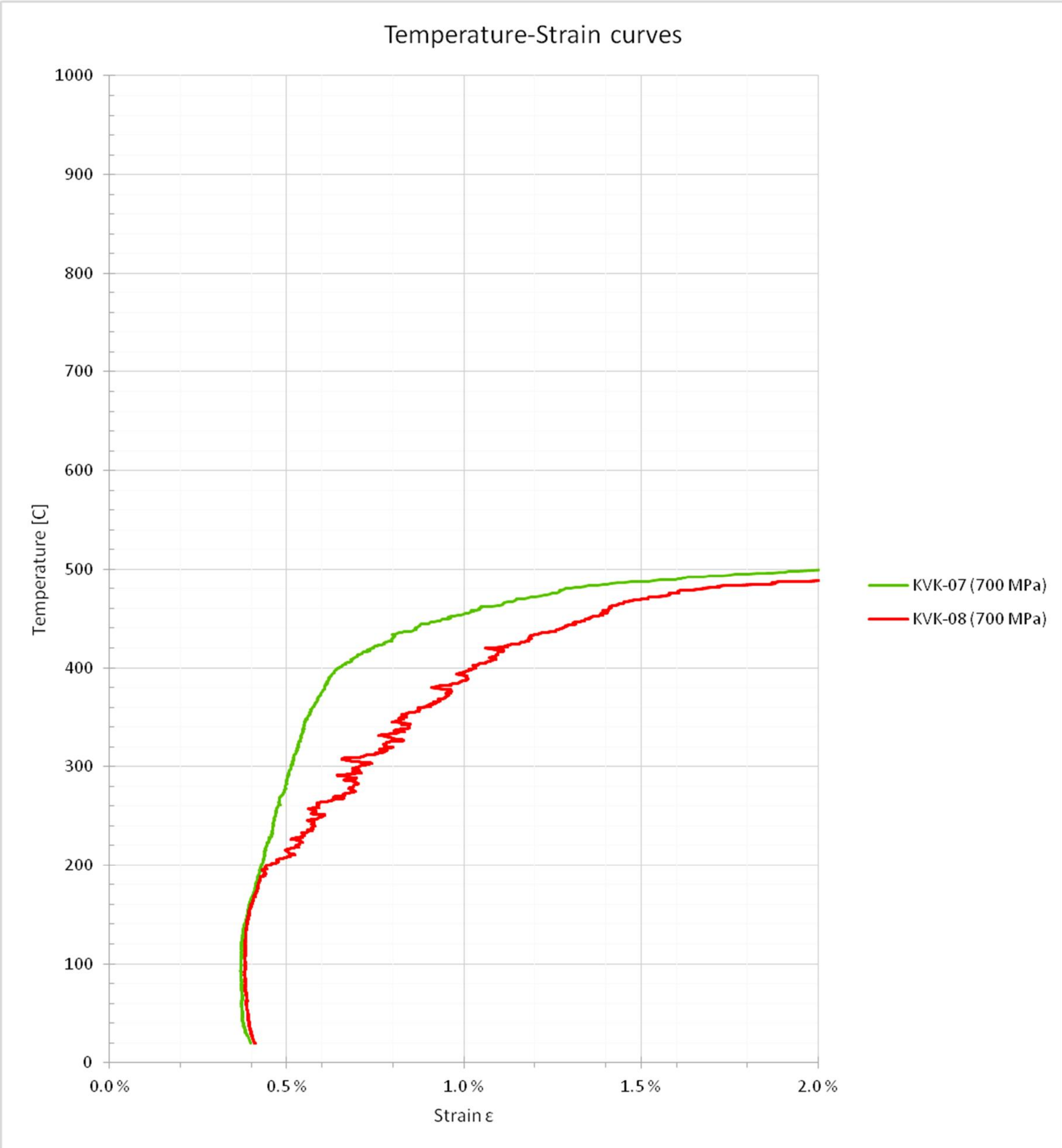
C.1 S960QC, 300MPa



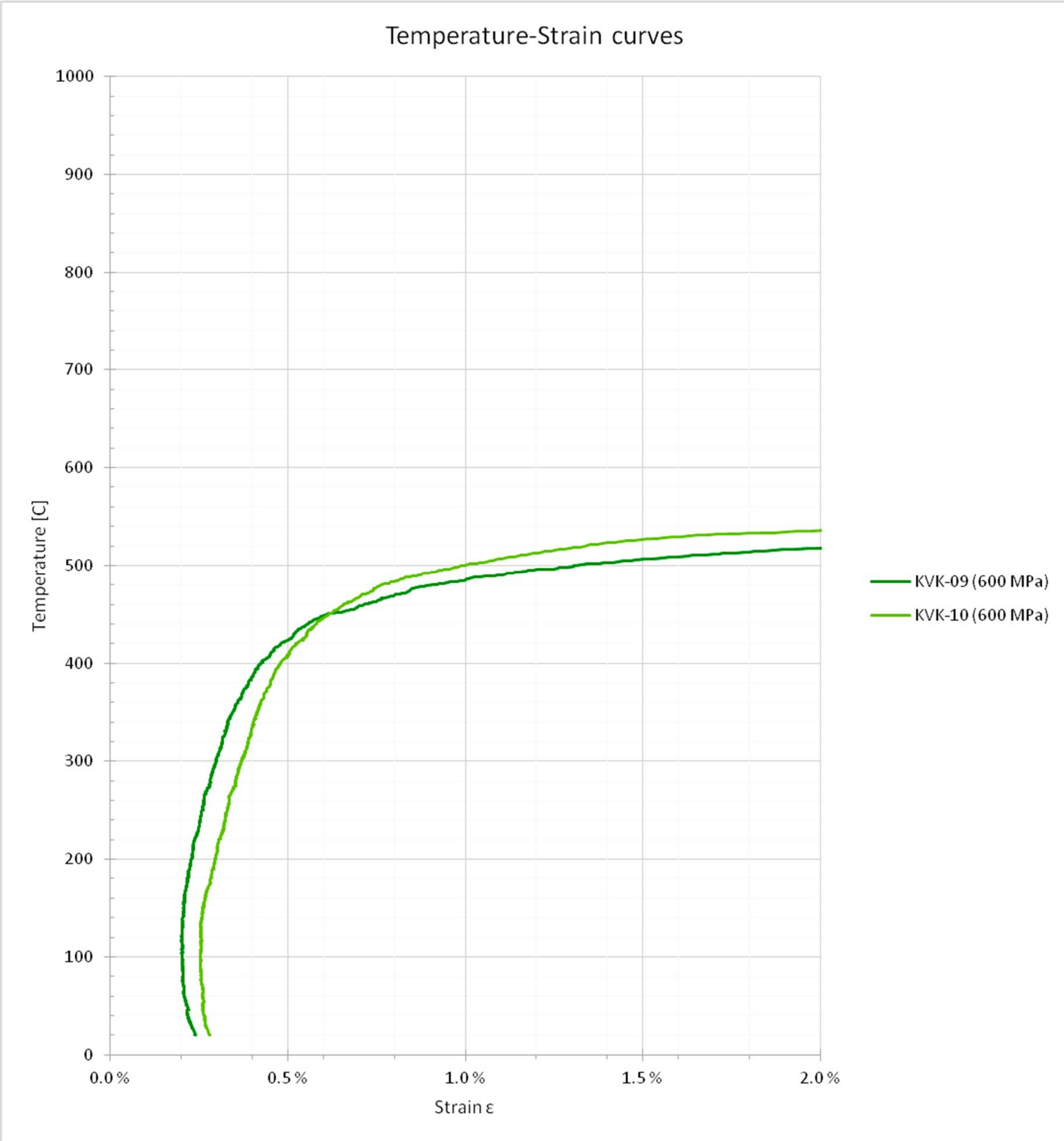
C.2 S960QC, 900 MPa



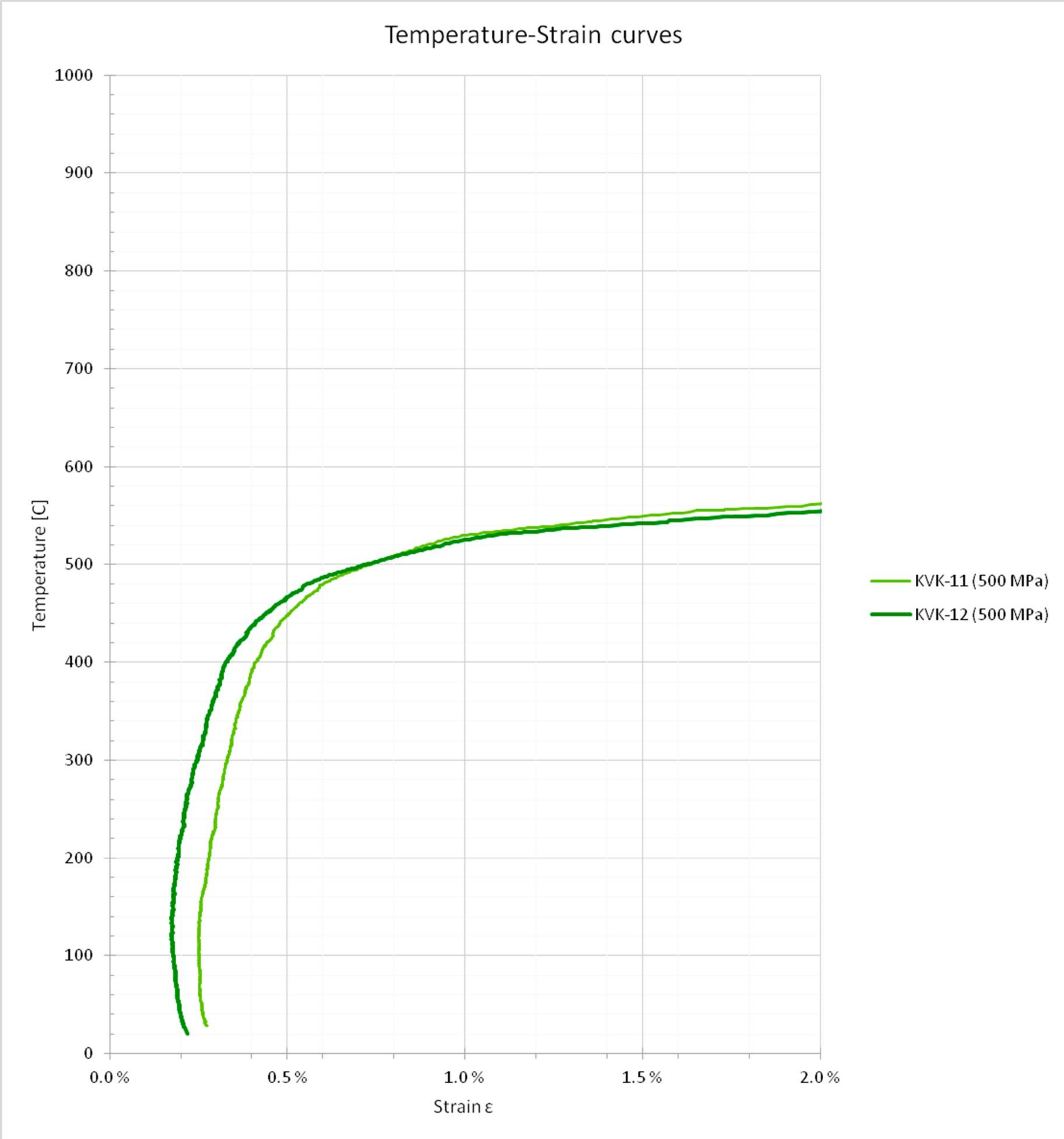
C.3 S960QC, 100MPa



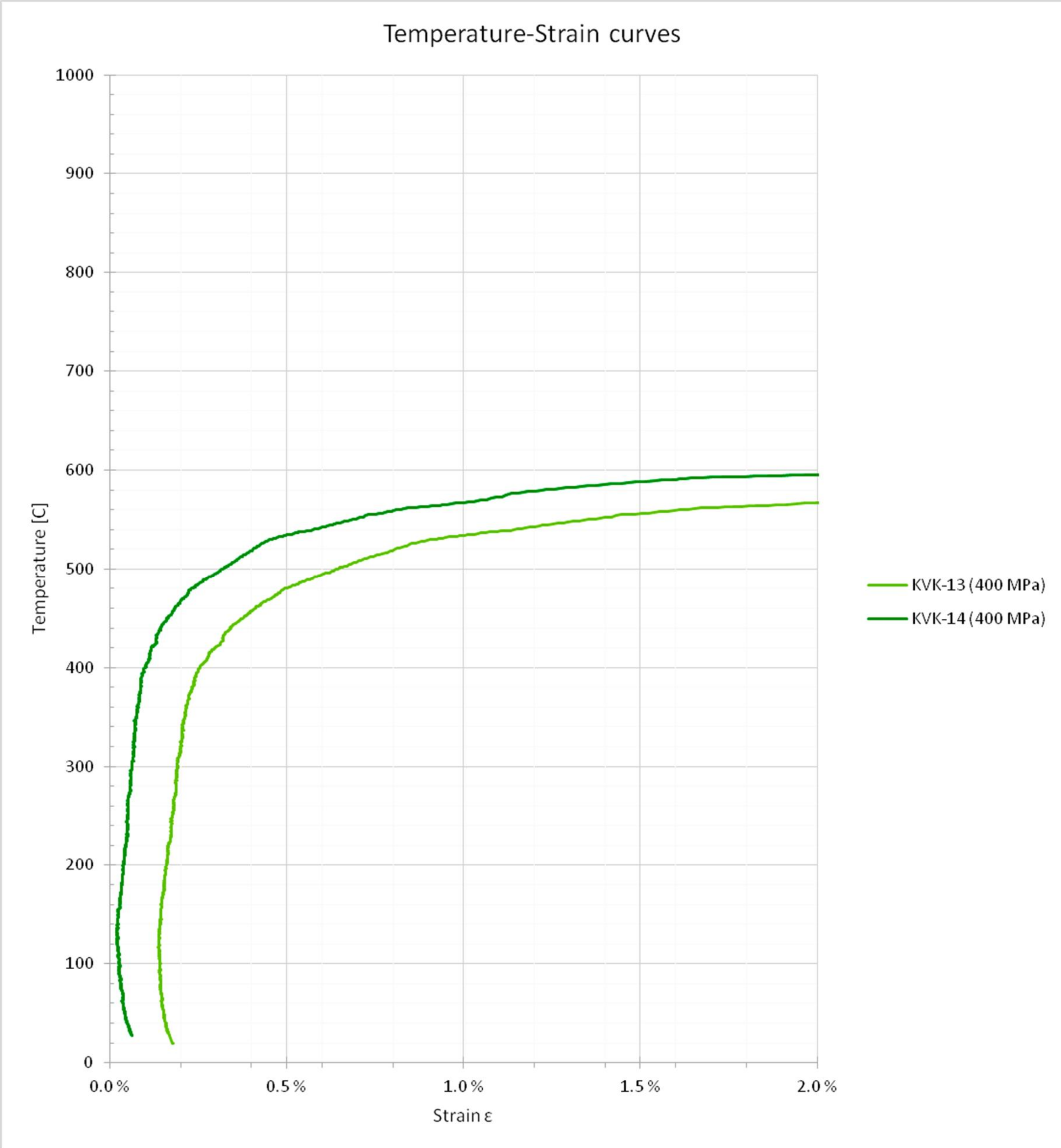
C.4 S960QC, 700MPa



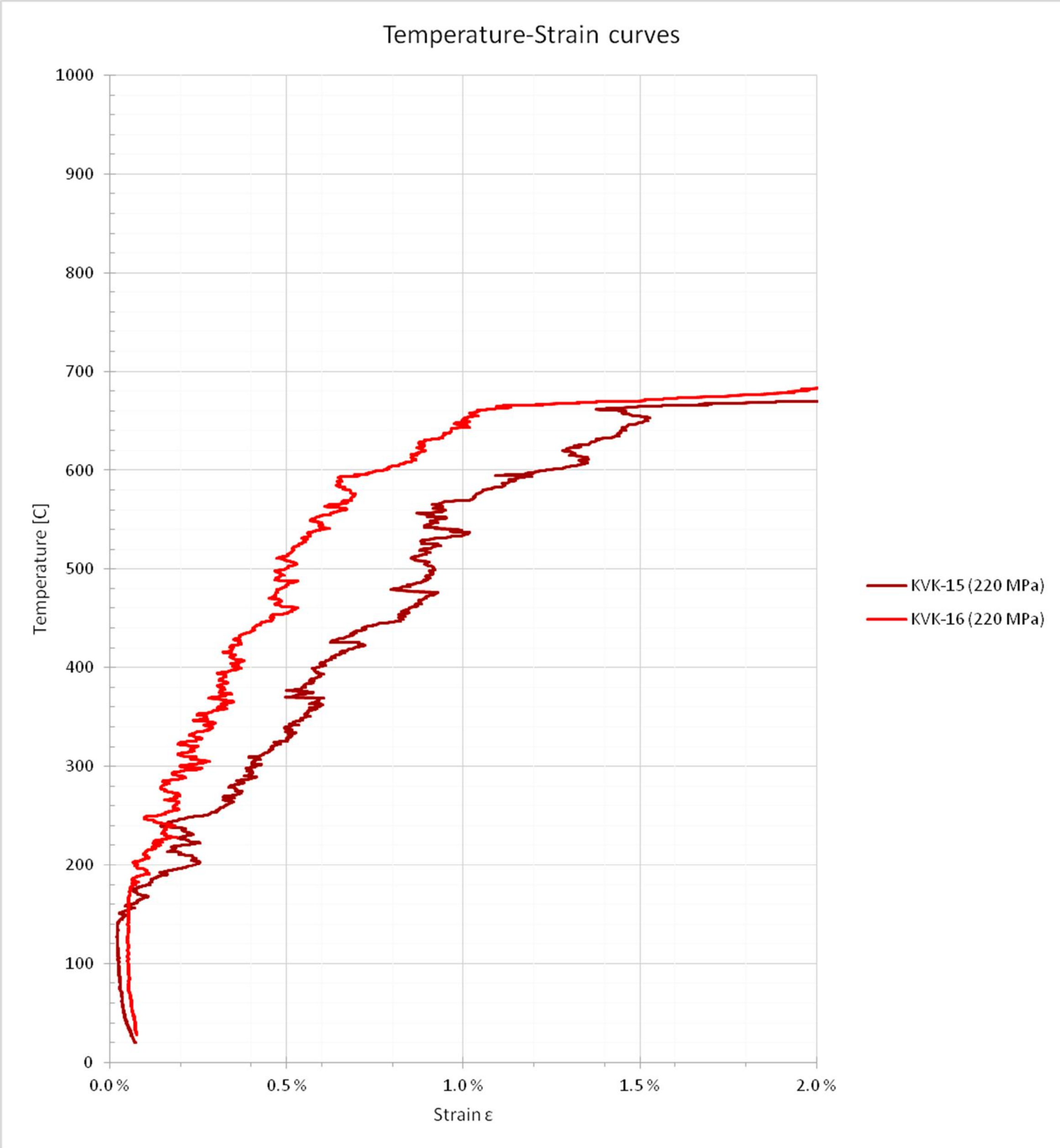
C.5 S960QC, 600MPa



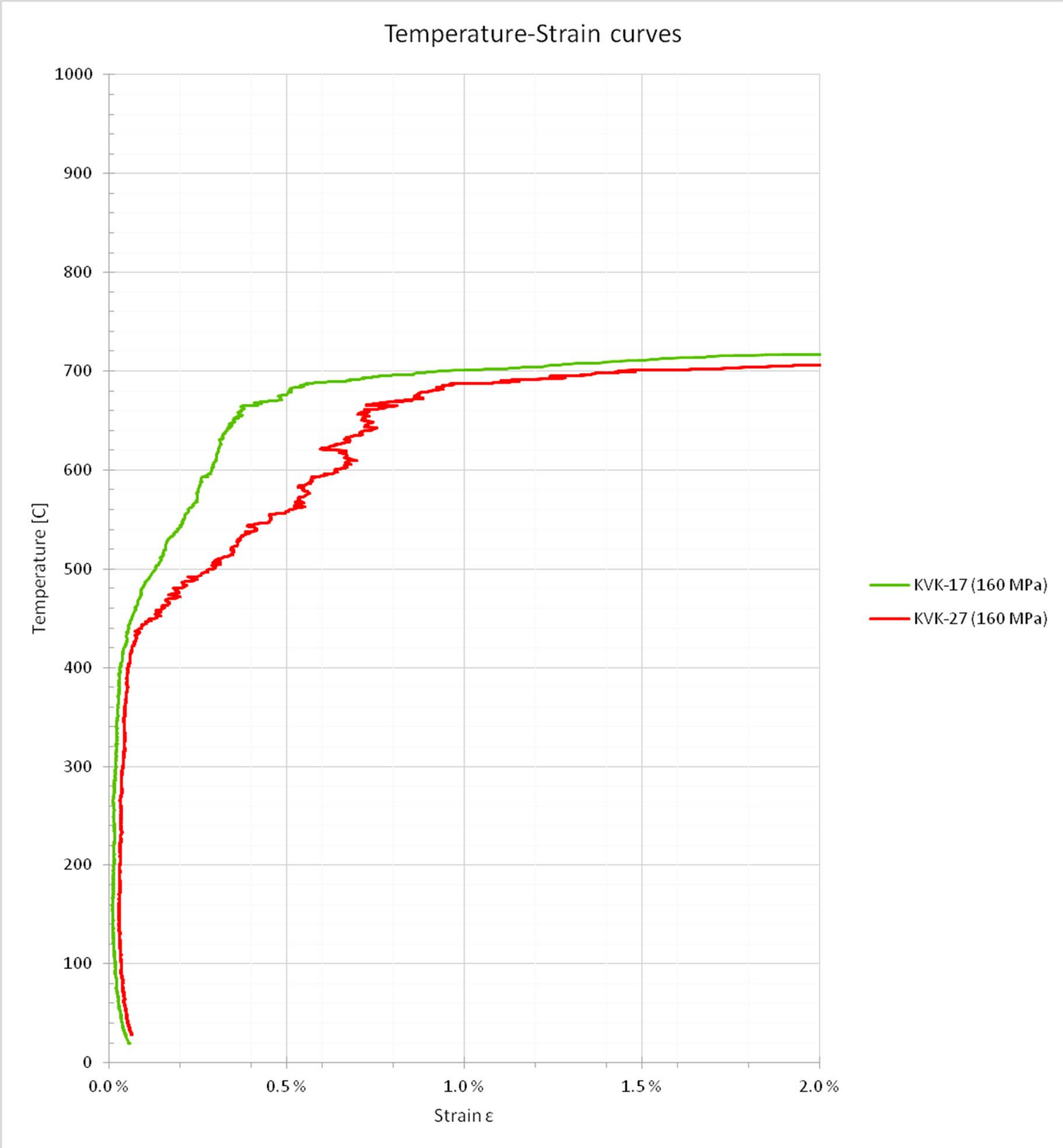
C.6 S960QC, 500MPa



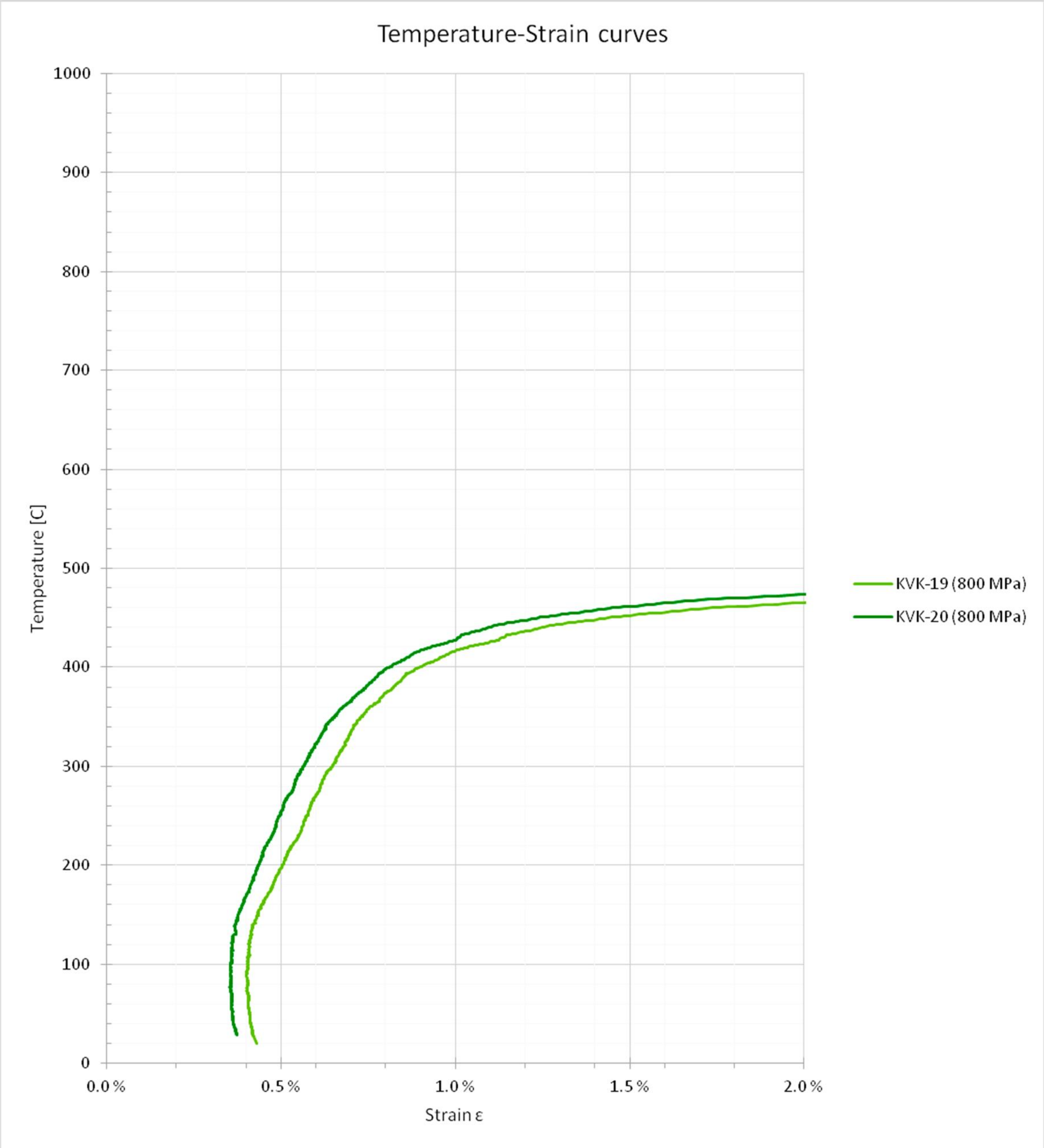
C.7 S960QC, 400MPa



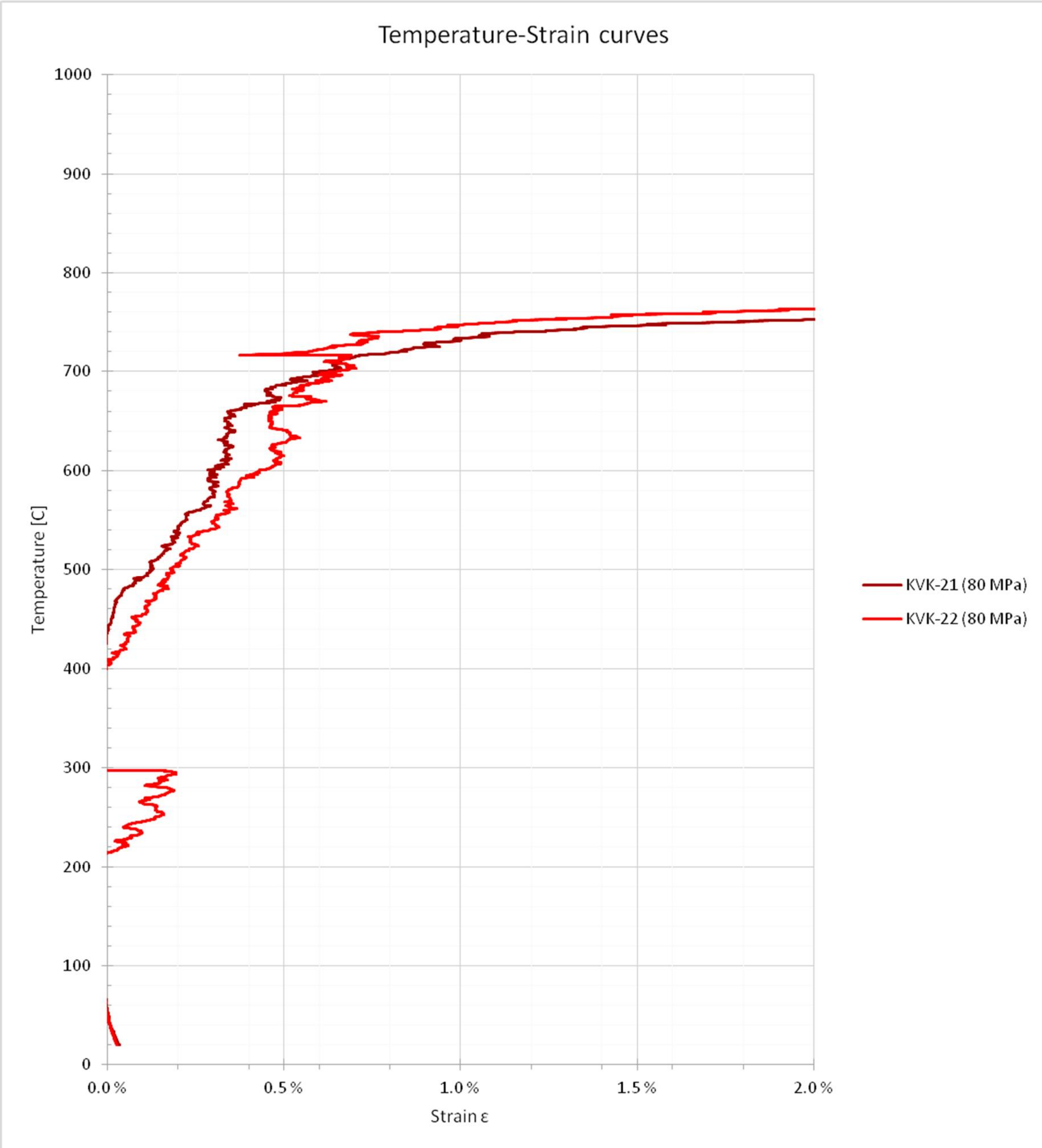
C.8 S960QC, 220MPa



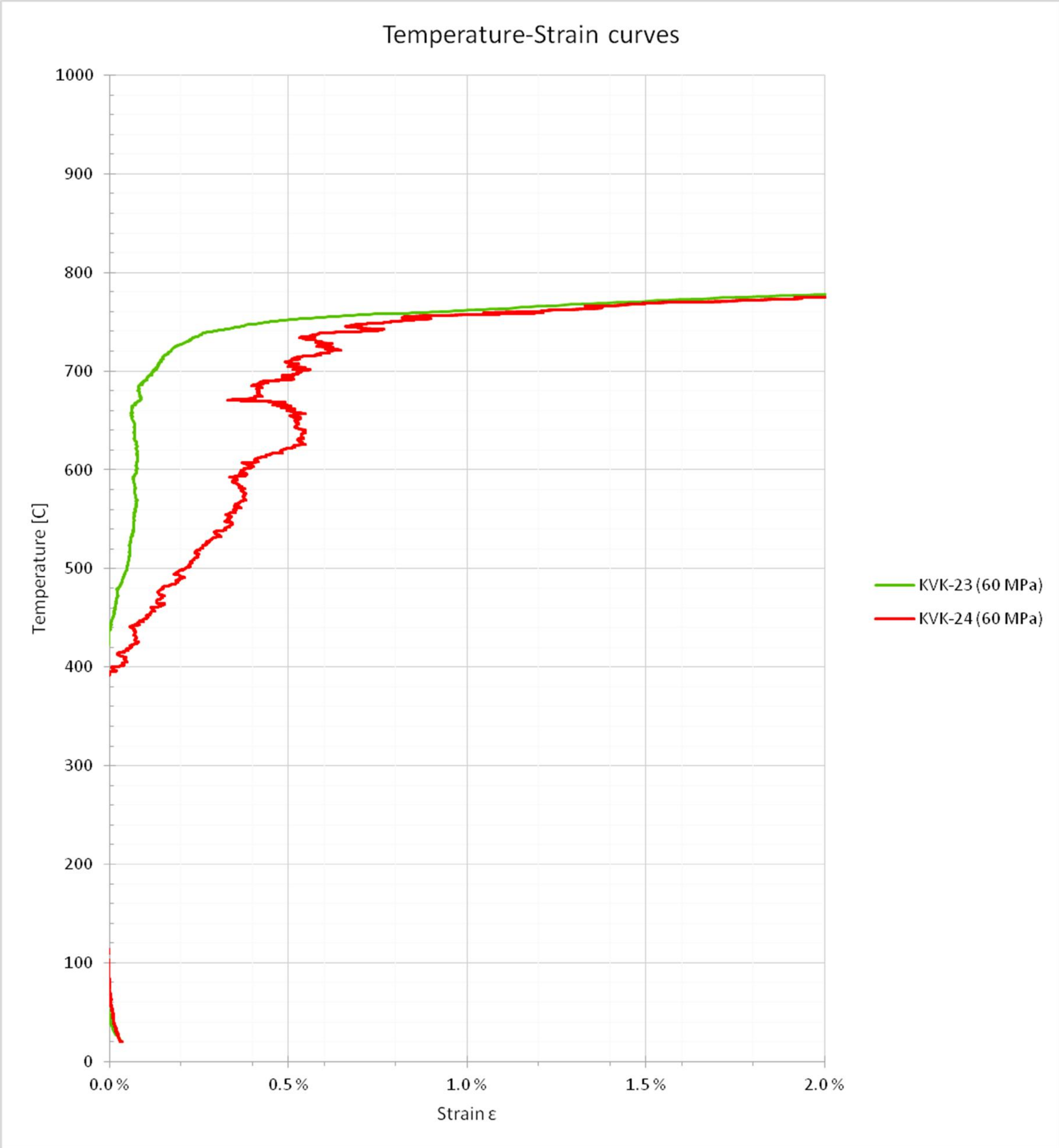
C.9 S960QC, 160 MPa



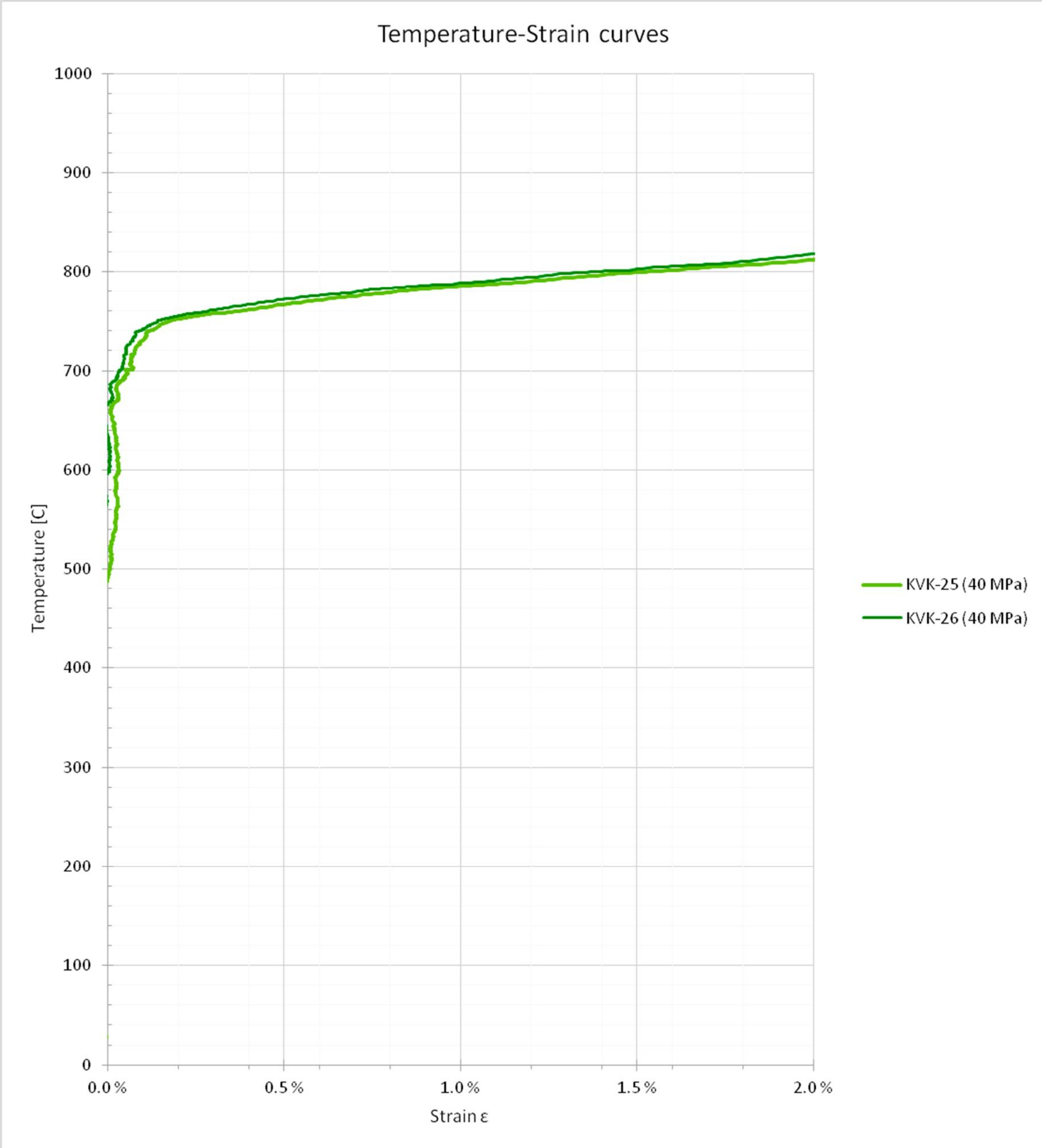
C.10 S960QC, 800MPa



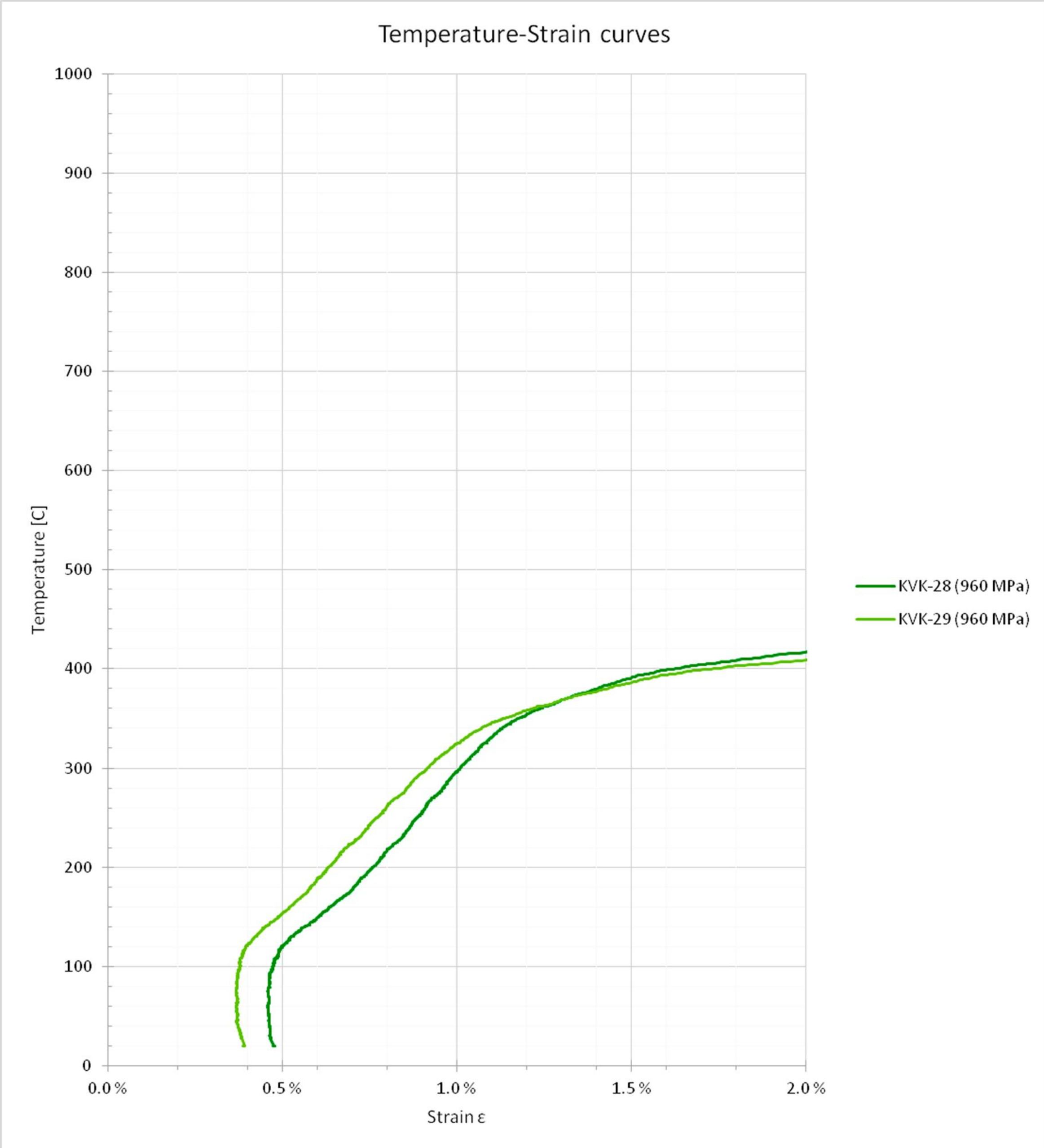
C.11 S960QC, 80MPa



C.12 S960QC, 60MPa

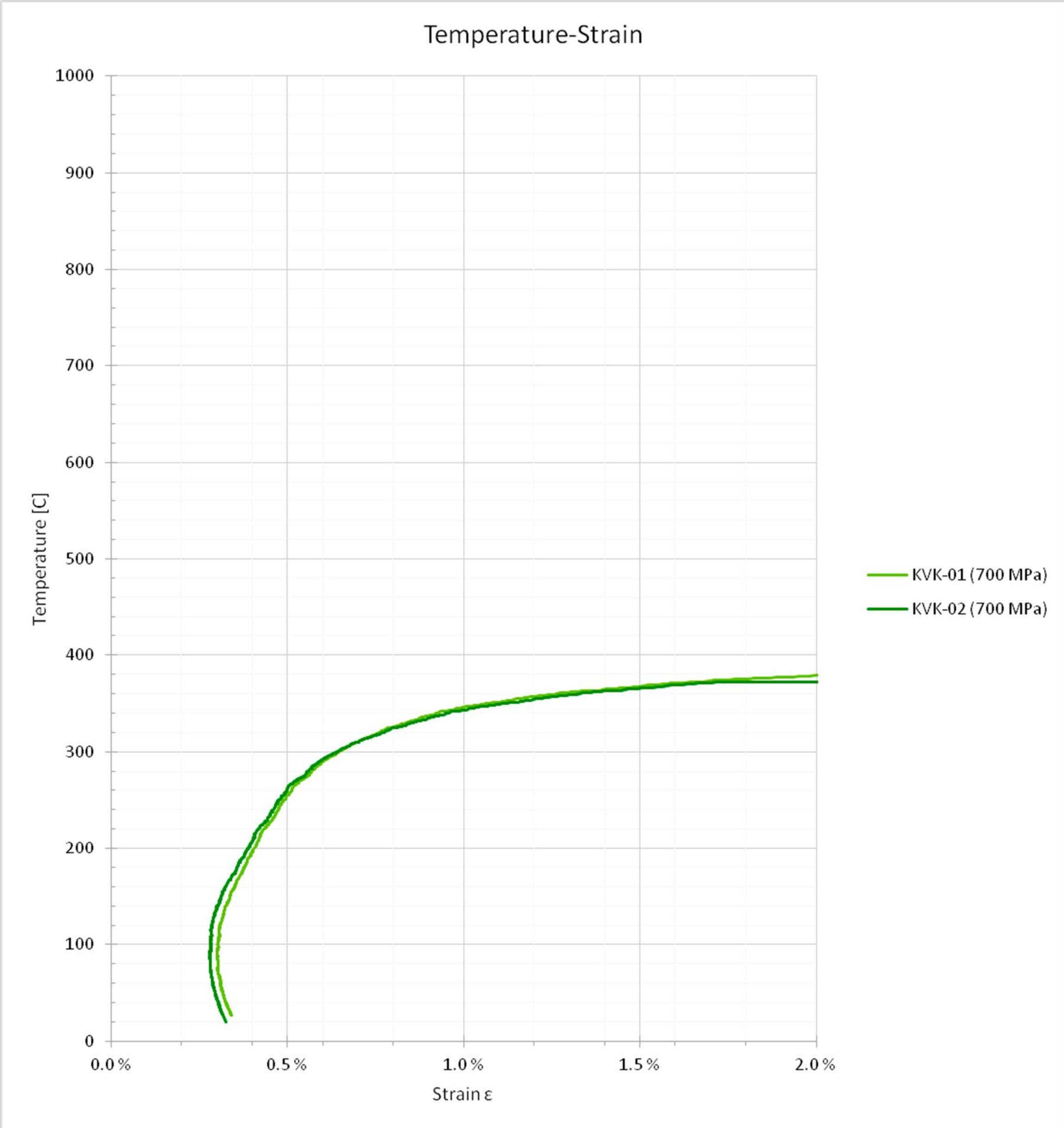


C.13 S960QC, 40MPa

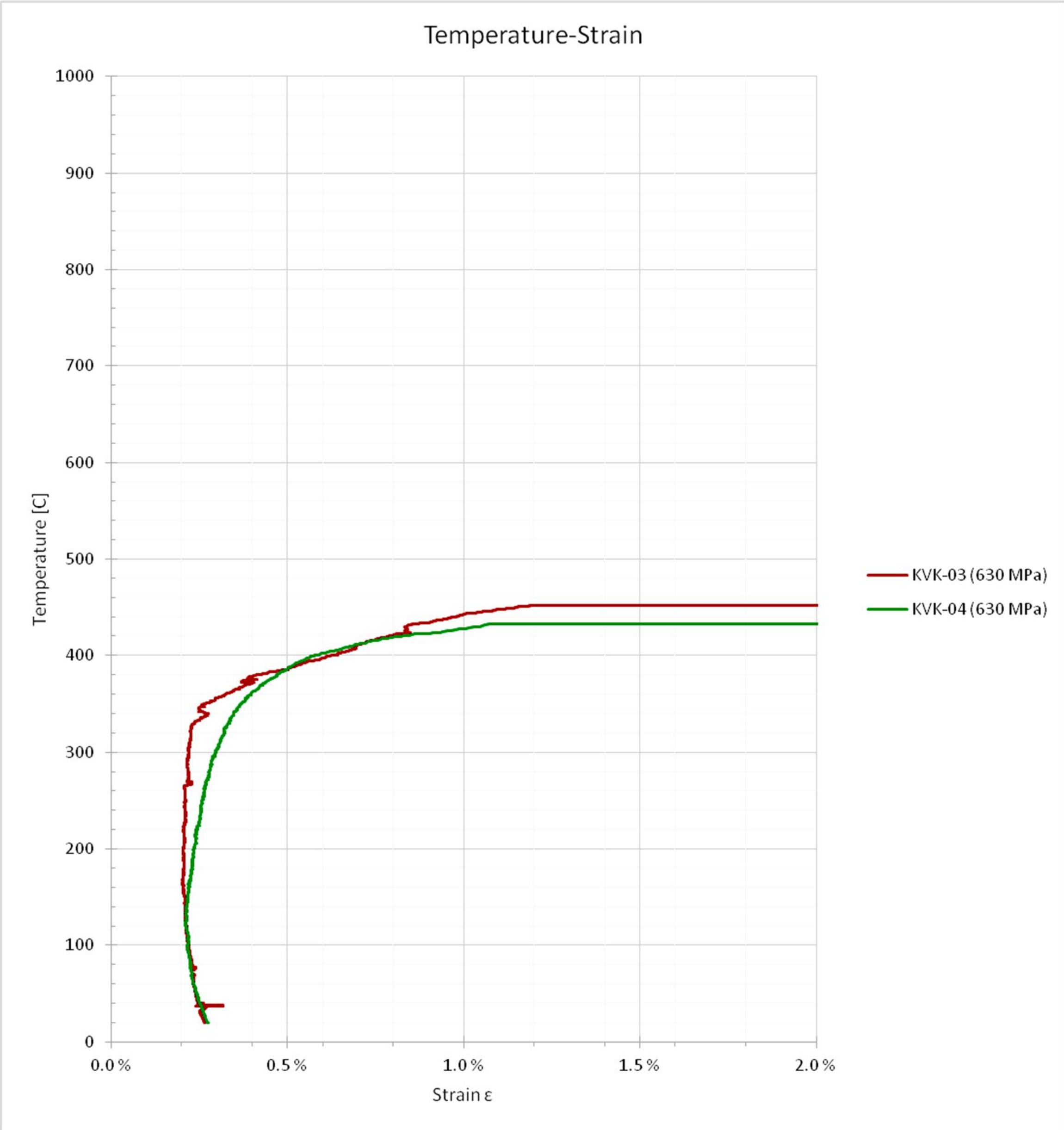


C.14 S960QC, 960MPa

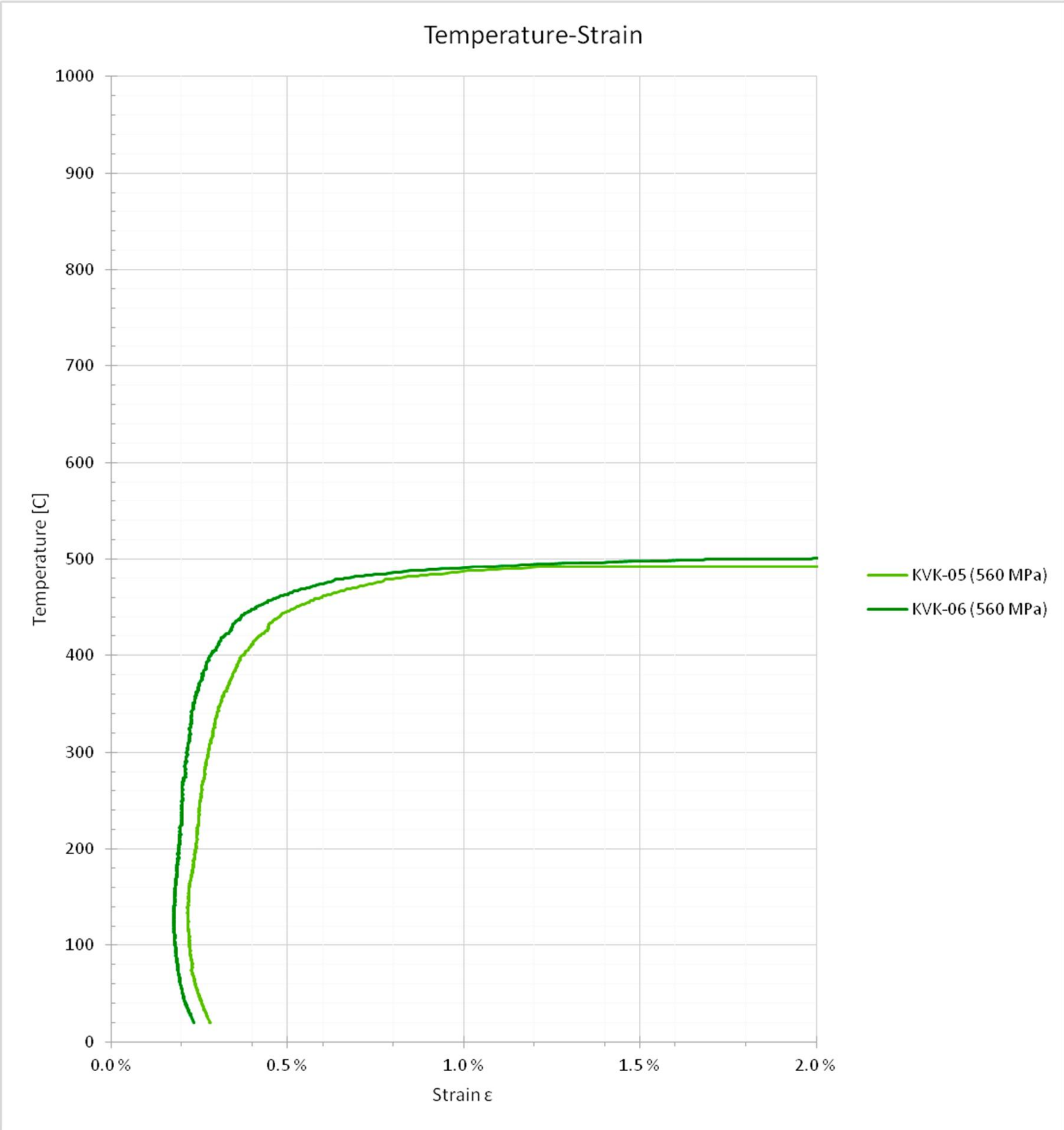
APPENDIX D: S700QL Transient state tests



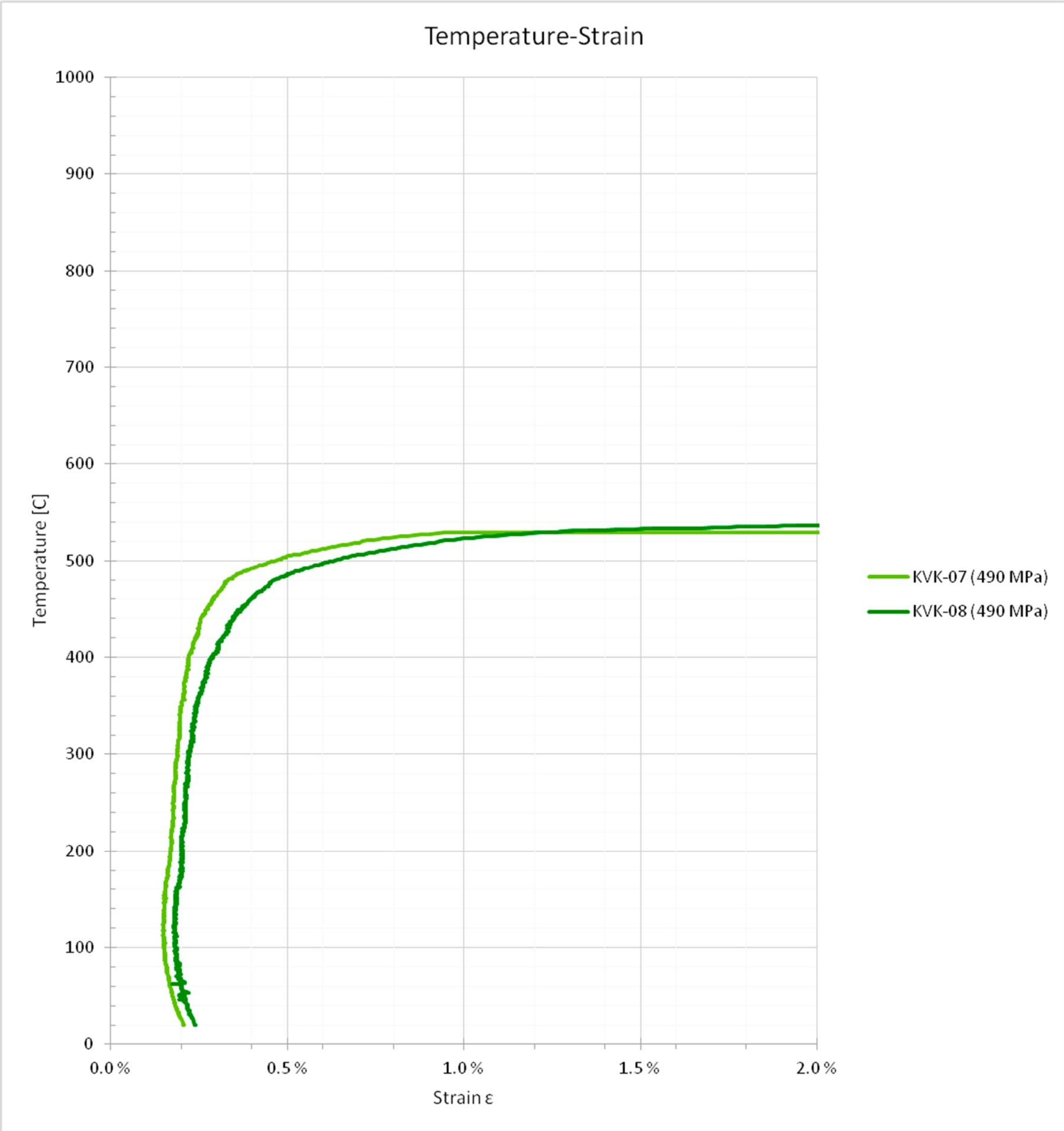
D.1 S700QL, 700MPa



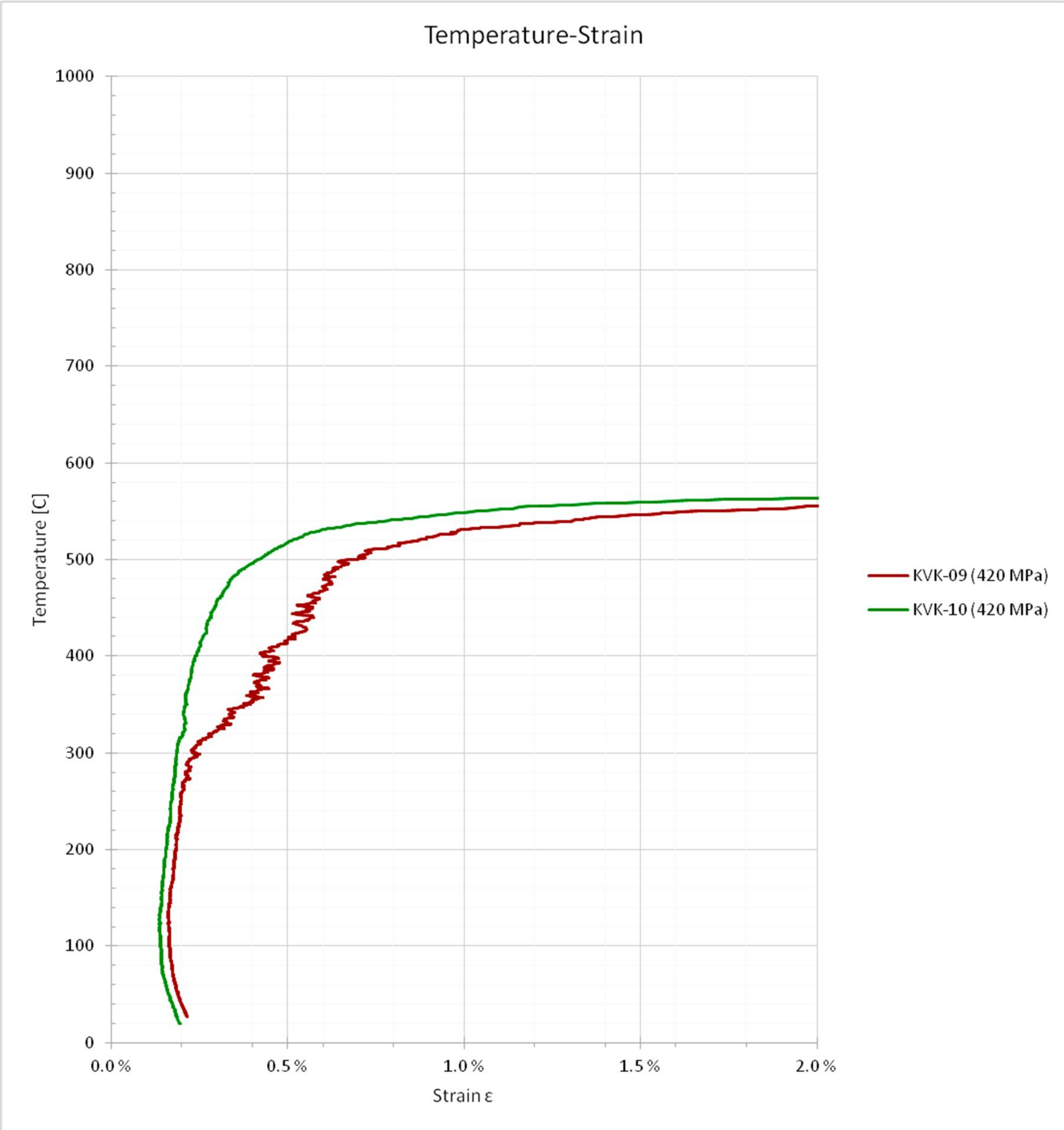
D.2 S700QL, 630 MPa



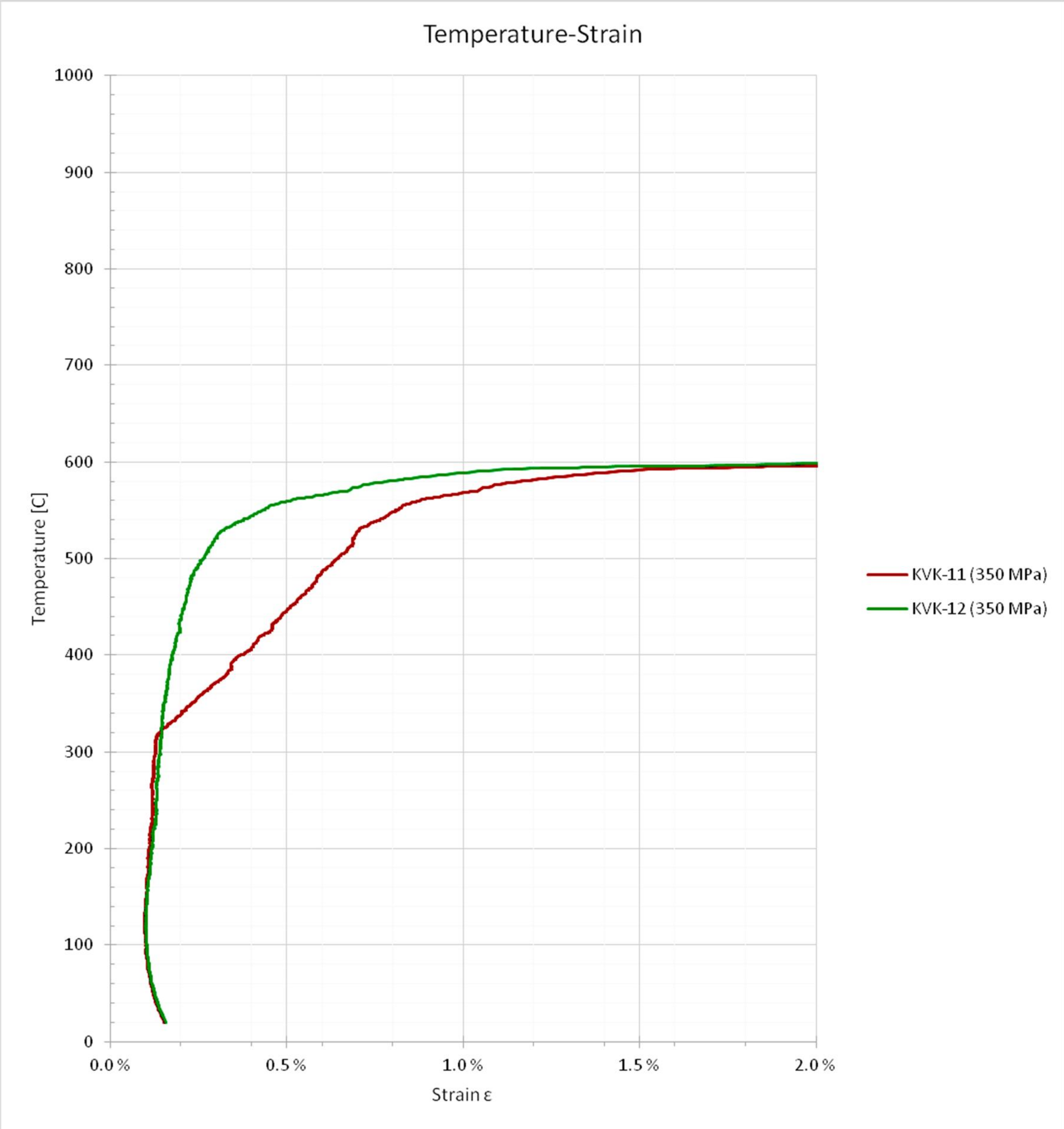
D.3 S700QL, 560MPa



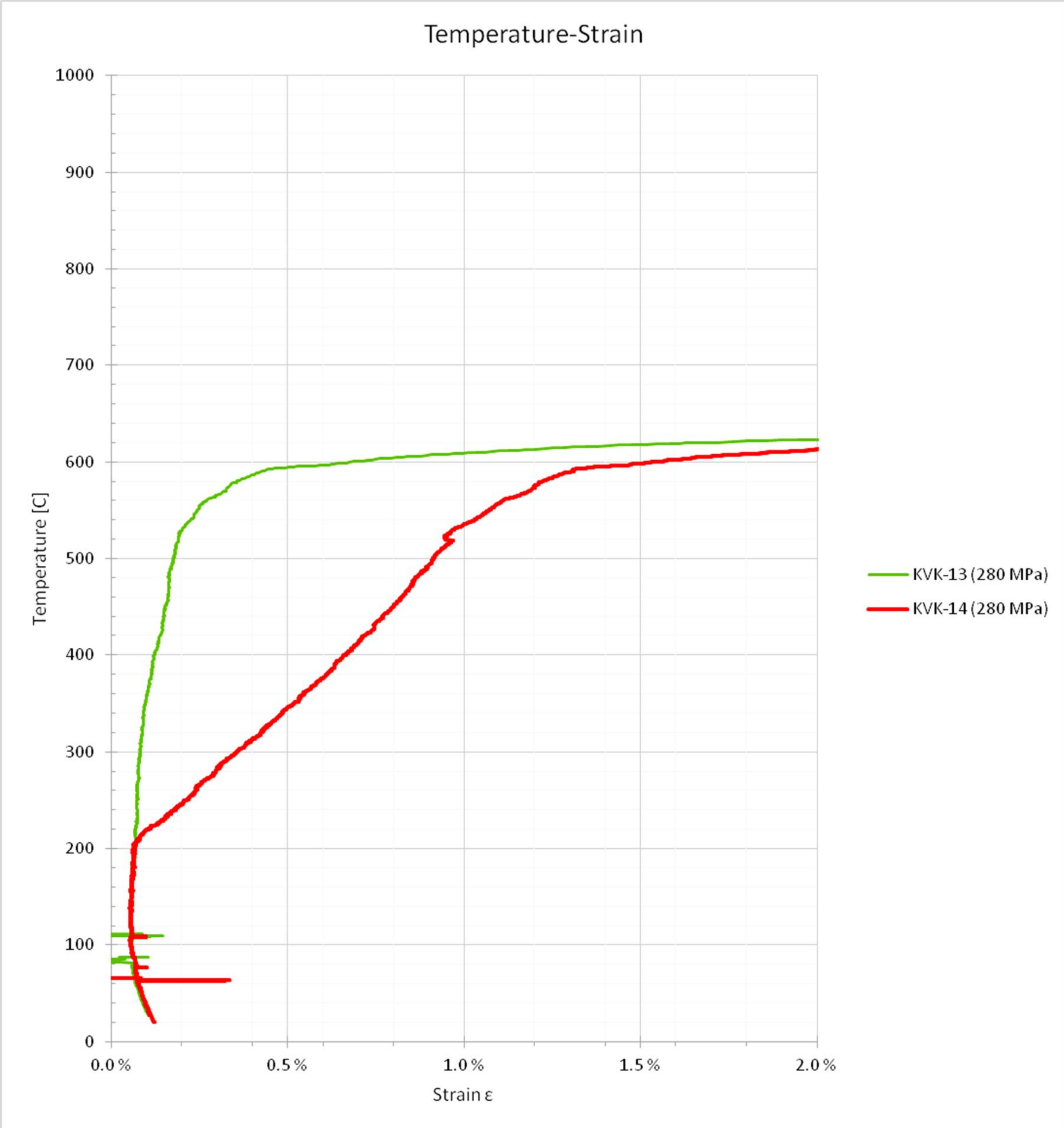
D.4 S700QL, 490MPa



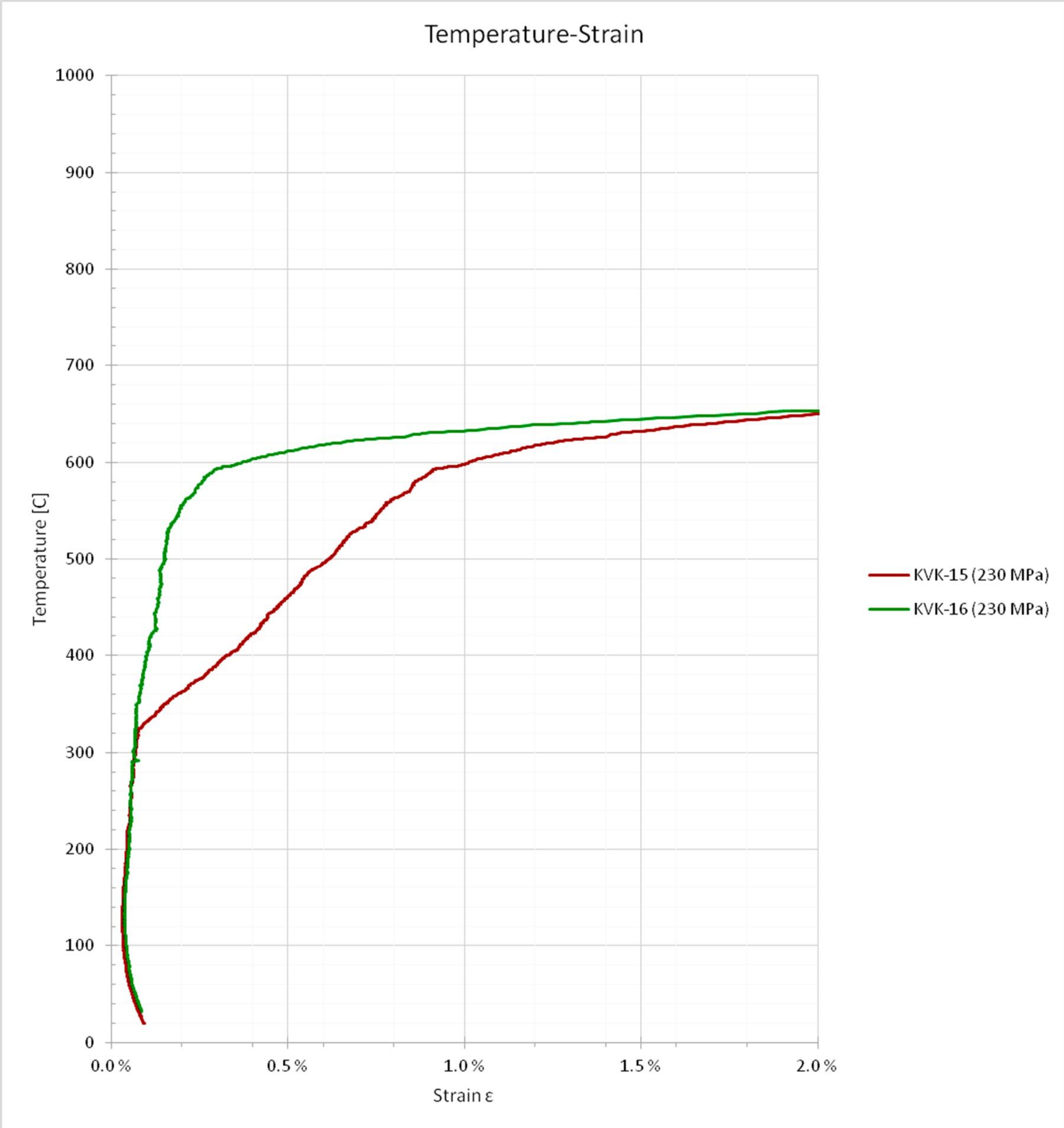
D.5 S700QL, 420MPa



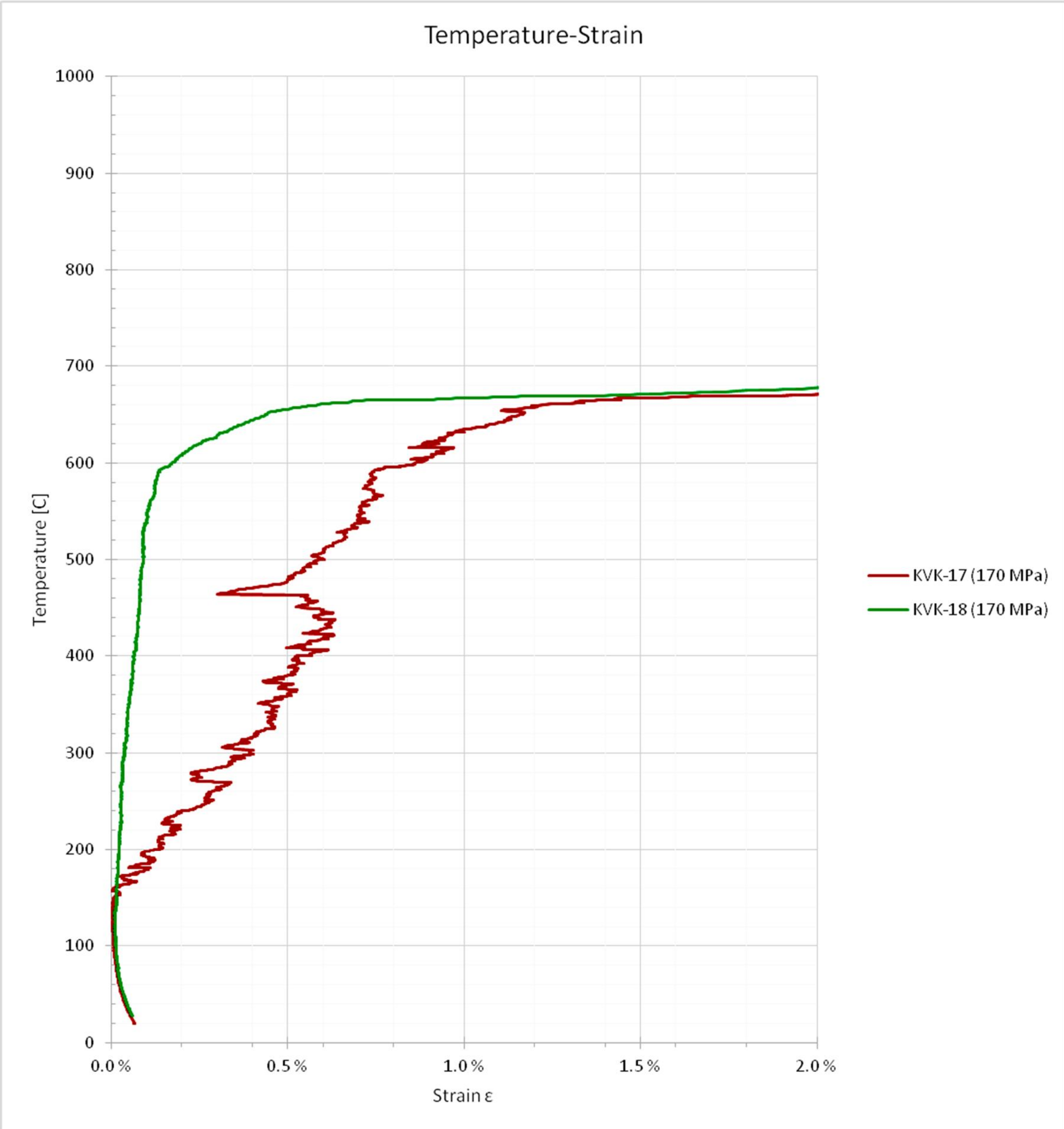
D.6 S700QL, 350MPa



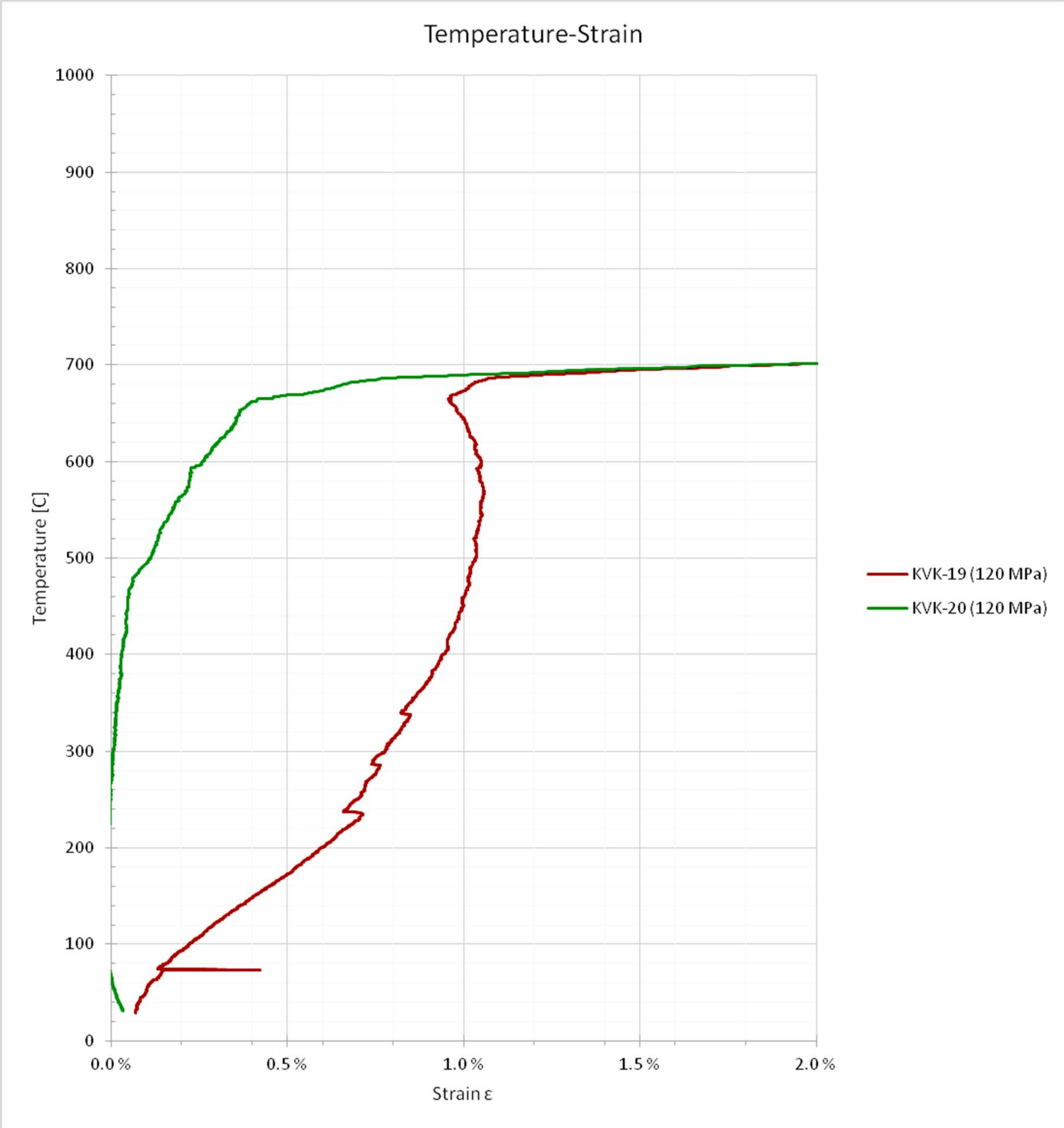
D.7 S700QL, 280MPa



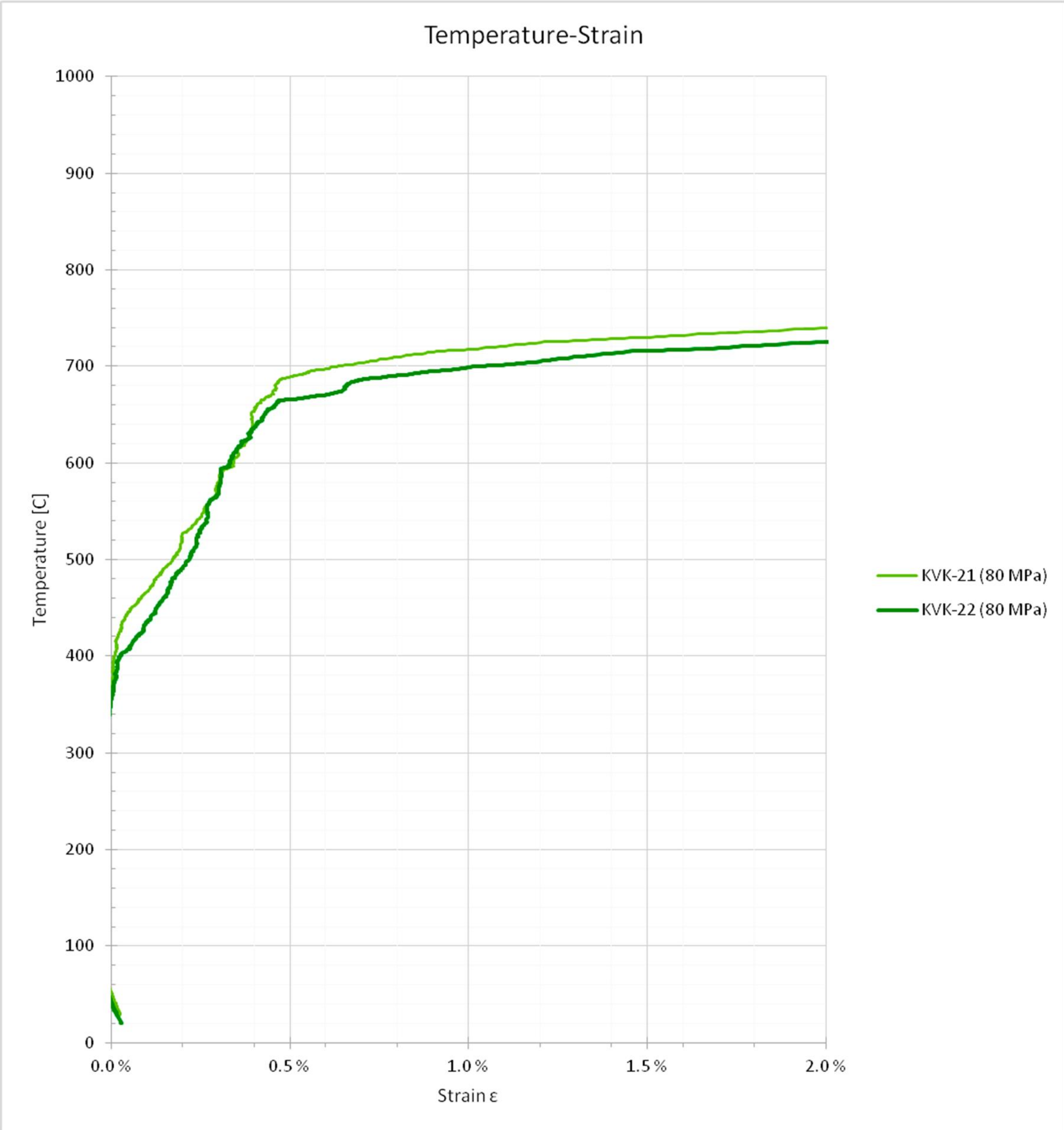
D.8 S700QL, 230MPa



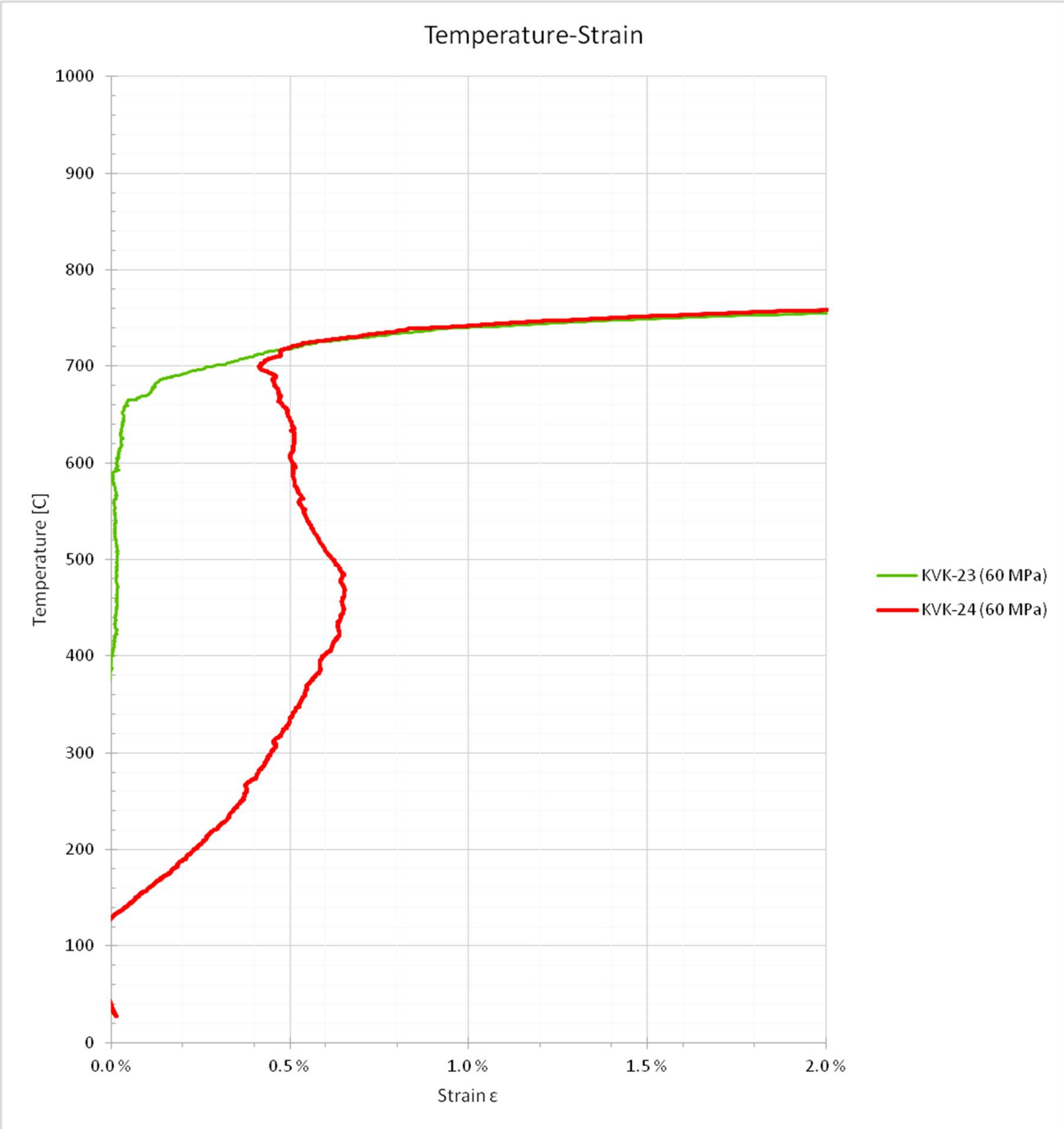
D.9 S700QL, 170MPa



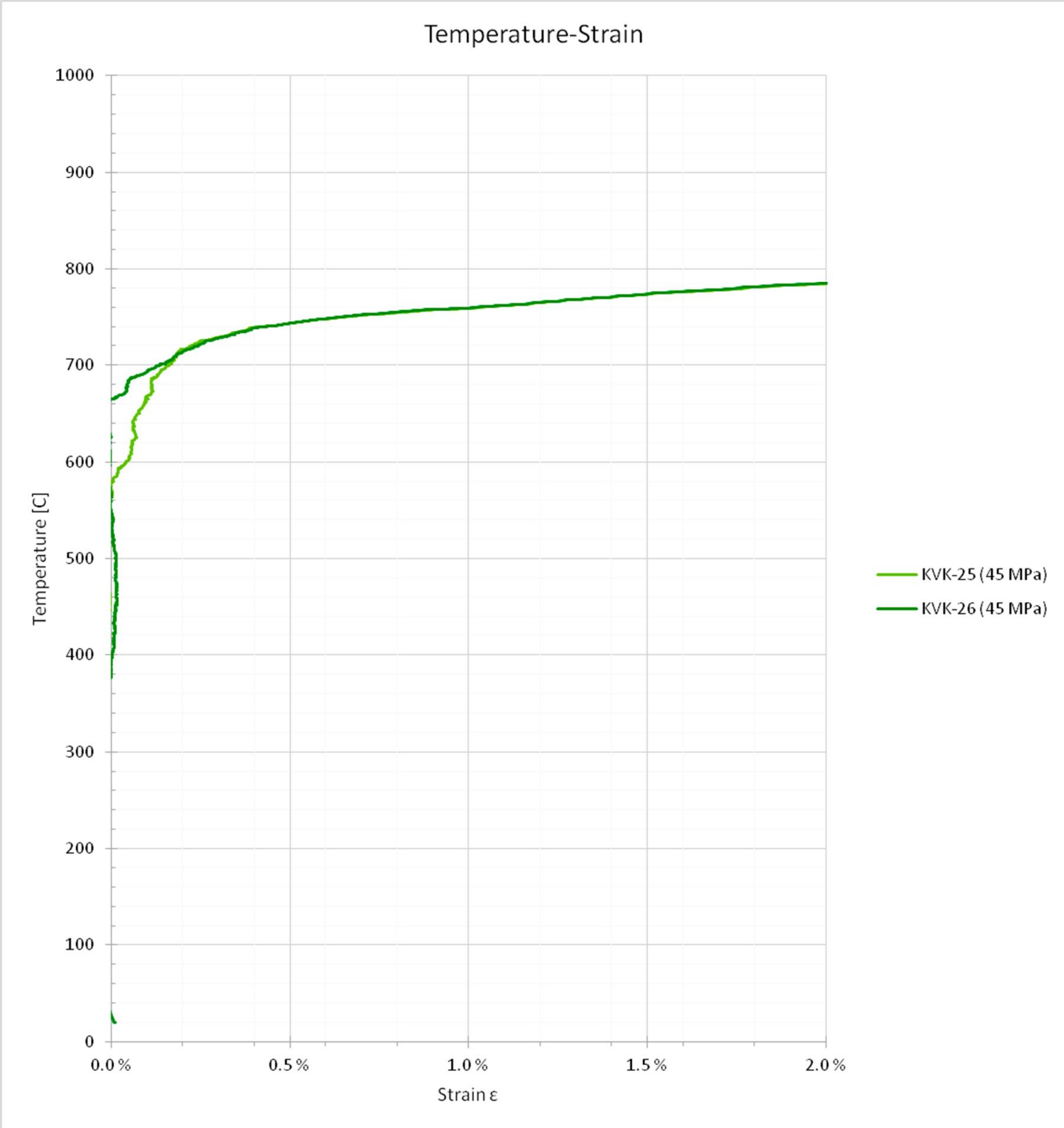
D.10 S700QL, 120MPa



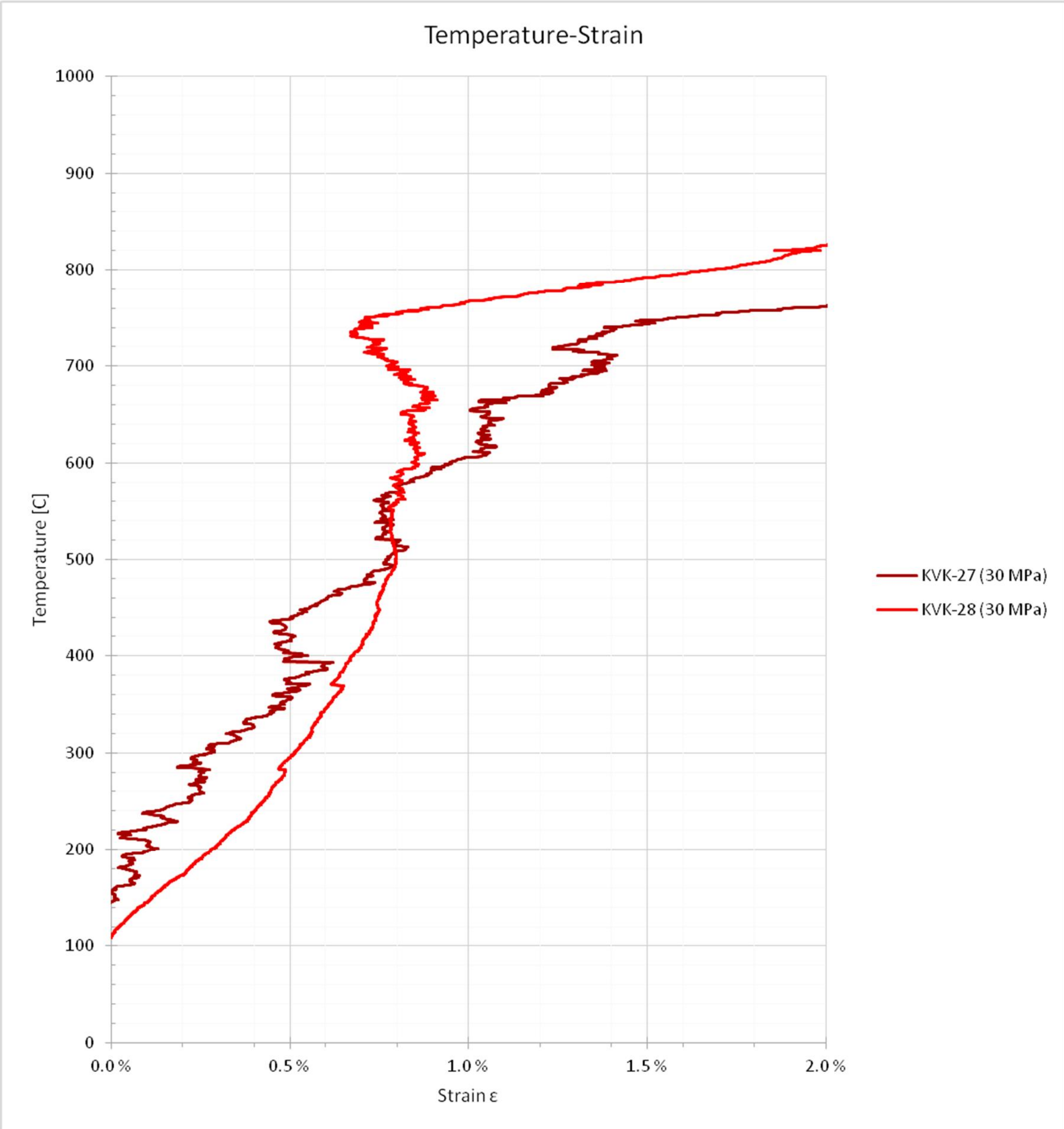
D.11 S700QL, 80MPa



D.12 S700QL, 60MPa



D.13 S700QL, 45MPa



D.14 S700QL, 30MPa