Austenitic Stainless Steels for Hydrogen Applications – Comparison of Properties based on the Chemical Composition

2024-06-27

Angela Philipp

angela.philipp@alleima.com

Alleima

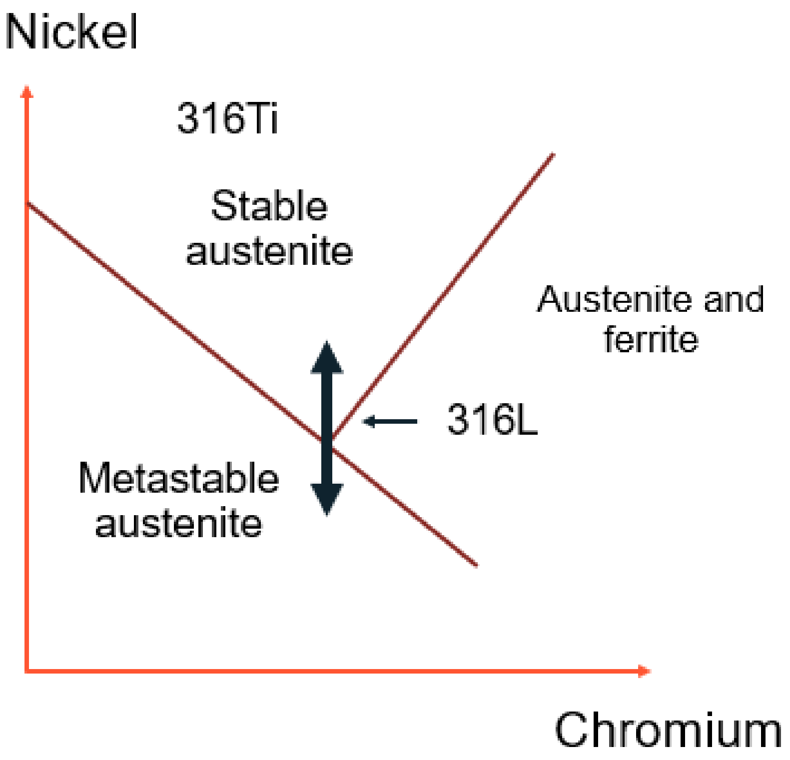
Hydrogen Tech World Conference 2024

Agenda

– Effect of hydrogen on austenitic stainless steels
– Hydrogen service automotive industry; SAE J2579
– Material tests and test results
– Key facts

Effect of hydrogen on austenitic alloys

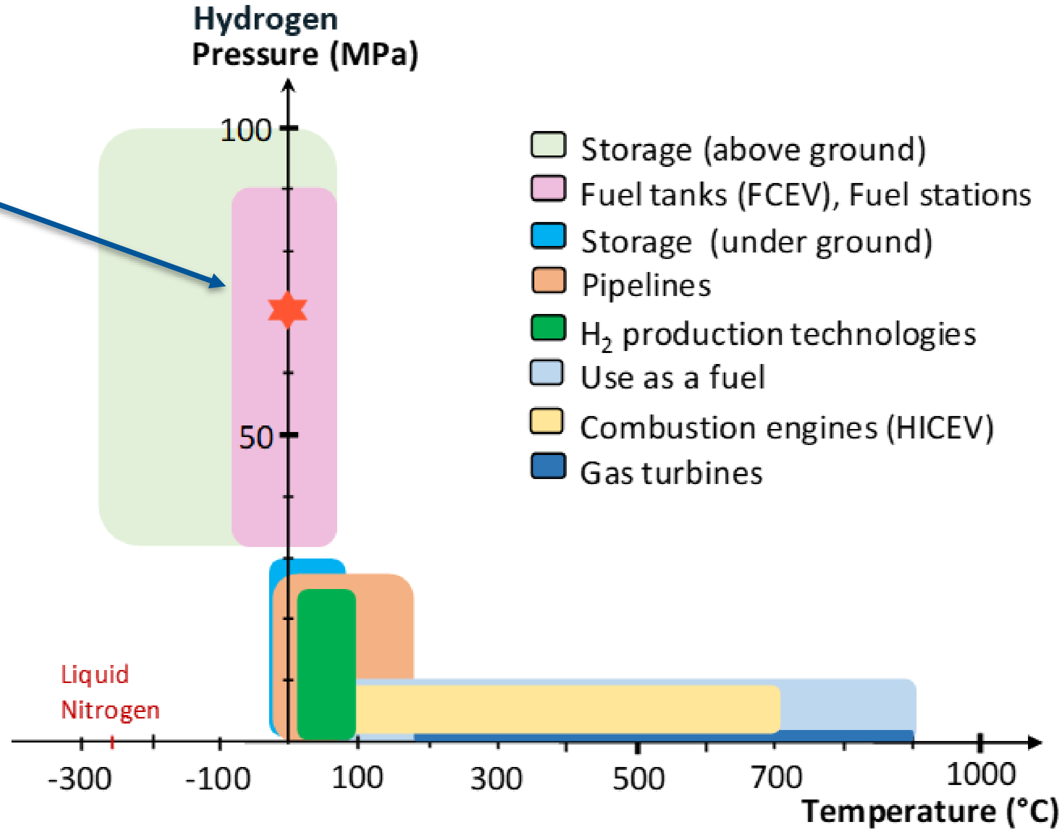
- 316L is a broad specification
- Nickel could be between **10%** and **14%**
- Stable austenite will not form brittle martensite when deformed
- The lower range of Ni in 316L is a metastable austenitic grade that can form deformation martensite at lower temperatures when deformed



Stainless steels for hydrogen service in the automotive industry

- Hydrogen gas systems for automotive applications
  - 35 or 70 MPa
  - Temperatures as low as -50°C

- For austenitic stainless steels for hydrogen vehicles, SAE J2579 stipulates testing:
  - SSRT, Slow Strain Rate Test
  - 125% of max. hydrogen gas pressure
  - At -45°C ± 5°C



Using the relative performance in Hydrogen and air is more conservative than SAE J2579

Property	$Rp_{0.2}$ [MPa]		Rm [MPa]		A [%]	Rm /$Rp_{0.2}$
Requirement	> Spec min.		> Spec min.		> 12	> 1.07
Grade	Spec. min.	H_2	Spec. min.	H_2	H_2	H_2
EN 1.4404	220	302	515	683	70.4	2.26
EN 1.4435	220	300	515	653	82.1	2.17

Thermal pre-charging and test evaluation

- **Pre-charging for 4 weeks, 13.9 MPa Hydrogen gas at 300°C**
- **Slow Strain Rate Test (SSRT) temperature – 40°C**
- Effect of hydrogen testing is largest below 0°C
- Comparison of relative ductility between testing in hydrogen gas vs innert environment
- Calculation ratio for reduction of area $R = \frac{Area\ reduction\ (hydrogen\ charged)}{Area\ reduction\ (unaffected)}$
- $R \approx 1$ indicates no embrittlement.
- $R = 0.9$ is an often-used limit when hydrogen embrittlement has not occured.

Chemistry austenitic stainless steels

Alloy	EN	C	Si	Mn	Cr	Ni	Mo	Ti	N	Ni_{eq}
316L/316	1.4404	0.01	0.39	1.8	16.6	**11.4**	2.0	-	0.06	**27.4**
316L/316	1.4435	0.02	0.37	1.5	17.2	**13.0**	2.6	-	0.05	**29.6**
316Ti	1.4571	0.04	0.45	1.3	16.9	**12.3**	2.1	0.41	0.05	**28.2**

- 316Ti = Ti stabilized grade with a Ni-content above 12%
  - The effect of Ti is unsure
  - 12% is an often-used limit for good performance in hydrogen

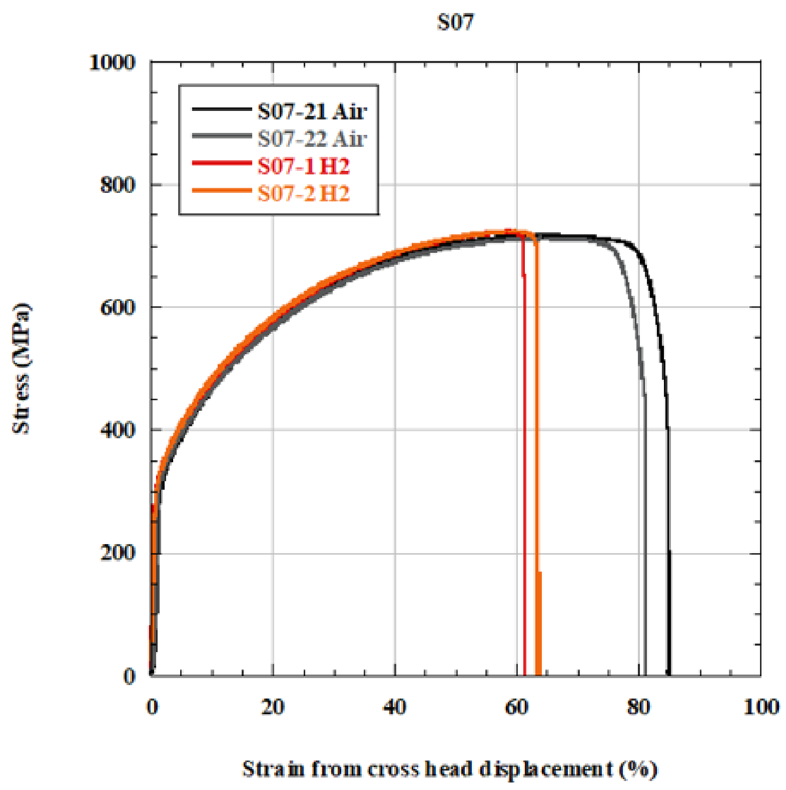
- All specimens were obtained from the solution-annealed and liquid-quenched material
  - Laboratory hot and cold rolled material from commercial heats

Tensile curves 1.4571 and 1.4404

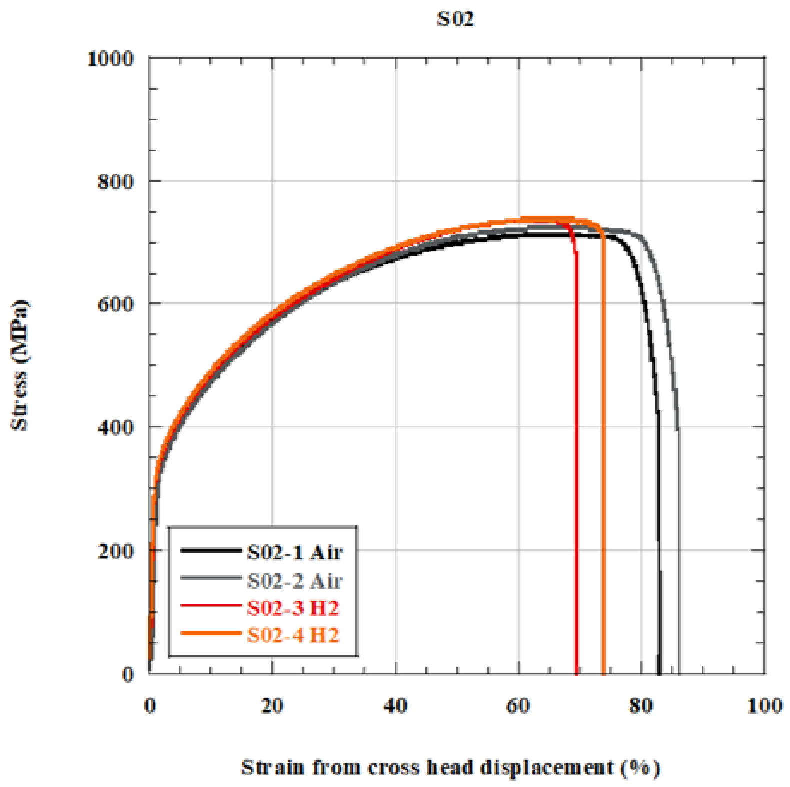
Black – air

Red – thermal pre-charged

1.4571



1.4404



Tensile test samples 1.4404 and 1.4571

For thermal pre-charged specimens, there is much less necking compared to the innert specimens

1.4404 – Inert

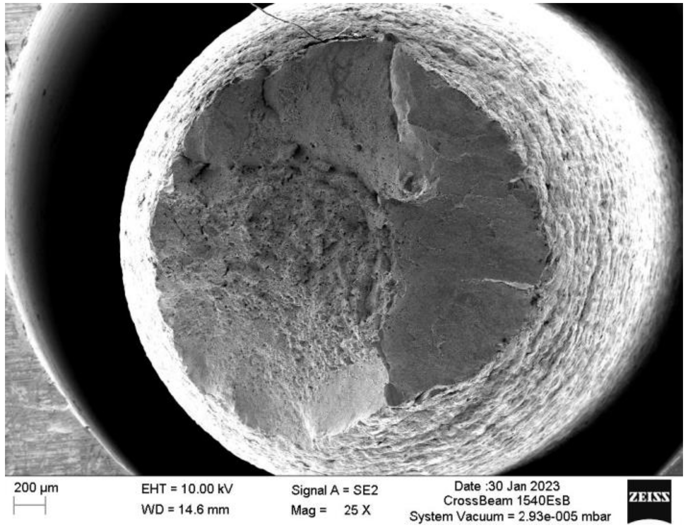
1.4404 – Charged

1.4571 – Inert

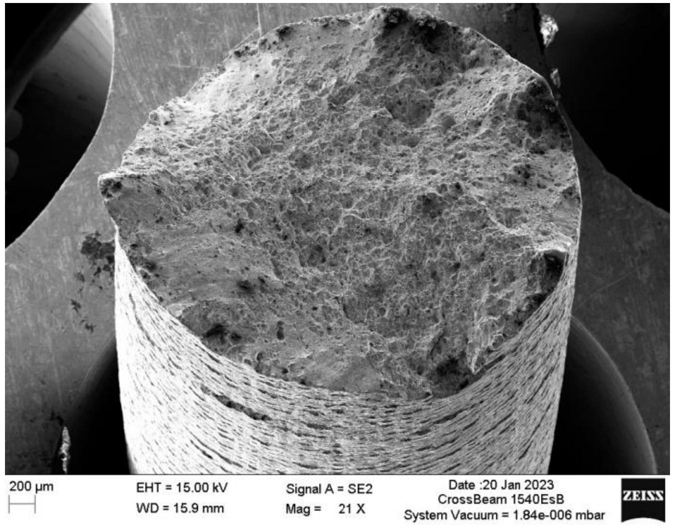
1.4571 - Charged

The less elongation for 1.4571 is visible

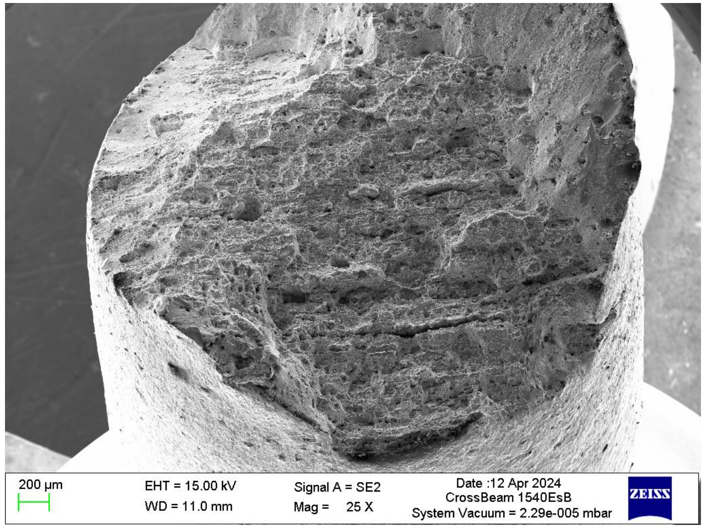
Scanning Electron Microscope (SEM)



EN 1.4435 – 13% Ni
Dimples, ductile fracture



EN 1.4404 – 11.4 % Ni
Area reduction is low. Near the sample edge, there are quasi-cleavage and intergranular cracking. In the middle, dimples are present.

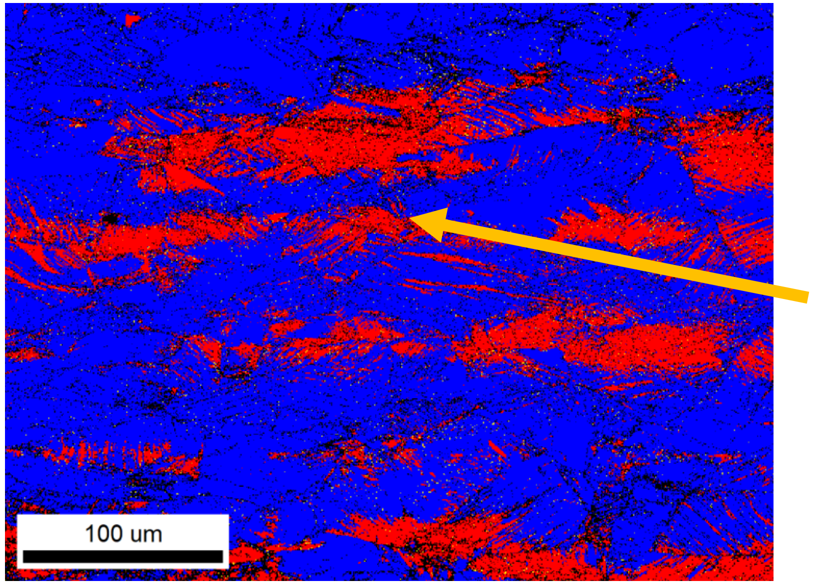


EN 1.4571 – 12.3 % Ni, 0.41 % Ti
Brittle Fracture

Electron Backscattering Diffraction(EBSD)

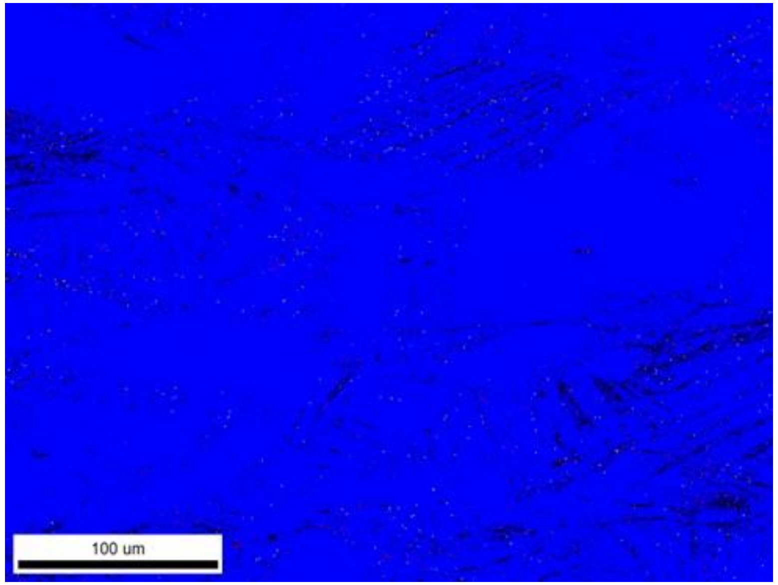
The low Ni version of 316L 1.4404
shows transformation to martensite

The high Ni version of 316L 1.4435
shows no transformation to martensite

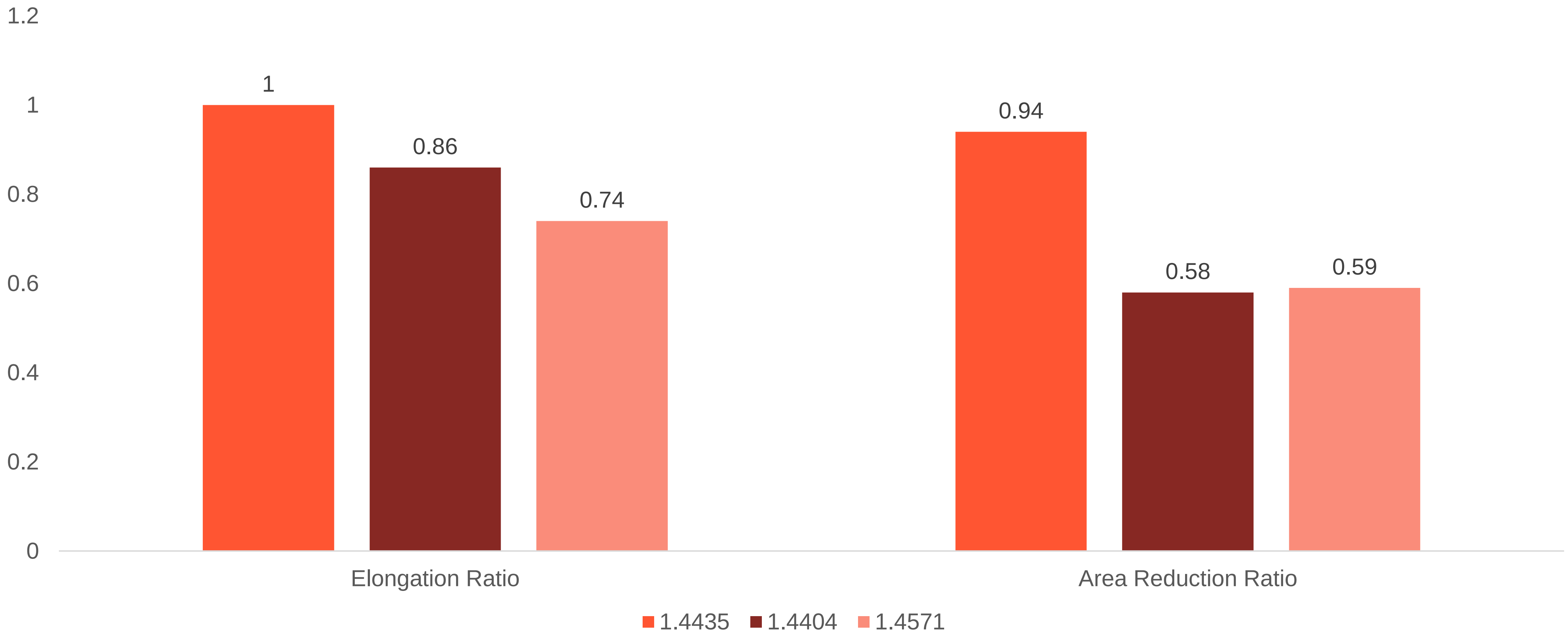


Blue – austenite

Red - martensite

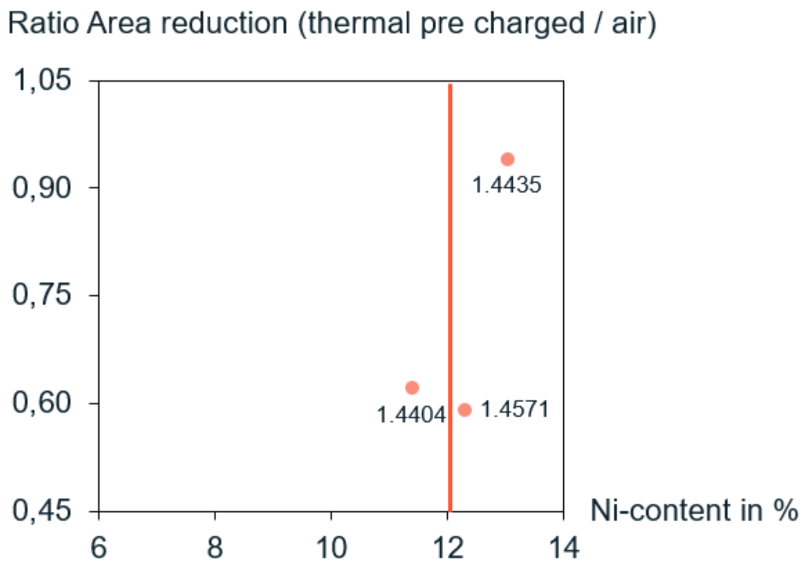


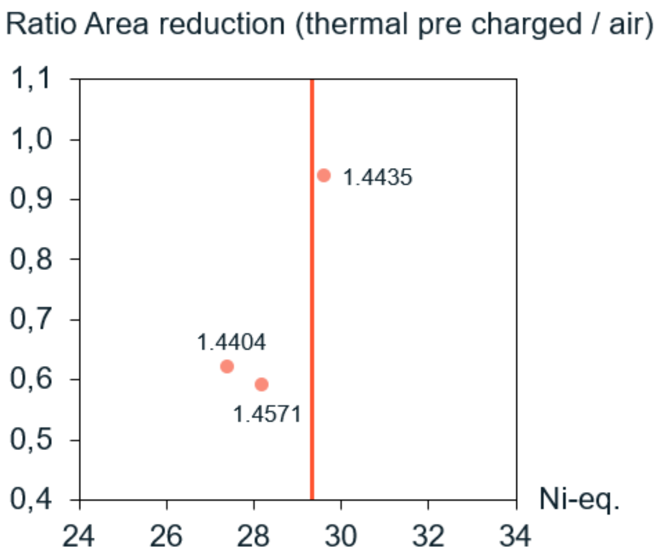
Results thermal pre-charging reference alloys



Nickel Equivalent Concept

- The “Ni-equivalent” of a grade can also be used for grades in H_2 environment
  - Ni_{eq} = Ni + 12.93×C + 1.11×Mn + 0.72×Cr + 0.88×Mo - 0.27×Si + 7.55×N
  - Ni_{eq} ≥ 29.5 has been a general guideline.
  - The concept of Ni_{eq} seems to fit for the grade 1.4571 (28.2)
  - The Ni content of 12.3% implies a good behaviour for 1.4571





Test results

- The test results show that 1.4435 does not suffer ductility loss after exposure to hydrogen.
  - High nickel content and high Ni-equivalent.

- Both 1.4404 and 1.4571 show severe ductility loss after exposure to hydrogen.
  - 1.4571 shows slightly larger effects of hydrogen than 1.4404 despite its high Ni content and higher Ni_{eq}.
    - Can titanium play a role here?

- Specifying a minimum Ni content for pressure-bearing parts is recommended for hydrogen applications.
  - Ni ≥ 12.5%
  - 1.4435 has Ni = 13%, depending on the fabricator

Key Facts

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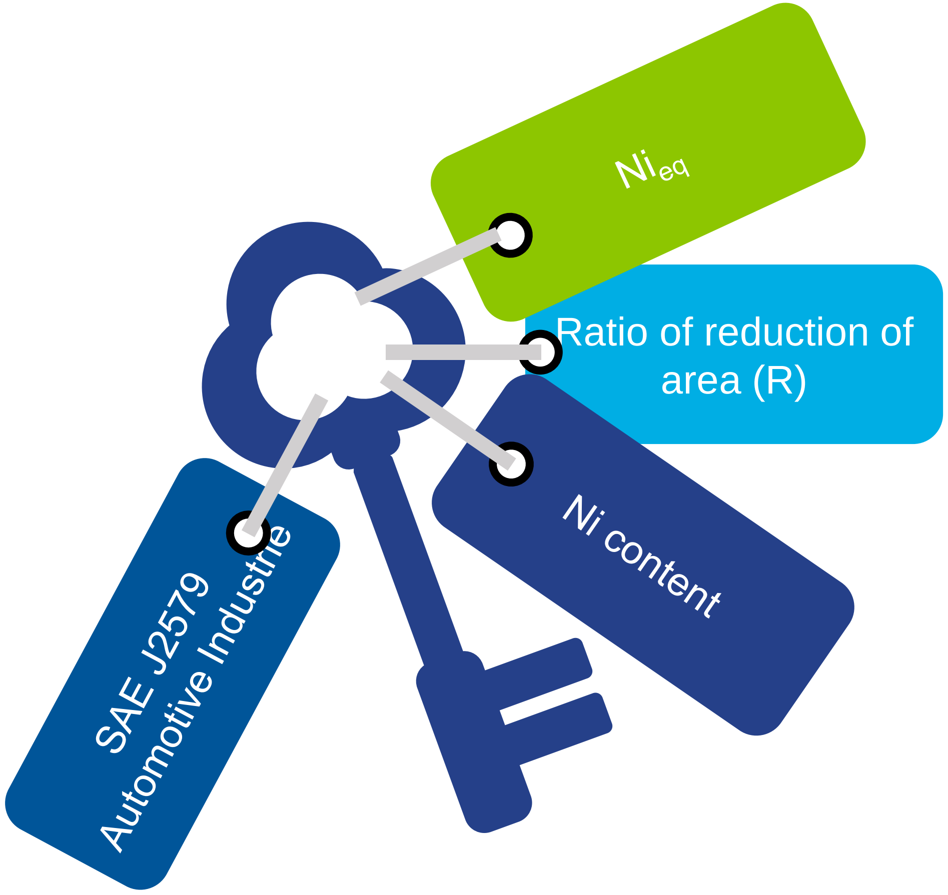

- Relative performance in H_2 and air is more conservative than SAE J2579
- The Ni content should be ≥ 12,5 %
- R=1 indicates no embrittlement
R=0.9 is an often used limit when hydrogen embrittlement has not occurred
- Ni-equivalent ≥ 29.5