Elevated temperature material properties of a new high-chromium austenitic stainless steel

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Outline

- A new high-chromium austenitic stainless steel 1.4420
- Experimental programme
- Reduction factors at elevated temperatures
- Material modelling
- Conclusions

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A new high-chromium austenitic stainless steel 1.4420

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EN 1.4420, ASTM UNS 31655

- A new high-chromium austenitic stainless steel developed by Outokumpu
- Trademark: Outokumpu Supra 316plus

- Basically an improved version of AISI 316L
- Compared to other Cr-Ni-Mo grades such as 1.4404 and 1.4432 this grade has
  - low nickel and molybdenum → lower price (alloy surcharge)
  - high chromium and nitrogen → higher strength & better corrosion resistance

- Austenitic → ductile down to cryogenic temperatures
- Excellent weldability & good formability

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Nominal mechanical properties of 1.4420 according to EN 10028-7:2016

Product form	$f_{0.2p}$ (MPa)	$f_{1.0p}$ (MPa)	f_u (MPa)	ε_f (%)
Cold-rolled strip	350	380	650 – 850	35
Hot-rolled strip	350	380	650 – 850	35
Hot-rolled plate	320	350	630 – 830	40

Nominal mechanical properties of 1.4404 according to EN 10028-7, EN 10088-2 and EN 10088-4

Product form	$f_{0.2p}$ (MPa)	$f_{1.0p}$ (MPa)	f_u (MPa)	ε_f (%)
Cold-rolled strip	240	270	520 – 670	40
Hot-rolled strip	220	260	520 – 670	40
Hot-rolled plate	220	260	520 – 670	45

Typical chemical compositions, PRE and current alloy surcharge

Grade	C (%)	Cr (%)	Ni (%)	Mo (%)	N (%)	PRE (-)	AAF* (€/t)
1.4420	0.02	20.3	8.6	0.7	0.19	26	1360
1.4404	0.02	16.7	10.1	2.0	0.05	24	1600

* Monthly alloy surcharge in September 2017 for European customers

Purpose of the present study

- This study focuses on the elevated temperature material properties of this new austenitic stainless steel grade 1.4420.

- **Aims:**
    - To investigate the material properties of grade 1.4420 at elevated temperatures
    - To assess the applicability of existing strength and stiffness reduction factors to this material
    - To propose design recommendations for the elevated temperature reduction factors for this material

Experimental programme

Experimental programme

A total of 164 tensile coupon tests at elevated temperatures

- 80 steady state tests (temperature ranges from 25 °C to 1100 °C)
- 84 transient state tests (stress level ranges from 10% to 90% of the 0.2% proof stress at room temperature)
- Coupons extracted from 1 mm thick cold-rolled & 6 mm thick hot-rolled sheet materials

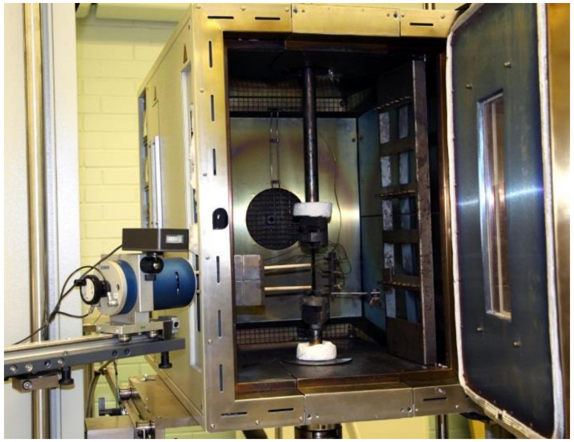
Summary of elevated temperature material tests

Testing method	Sheet material	Nominal thickness (mm)	No. of tests
Steady state tests	Cold-rolled	1.0	**42**
	Hot-rolled	6.0	**38**
Transient state tests	Cold-rolled	1.0	**44**
	Hot-rolled	6.0	**40**

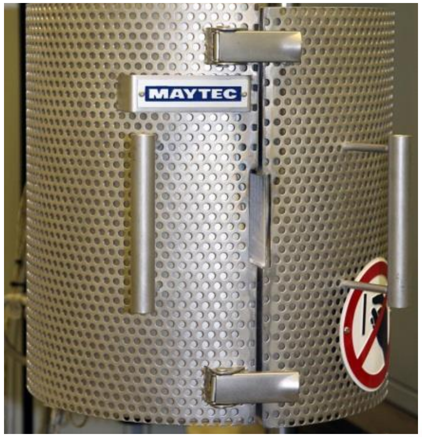
Testing apparatus

- Zwick Z250/SW5A testing machine
- Environmental chamber (isothermal tests at temperatures ≤ 550°C)
- High temperature furnace (isothermal tests at temperatures > 550°C and anisothermal tests)

Tensile testing machine



Environmental chamber



High temperature furnace

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Steady state tests

- The coupons were heated to a specified temperature and then loaded until fracture
- 18 specified temperatures: every 100 °C between room temperature and 500 °C, and every 50 °C between 500 °C and 1100 °C
- At each specified temperature, 2 or 3 repeated tests were conducted
- Testing speeds conformed to requirements given in EN ISO 10002-5:
    - 0.4 mm/min up to a strain value of 2.5% for the hot-rolled coupons and 3.5% for the cold-rolled coupons
    - 15 mm/min afterwards until fracture of the coupon

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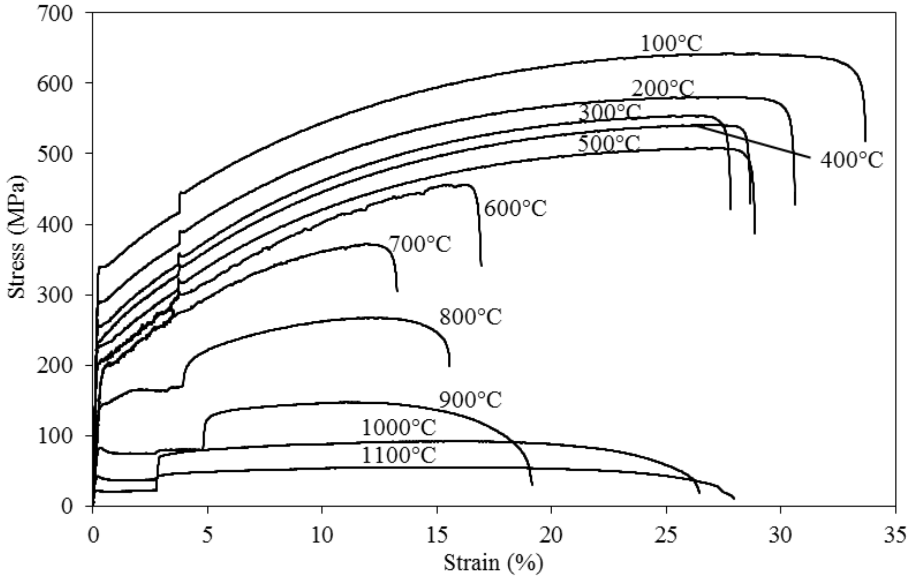
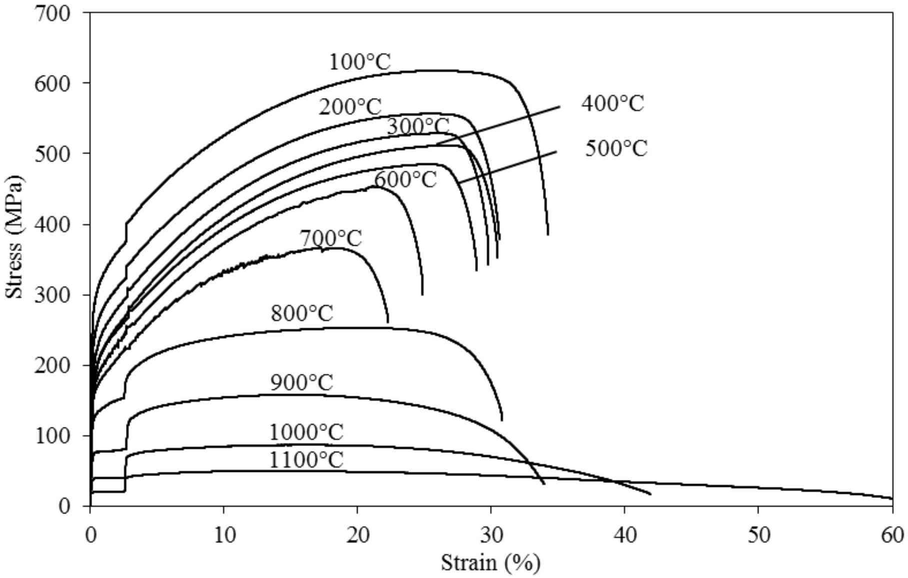
Steady state test results:
Stress-strain curves

- The step in the stress–strain curves is caused by, which the rapid change in the loading rate from 0.4 mm/min to 15 mm/min.



Cold-rolled specimens



Hot-rolled specimens

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Transient state tests

- The coupons were firstly loaded in tension to a target stress level, and then heated until failure
- 17 stress levels: from 10% to 90% of the 0.2% proof (yield) stress at room temperature in increments of 5%
- At each stress level, two or three repeated tests were conducted
- Heating rate: 10 °C/min
- Additional transient state tests with a small stress level of 4 MPa were conducted to measure the thermal strains of the coupons at elevated temperatures

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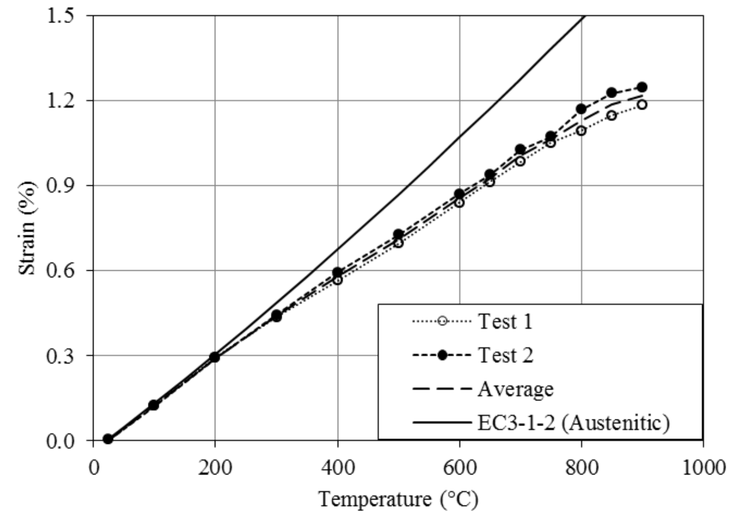
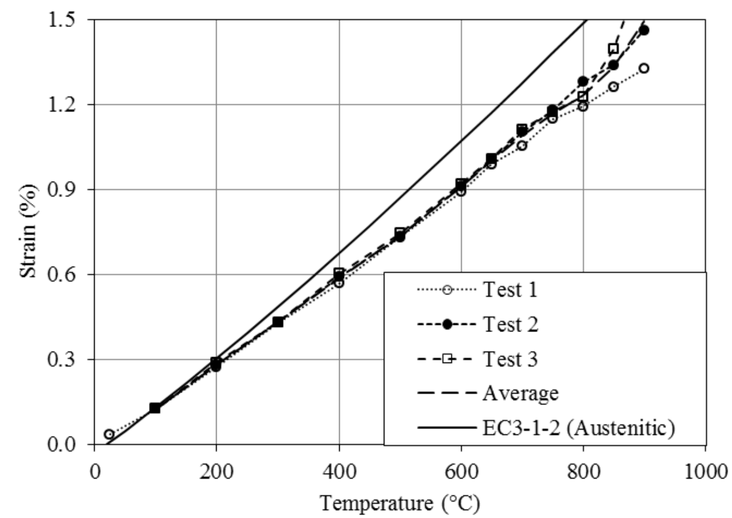
Transient state test results: Thermal strains

- The thermal strain varied linearly with temperature up to 800 °C, beyond which slightly nonlinear variation was observed, attributed principally to bowing of the coupons at higher temperatures.
- The EC3-1-2 thermal expansion curve shows a slight over-estimation of the thermal strain of the new grade 1.4420.
- Deduction of thermal strains from the total strains measured from the transient state tests yields the actual strain–temperature curves at various stress levels, which can be used for deriving the elevated temperature stress-strain curves.



Cold-rolled specimens



Hot-rolled specimens

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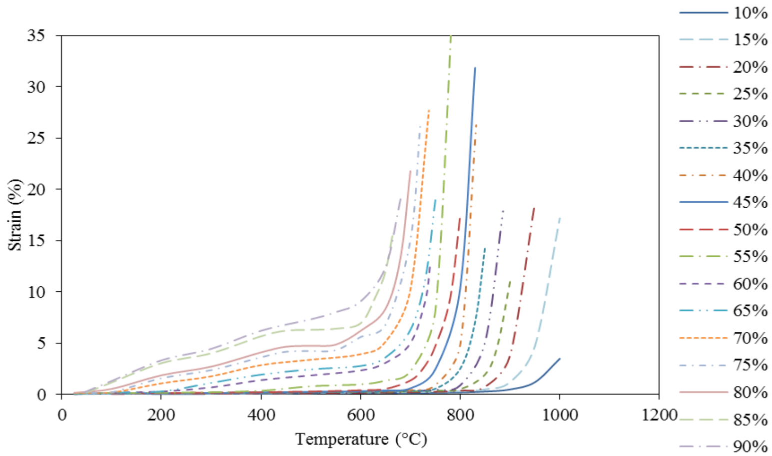
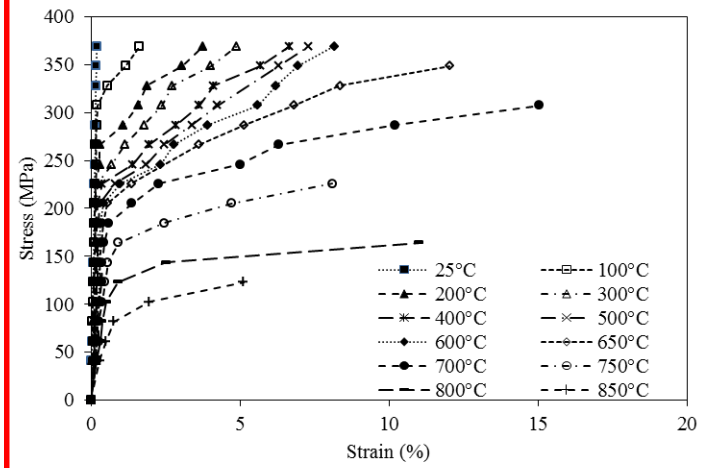
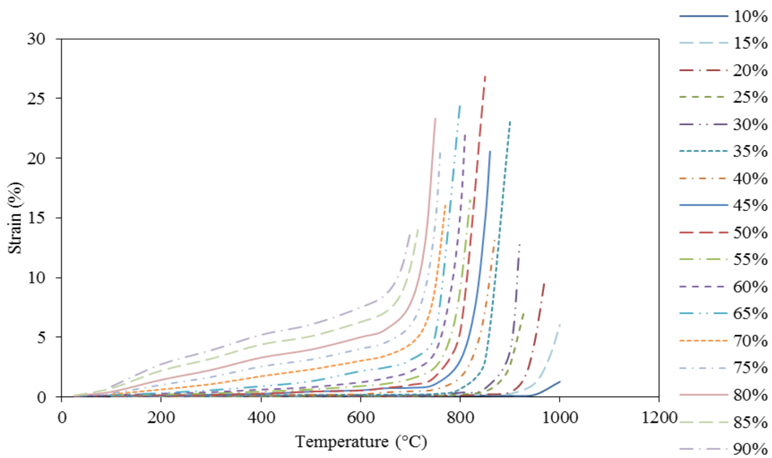
Transient state test results:
Stress-strain curves

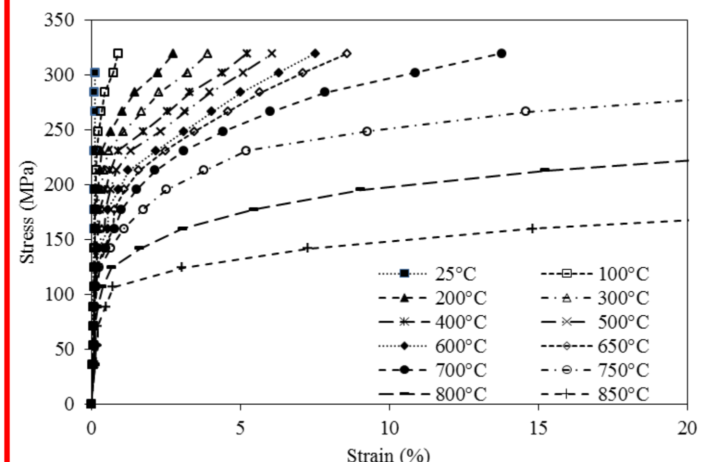
Cold-rolled





Hot-rolled





Strain-temperature curves with thermal strains deducted

Derived stress-strain curves

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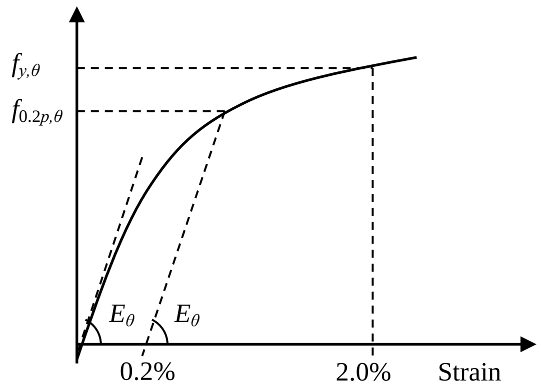
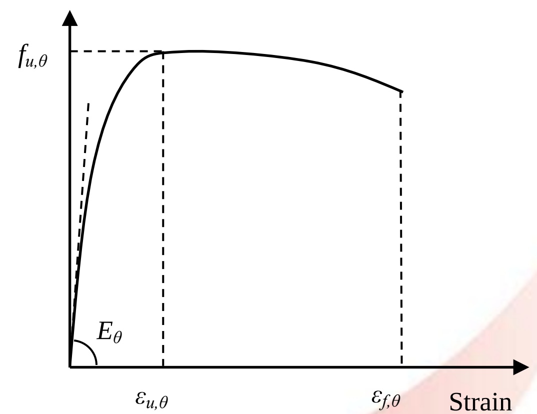
Reduction factors at elevated temperatures

Elevated temperature material properties

- Temperature-dependent material properties were determined for each stress-strain curve obtained from isothermal and anisothermal tests, including:
  - Young's modulus E_θ
  - 0.2% proof strength $f_{0.2p,\theta}$
  - Strength at 2% total strain $f_{y,\theta}$
  - Ultimate strength $f_{u,\theta}$
  - Ultimate strain $\varepsilon_{u,\theta}$
  - Fracture strain $\varepsilon_{f,\theta}$



Initial portion of stress-strain curve



Full stress-strain curve

Material properties at room temperature (25 °C)

Sheet material	Nominal thickness (mm)	E (GPa)	$f_{0.2p}$ (MPa)	$f_{2.0}$ (MPa)	f_u (MPa)	ε_u (%)	ε_f (%)
Cold rolled	1.0	174.5	410	474	740	25.4	42.0
Hot rolled	6.0	227.0	358	429	689	25.8	48.0

Reduction factors at elevated temperatures

- The reduction factors of the Young's modulus (E_{θ}/E), 0.2% proof strength ($f_{0.2p,\theta}/f_{0.2p}$), ultimate strength ($f_{u,\theta}/f_u$), ultimate strain ($\varepsilon_{u,\theta}/\varepsilon_u$) and fracture strain ($\varepsilon_{f,\theta}/\varepsilon_f$) at each elevated temperature are obtained.

- EC3-1-2 uses a coefficient $k_{2\%,\theta}$ a formula for determining $f_{y,\theta}$. Values of the $k_{2\%,\theta}$ coefficient are back-calculated based on the experimental results for $f_{0.2p,\theta}$, $f_{y,\theta}$ and $f_{u,\theta}$.

- The elevated temperature reduction factors obtained from the steady and transient state tests are compared with the corresponding reduction factors given by:
  - EN 1993-1-2 for grade 1.4301
  - Gardner et al. in [19] for the austenitic I group

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Reduction factors at elevated temperatures

- The European code EN 1993-1-2 provides three sets of reduction factors for austenitic stainless steel grades 1.4301, 1.4401/4 and 1.4571
- Gardner et al. collected material fire test data on seven austenitic stainless steel grades, placed them into three groups – austenitic I (1.4301, 1.4318 and 1.4818), austenitic II (1.4401, 1.4404 and 1.4541) and austenitic III (1.4571), based on the stability of the microstructure, and then proposed reduction factors for each group. The purpose of this was to rationalise the number of sets of reduction factors provided to structural engineers.
- In the present work, it was generally found that the elevated temperature material properties of grade 1.4420 are most similar to those for grade 1.4301 given in EN 1993-1-2 and those for the austenitic I group proposed by Gardner et al., both of which are compared with our experimental results.

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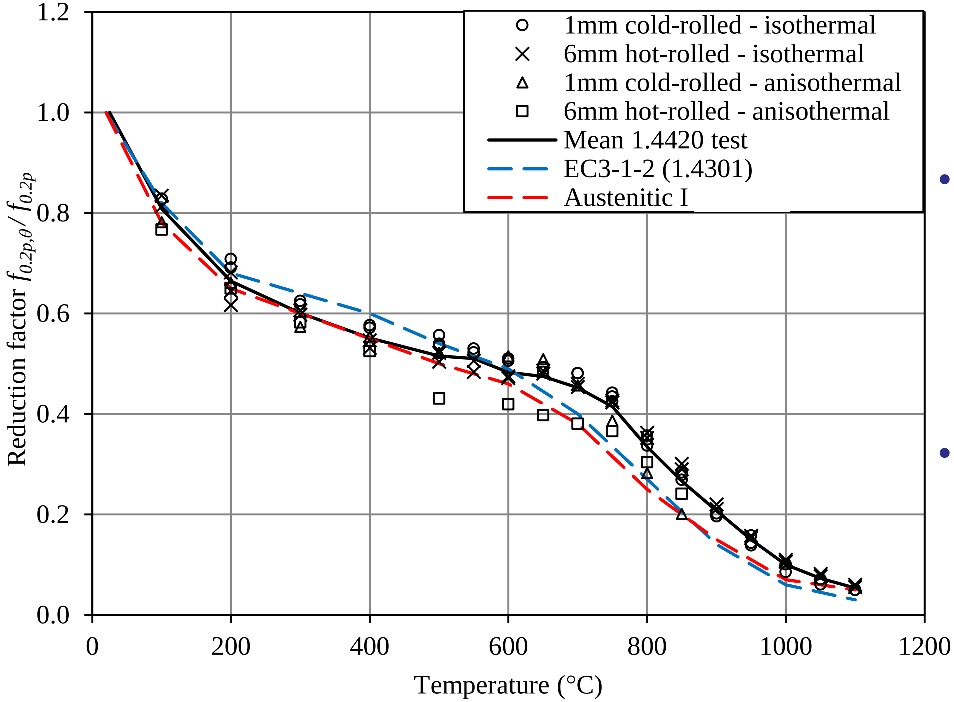
Reduction factor for the 0.2% proof stress



- Both the discrepancy between the isothermal and anisothermal test results and the difference between the experimental results on cold-rolled and hot-rolled materials are rather small.
- The mean values of the experimental reduction factors for the 0.2% proof stress are well represented by the reduction factor curve proposed by Gardner et al.
- The EC3-1-2 grade 1.4301 reduction factor curve agrees well with the mean test values at high temperatures, but lies slightly above the mean value curve for temperatures from 200 °C to 600 °C (i.e. resulting in over-estimated $f_{0.2p,\theta}$).

It is recommended that **the 0.2% proof stress reduction factors for austenitic I group** be employed for the new studied austenitic stainless steel grade 1.4420.

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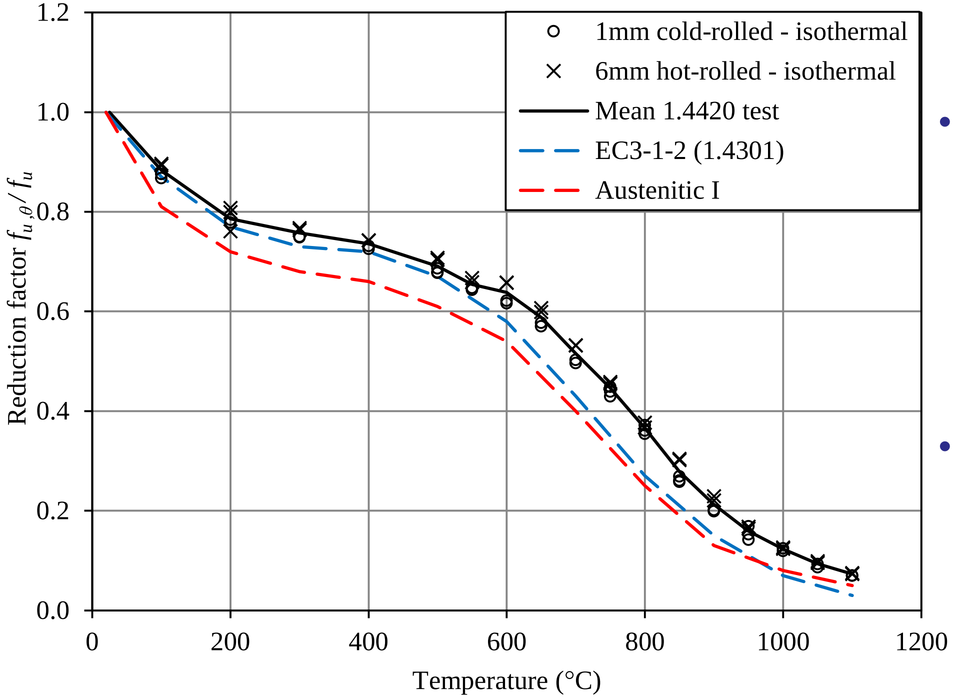
Reduction factor for the ultimate strength



- The reduction factors for the ultimate strength obtained from the tests on cold-rolled and hot-rolled materials are very similar.
- Both EC3-1-2 and austenitic I group reduction factor curves follow closely the trend but lie below the mean experimental values, yielding safe-sided predictions of the ultimate strength of grade 1.4420 at elevated temperatures.
- Compared to the curve for austenitic I group , the EC3-1-2 reduction factor curve follows more closely the mean test values for temperatures ≤ 600 °C, (i.e. more accurate predictions of $f_{u,\theta}/f_u$); for temperatures > 600 °C, both reduction factor curves yield a similar level of conservatism.

It is recommended that **the ultimate strength reduction factors tabulated both for grade 1.4301 in EC3-1-2 and proposed for austenitic I group** can be applied to the new grade 1.4420.

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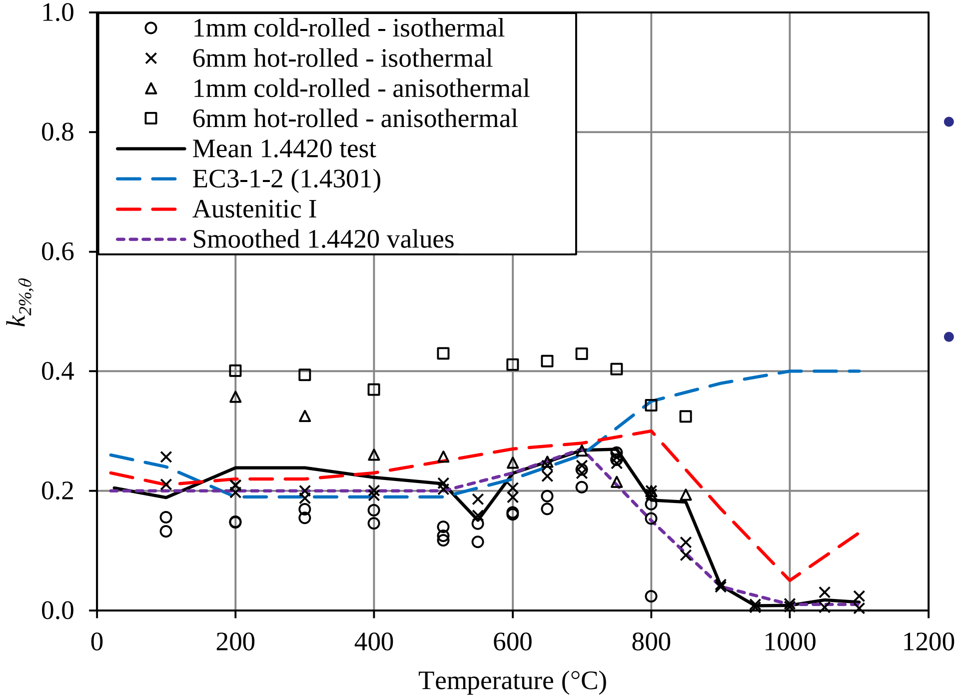
Coefficient $k_{2\%,\theta}$



- The curve for predicting $k_{2\%,\theta}$ given in EC3-1-2 does not fully represent the trend of the mean test data, particularly at higher temperatures.
- The curve proposed by Gardner et al. captures well the general distribution of the mean experimentally derived values.
- The rapid change in loading in isothermal tests leads to a step in the stress–strain curve and higher $f_{u,\theta}$ than those that would be derived from tests with a constant loading rate. An increase in the values of $k_{2\%,\theta}$ would be expected if $f_{0.2p,\theta}$, $f_{y,\theta}$ and $f_{u,\theta}$ were determined at the same testing speed. This would shift the data even closer to the values of $k_{2\%,\theta}$ for the austenitic I group.

It is recommended that **the values of the $k_{2\%,\theta}$ coefficient proposed for austenitic I group** be used for the new austenitic stainless steel grade 1.4420.

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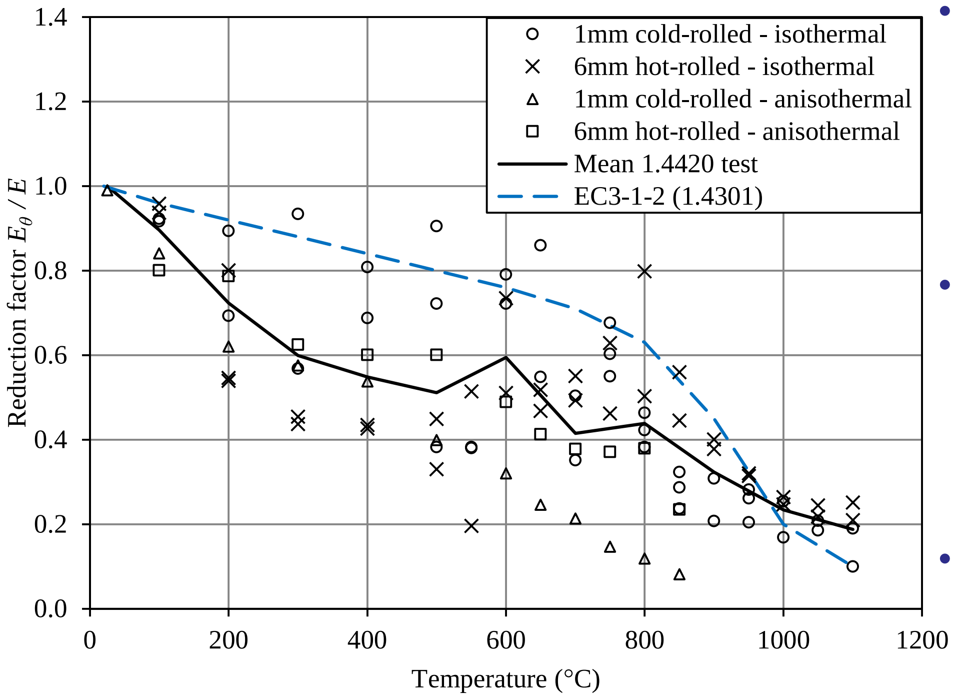
Reduction factor for the modulus of elasticity



- The results are very scattered; imperfect alignment of the thin tensile coupons and the use of a side-entry extensometer may have contributed to measurement errors.

- The EC3 reduction factor curve for the elastic modulus is shown to over-estimate the mean values of the experimental data for E_θ/E across almost the full temperature range.

- Revised recommendations are considered to be not warranted at this stage, but further work is required to derive more reliable Young's modulus reduction factors.

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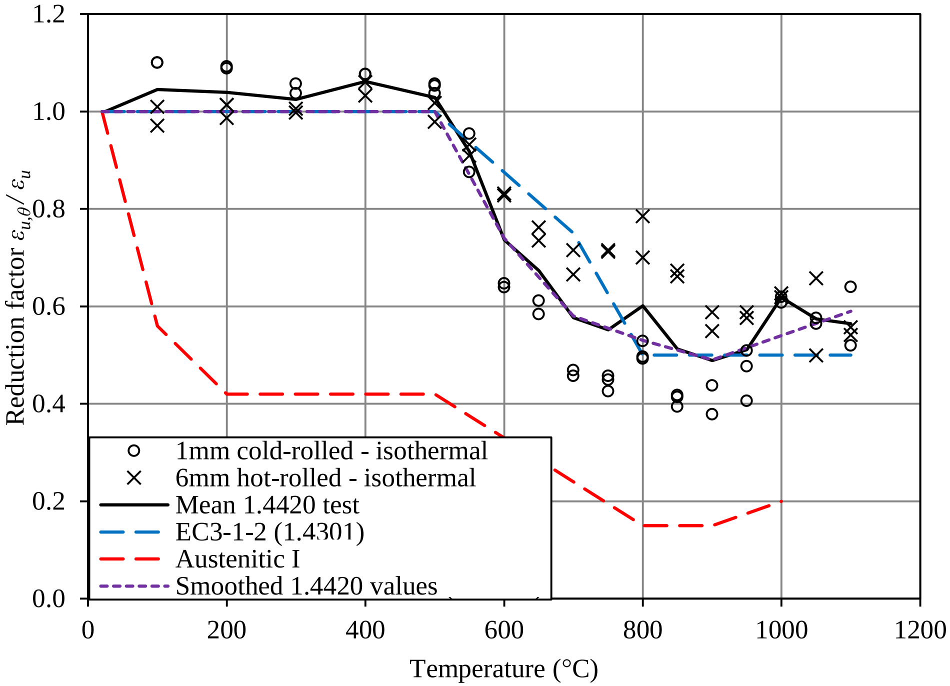
Reduction factor for the ultimate strain



- The EC3 reduction factor curve may be seen generally to reflect accurately the mean values of the experimental data.
- The austenitic I reduction factors lie well below the mean test results.

It is recommended to use **either the grade 1.4301 reduction factors given in EC3-1-2 or the grade specific reduction factors for $\varepsilon_{u,\theta}/\varepsilon_u$ provided in the table below** for determining $\varepsilon_{u,\theta}/\varepsilon_u$ for grade 1.4420 at elevated temperatures.

Grade specific $\varepsilon_{u,\theta}/\varepsilon_u$ reduction factors for EN 1.4420 based on 'smoothed' mean test data

Reduction factor	Temperature θ (°C)											
	20	100	200	300	400	500	600	700	800	900	1000	1100
$\varepsilon_{u,\theta}/\varepsilon_u$	1.00	1.00	1.00	1.00	1.00	1.00	0.74	0.58	0.53	0.49	0.54	0.59

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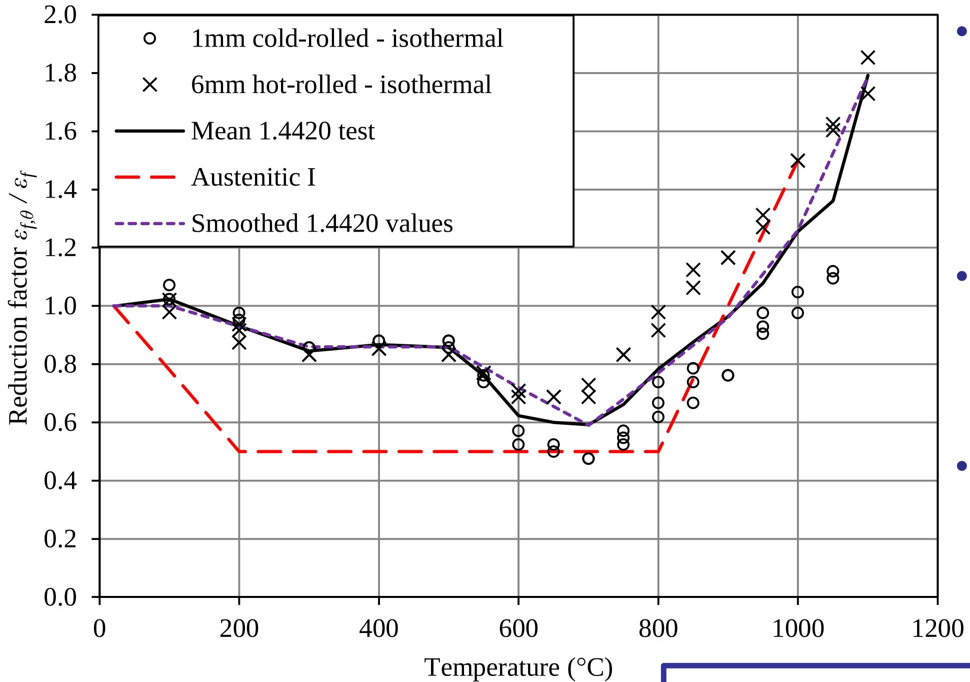
Reduction factor for the fracture strain



- Results for the cold-rolled and hot-rolled coupons are very consistent for temperatures ≤ 550 °C, beyond which the hot-rolled coupons possess slightly higher values of $\varepsilon_{f,\theta}/\varepsilon_f$.
- The mean values generally exhibit a decreasing trend for temperatures ≤ 700 °C, followed by a steeper increase at higher temperatures.
- The reduction factors for the austenitic I group under-estimate the $\varepsilon_{f,\theta}/\varepsilon_f$ data for temperatures ≤ 600°C but provide reasonable predictions thereafter.

The grade specific $\varepsilon_{f,\theta}/\varepsilon_f$ reduction factors provided in the table below are recommended to be used for grade 1.4420.

Grade specific $\varepsilon_{f,\theta}/\varepsilon_f$ reduction factors for EN 1.4420 based on 'smoothed' mean test data

Reduction factor	Temperature θ (°C)											
	20	100	200	300	400	500	600	700	800	900	1000	1100
$\varepsilon_{f,\theta}/\varepsilon_f$	1.00	1.00	0.93	0.86	0.86	0.86	0.72	0.59	0.77	0.96	1.26	1.79

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Summary of design recommendations

- The reduction factors $f_{0.2p,\theta}/f_{0.2p}$ and $f_{u,\theta}/f_u$, and the $k_{2\%,\theta}$ coefficient, proposed by Gardner et al. for austenitic I group, match closely the experimental values for the new grade 1.4420 austenitic stainless steel.

- For ultimate strain and fracture strain, the agreement was less good, particularly at the lower temperatures. It should be noted that these reduction factors for the austenitic I group were based on a relatively small dataset, and it is recommended that these are reviewed in light of the newly available data.

- Regarding to the Young's modulus, further experimental investigations are required, since the obtained test data are rather scattered.

Summary of design recommendations

- For accurate, grade specific reduction factors, the values given in the table below are recommended.

Recommended grade specific reduction factors for EN 1.4420 stainless steel based on ‘smoothed’ mean test data

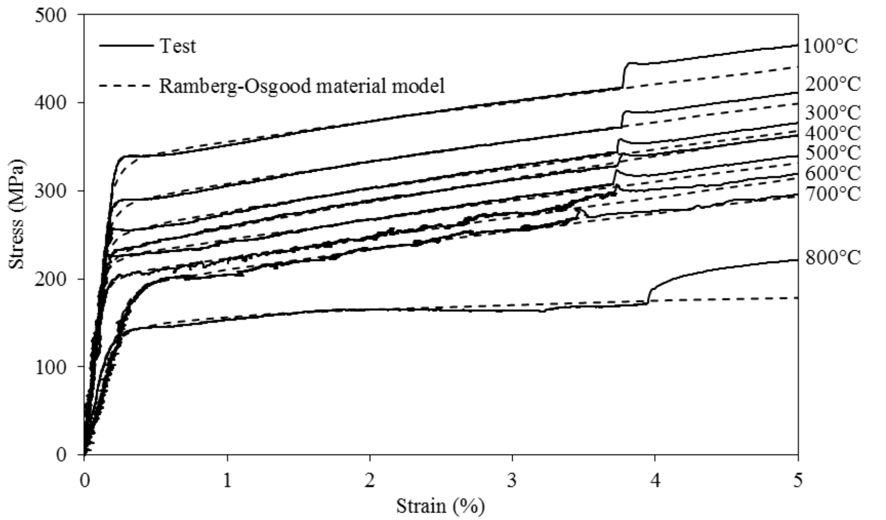
Reduction factor	Temperature θ (°C)											
	20	100	200	300	400	500	600	700	800	900	1000	1100
$f_{0.2p,\theta}/f_{0.2p}$	1.00	0.81	0.67	0.60	0.55	0.52	0.48	0.45	0.34	0.21	0.10	0.05
$f_{u,\theta}/f_u$	1.00	0.88	0.79	0.76	0.74	0.69	0.64	0.52	0.37	0.21	0.12	0.07
E_θ/E	–	–	–	–	–	–	–	–	–	–	–	–
$\varepsilon_{u,\theta}/\varepsilon_u$	1.00	1.00	1.00	1.00	1.00	1.00	0.74	0.58	0.53	0.49	0.54	0.59
$\varepsilon_{f,\theta}/\varepsilon_f$	1.00	1.00	0.93	0.86	0.86	0.86	0.72	0.59	0.77	0.96	1.26	1.79
$k_{2\%,\theta}$	0.20	0.20	0.20	0.20	0.20	0.20	0.23	0.27	0.15	0.04	0.01	0.01

Material modelling

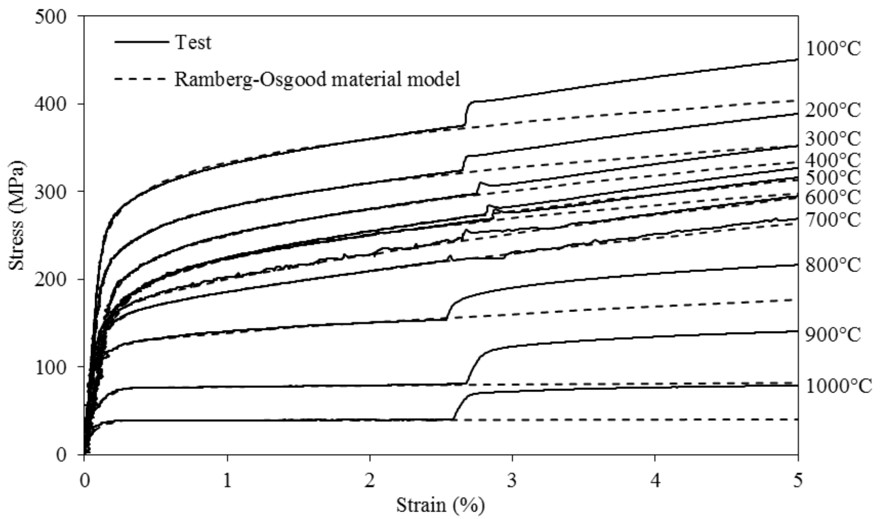
Material modelling

- The two-stage Ramberg–Osgood material model was used to describe the elevated temperature stress–strain response of the new grade 1.4420.
  - The first stage adopts the original Ramberg–Osgood expression, based on material properties measured at elevated temperature
  - The second stage passes through $f_{y,\theta}$, in accordance with the proposals by Gardner et al. in [19].

- Comparisons of the two-stage Ramberg–Osgood material model with the measured elevated temperature indicate excellent agreement.



Cold-rolled specimens



Hot-rolled specimens

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Conclusions

Conclusions

- 164 tensile coupon tests on the new grade 1.4420 austenitic stainless steel were conducted at elevated temperatures

- The reduction factors for the 0.2% proof strength and ultimate strength and the $k_{2\%,\theta}$ coefficient for the austenitic I group are applicable to grade 1.4420, while those for ultimate and fracture strains were less accurate.

- Grade specific elevated temperature reduction factors for all properties were provided for grade 1.4420.

- A two-stage Ramberg–Osgood material model can be used to capture the elevated temperature stress–strain response of the new stainless steel grade.

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