Ausferrite stability in thin sections

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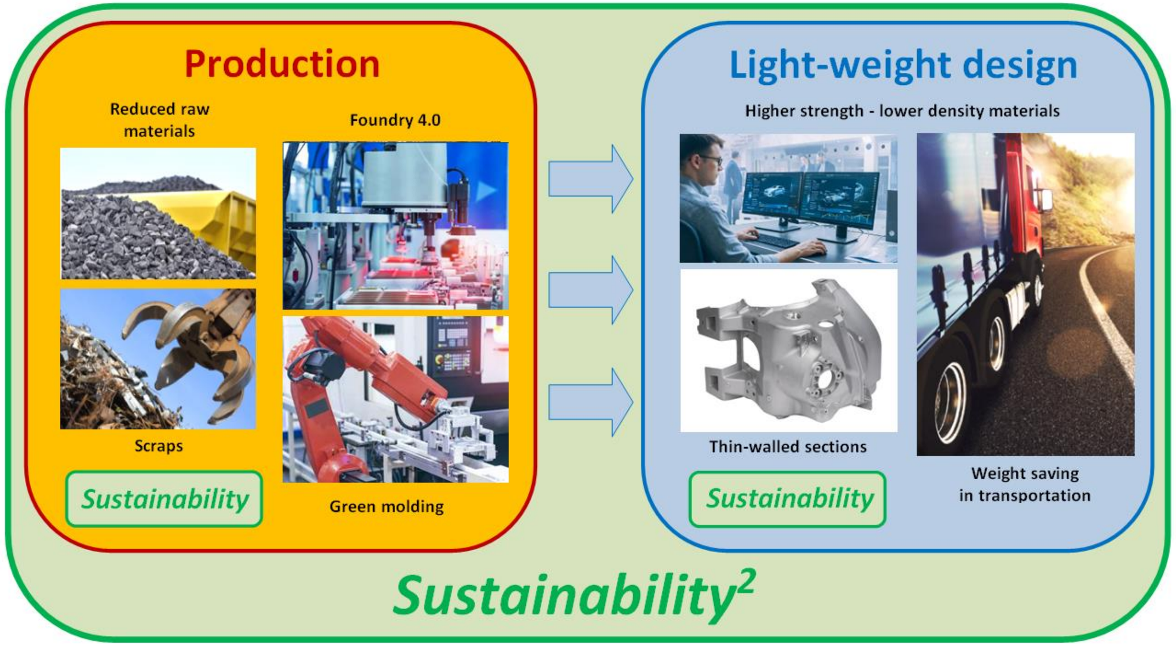
Contents

- Austempered Ductile Irons (ADIs)
- Stability of ausferrite
- XRD investigations
- Dorazil method for mechanically stability investigation
- Austenitic Ductile Irons (Ni-Resist)

NetCastPL4.0 project

https://netcastpl4-0.agh.edu.pl/about-project/

- The project targets thin-sections of high-quality ductile irons and Al-Cu alloys for the Green Foundry Challenge in Poland

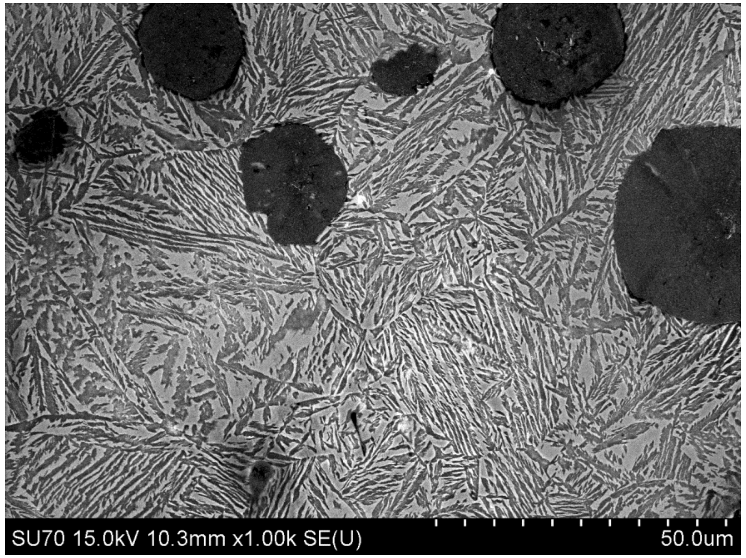


Thin-section castings

- **ADIs**
- **Si-Mo ductile irons**
- **AlCu alloys**

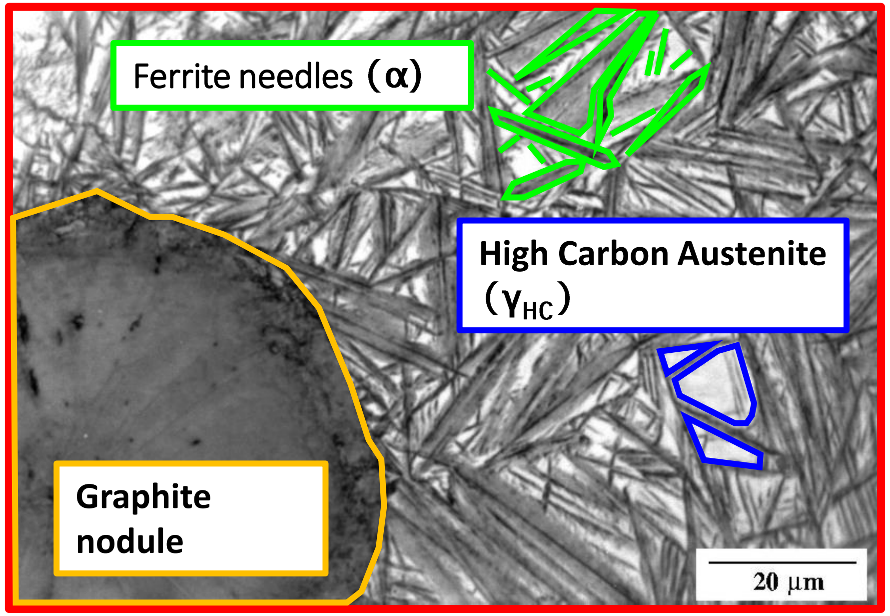
Austempered Ductile Irons (ADIs)

- Austempered Ductile Irons have an auferritic structure that confers high strength and toughness comparable to quenched and tempered steels.
- They have 10-12% lower density than steels.
- ADIs are alternative to steels in many industrial applications
- The lower hardness grades (ADI JS 800-10, and 1050-6) have good fatigue properties, so they can be used in shafts, hubs, suspension arms, steering knuckle, railway and defence applications.
- The higher hardness grades (ADI JS 1400-1, HBW450 and $ADIWR_{PAT}$) are abrasive wear resistant, so they can be used in mining and other wear applications.



Austempered Ductile Irons (ADIs)

- Ausferritic microstructure comes into Widmanstätten acicular structure consisting of ferritic bainite plates (α) and austenite reach in C (γ_{HC})



γ_{HC}
Carbon-stabilized Austenite (metastable)
HC = High Carbon

α
Hard Bainitic acicular ferrite

Ausferrite matrix

- Ausferritic microstructure behavior depends on the austenite stability, in turn depending on the process applied.

https://www.phase-trans.msm.cam.ac.uk/2001/adi/adimore.html

Austempered Ductile Irons (ADIs)

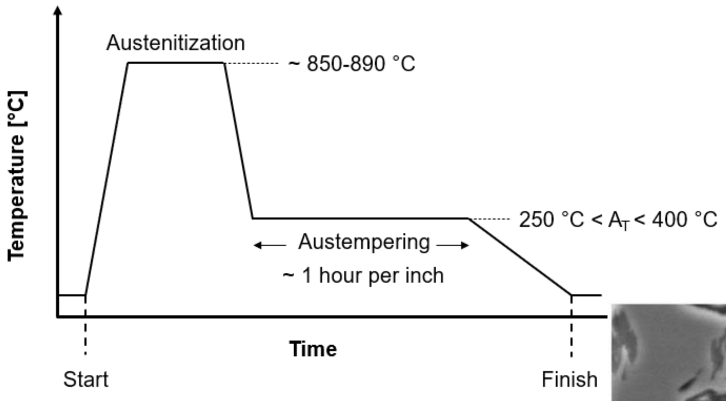
Ausferrite formation after two steps heat treatment of conventional ductile iron:

1. austenitization (850-890°C);
2. then quenching in salt bath (250-400°C)

for the isothermal austempering transformation (Stage II):

$$\gamma \rightarrow \alpha + \gamma_{HC}$$

3. cooling to room temperature.



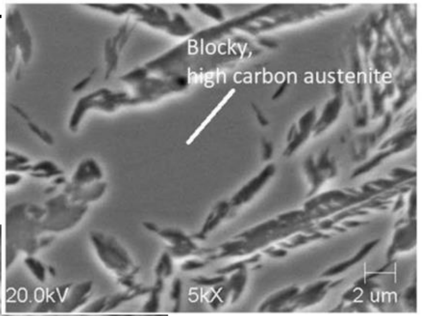
a. An **<u>optimal time</u>** for Stage II for having the highest volume fraction of stable γ_{HC};

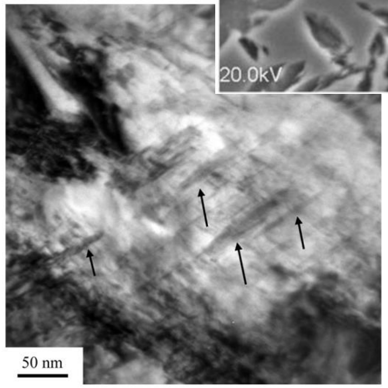
b. for shorter austempering times (Stage I) - blocky γ_{HC} results thermal and mechanical unstable after cooling → **<u>embrittlement of ADIs</u>**;

c. for longer austempering times (Stage III) - γ_{HC} decomposes according to:

$$\gamma_{HC} \rightarrow \alpha + \varepsilon'$$

ε' is a metastable carbide Fe-C → **<u>embrittlement of ADIs</u>**.

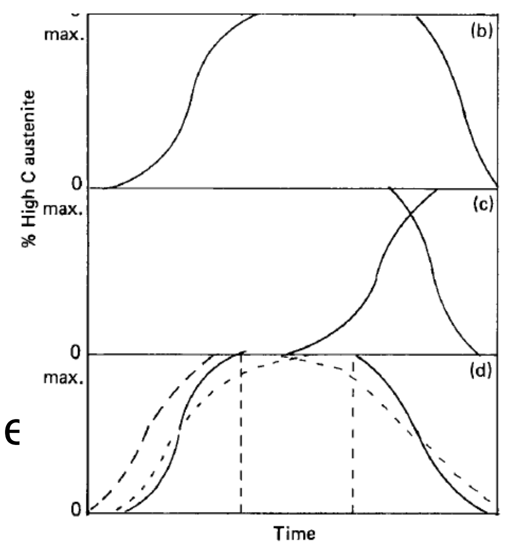


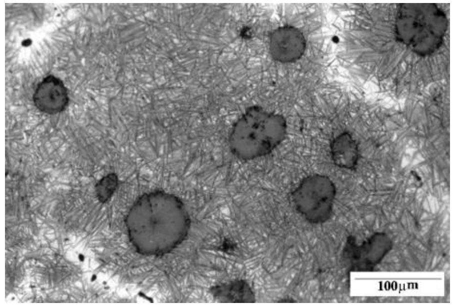


Donnini R.; Fabrizi A.; Bonollo F.; Zanardi F.; Angella G., *Assessment of the Microstructure Evolution of an Austempered Ductile Iron During Austempering Process Through Strain Hardening Analysis*, **Metals and Materials International** (Online), 2017, 23(5), pp. 855–864

Stability of ausferrite

- For the foundry a proper austempering process is even more difficult because of technological challenges:
  - Hardenability depends on the ratio (casting mass):(salt bath mass), turbulence and heat transfer in the salt bath;
  - Hardenability depends on thickness section (constant section is better);
  - Hardenability depends on chemical composition:
    a. Higher alloying improve hardenability;
    b. However, higher alloying causes **<u>segregations</u>**, requiring different optimized austempering time in different positions of the component
    → competence, expertise, robust processes.

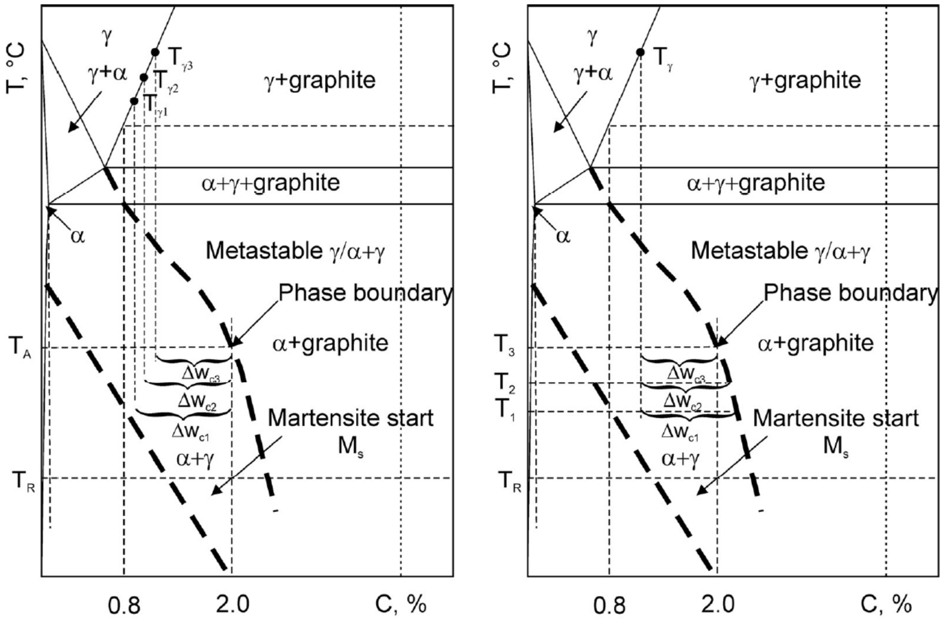




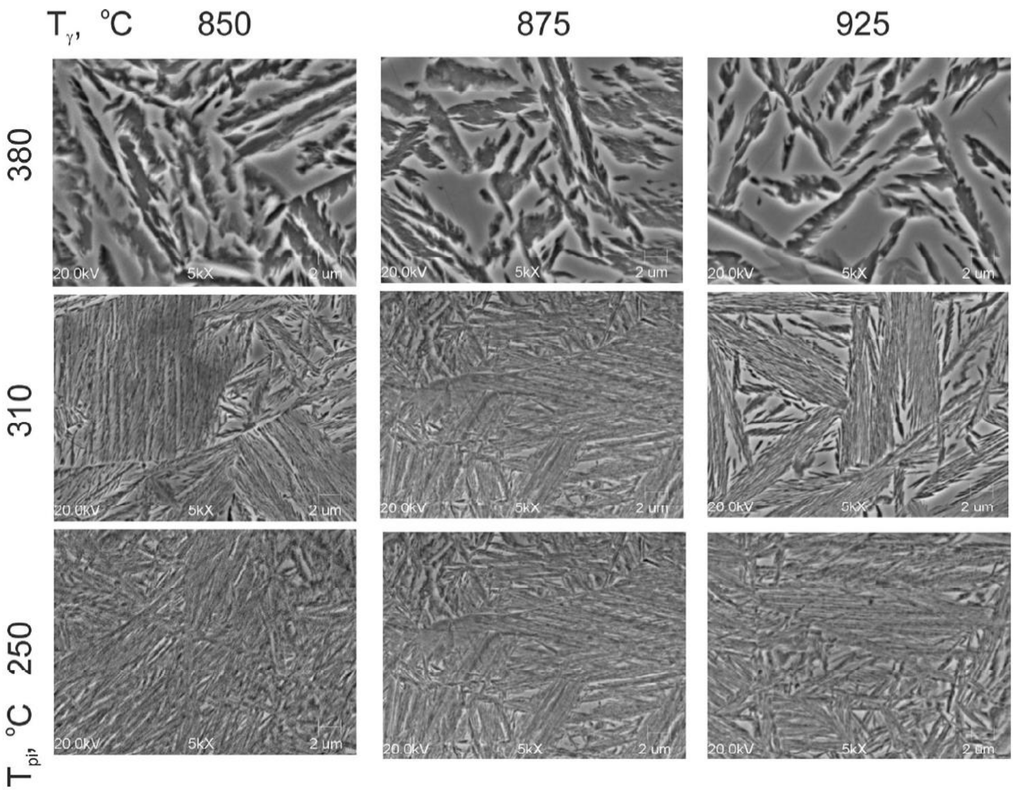
https://www.phase-trans.msm.cam.ac.uk/2001/adi/adimore.html

Stability of ausferrite

Stability comes from austempering conditions: austempering driving force depends on chemistry, austenitization temperature, austempering temperature and time.



Górny M., Gondek Ł., Tyrała E., Angella G., Kawalec M. , *Structural Homogeneity and thermal stability of Austempered Ductile Iron*, **Metal Mater Trans A**, Vol. 52A (2021), pp. 2021-2227

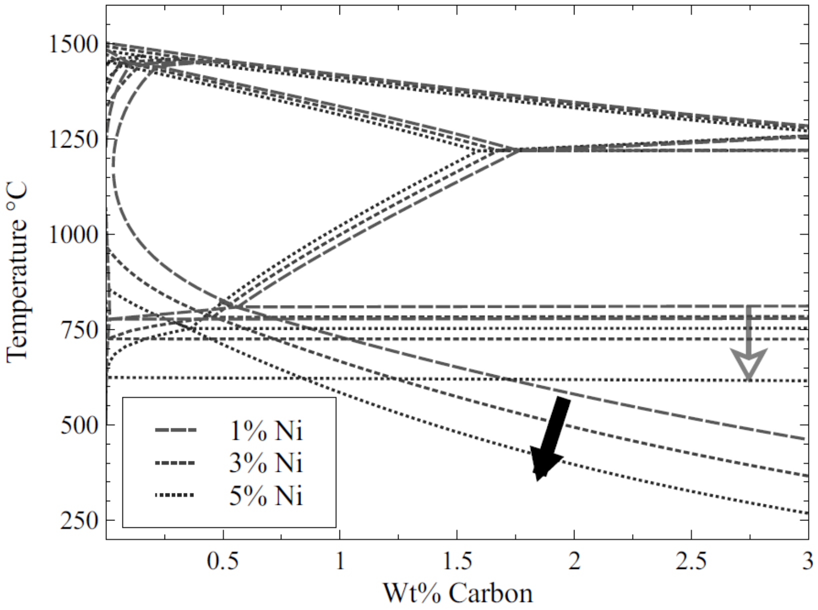


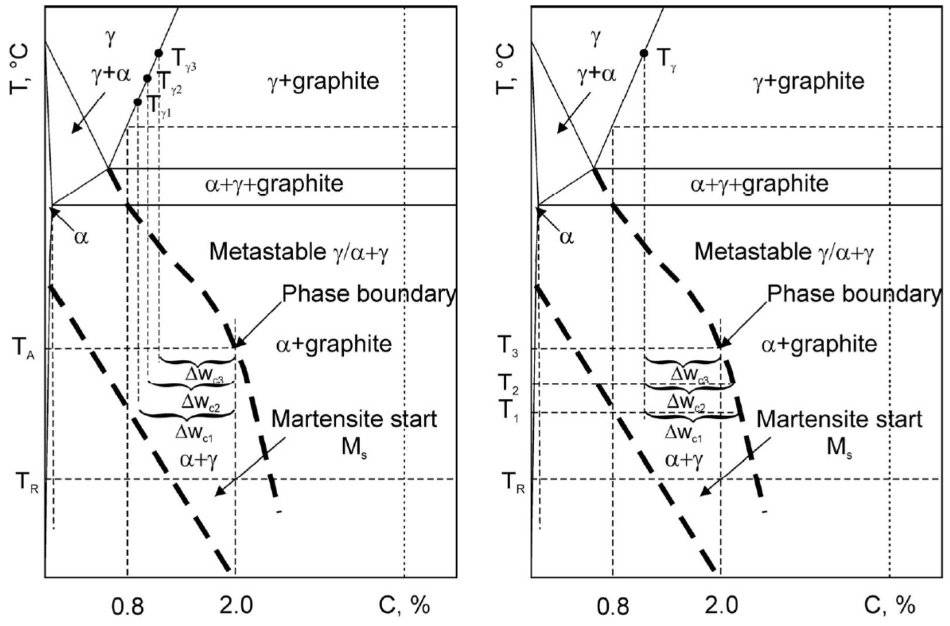
Stability of ausferrite

Effects of chemistry: the nickel.

The gray arrow indicates a strong downward shift in the minimum equilibrium temperature of austenite;

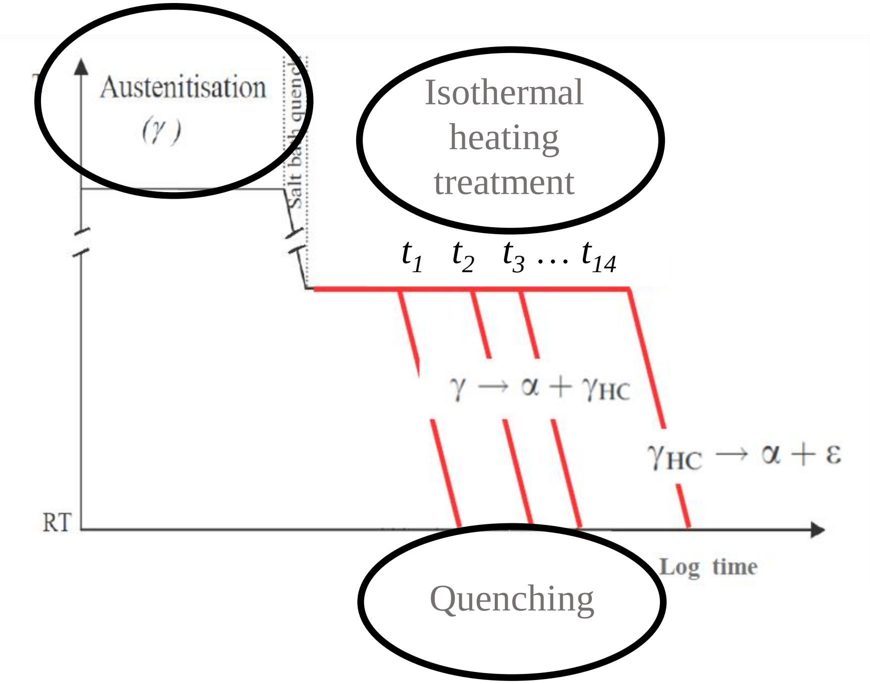
The black arrow shows a strong decrease in the temperature of the metastable austenite/ferrite boundary.

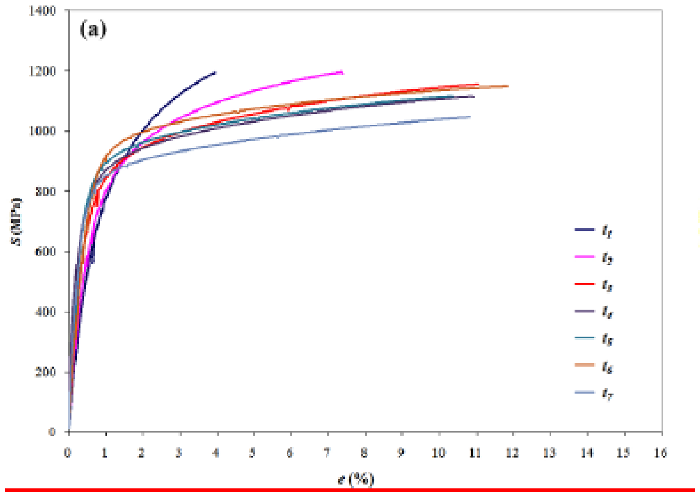


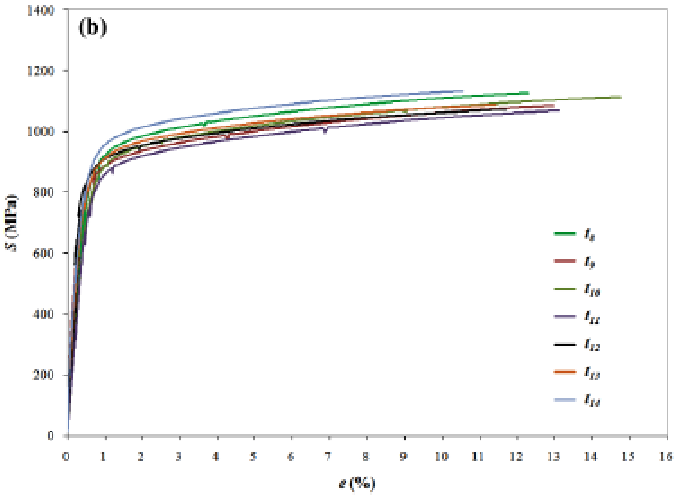


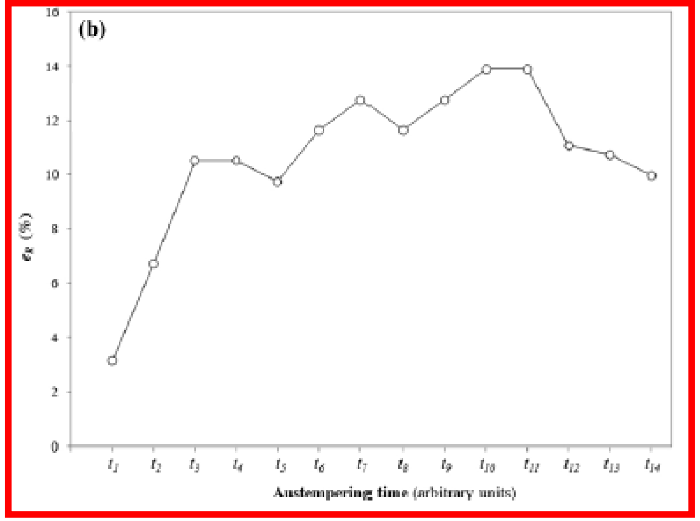
Dorazil method for mechanical stability investigation

Dorazil method to measure optimal time is based on tensile ductility (e_R).









- Difficult to identify an optimal austempering time;
- Fracture depends also on local defects;
- So, ductility is sensitive to fluctuations.

Refinement of Dorazil method

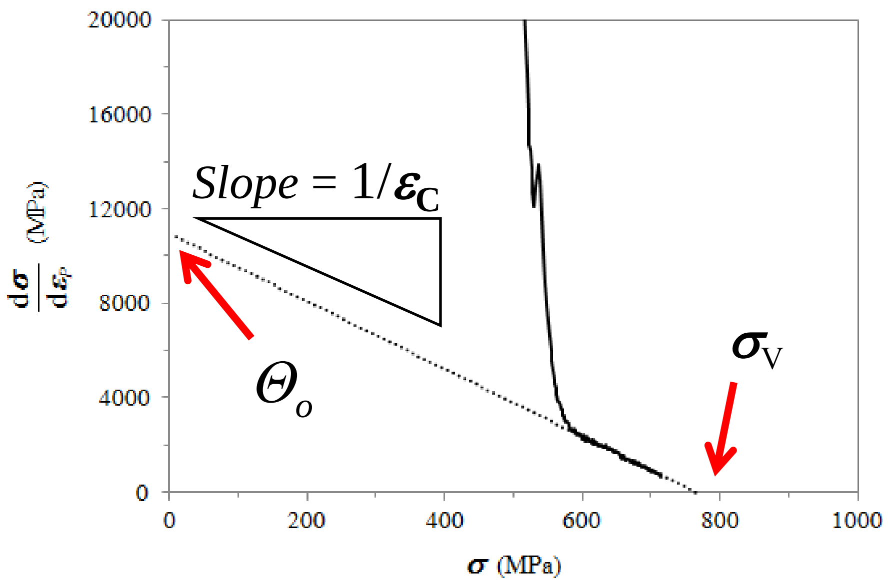
Voce parameters are found through **strain hardening analysis**, i.e. by considering the differential form of the Voce equation:

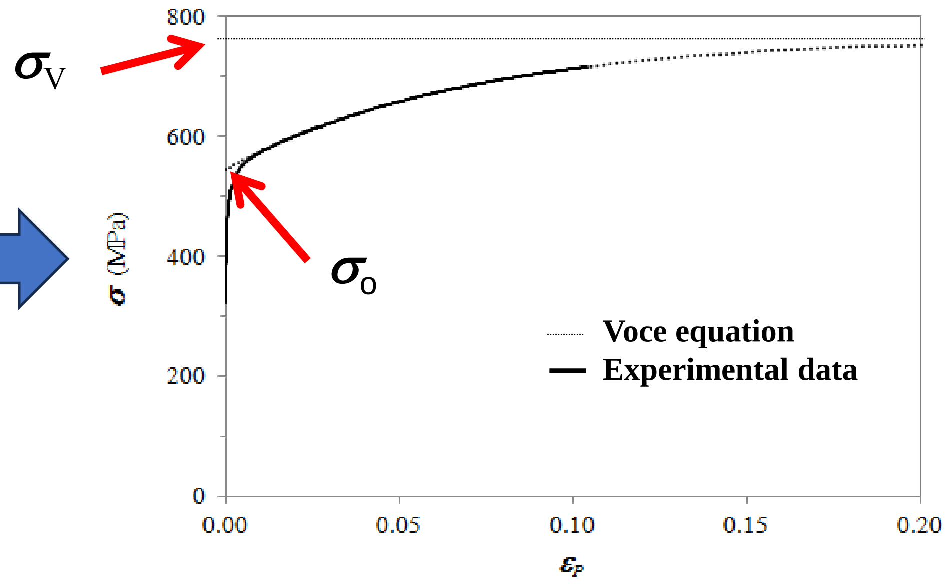
$$\frac{d\sigma}{d\varepsilon} = \Theta_o - \frac{1}{\varepsilon_C} \cdot \sigma$$

Physical bases

Θ_o = athermal dislocation storage rate ($1/\lambda$)

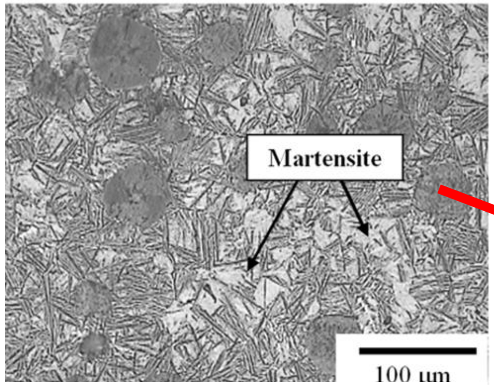
$1/\varepsilon_C$ = dynamic recovery term

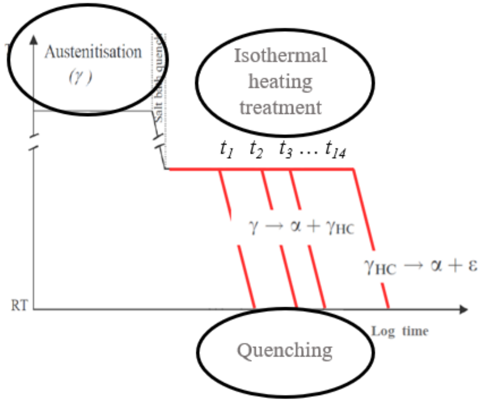




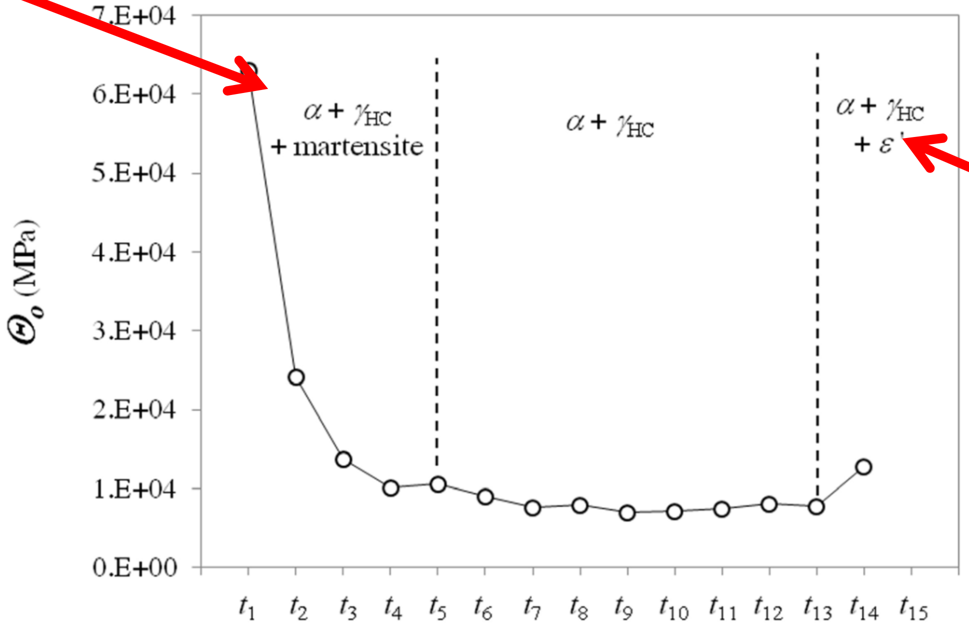
Refinement of Dorazil method

Considering Θ_o as a function of austempering time a through-like behaviour is shown:





$$\frac{d\sigma}{d\varepsilon} = \Theta_o - \frac{1}{\varepsilon_C} \cdot \sigma$$



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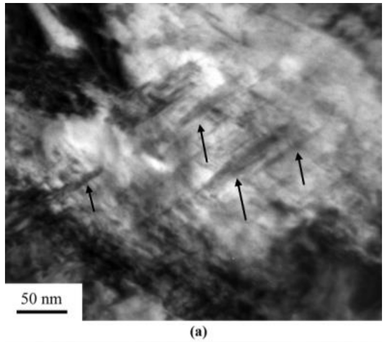
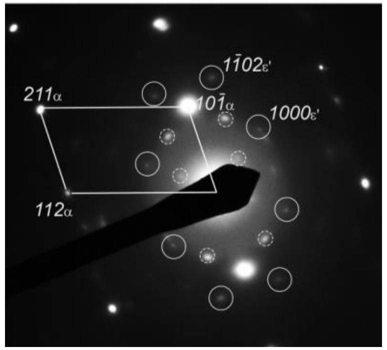


Carbide ε' needles



HCP - $P6_322$

a = 0.275 nm

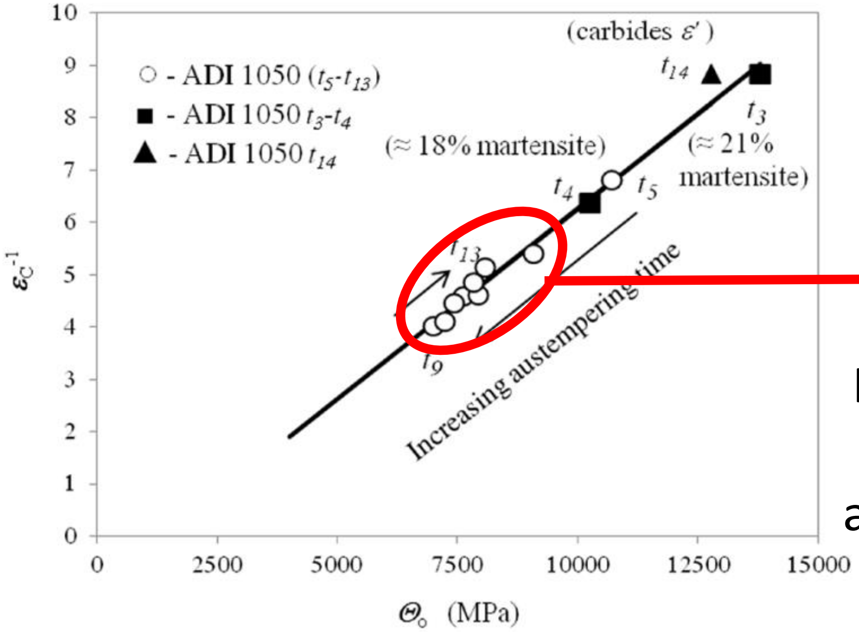
c = 0.435 nm

Refinement of Dorazil method

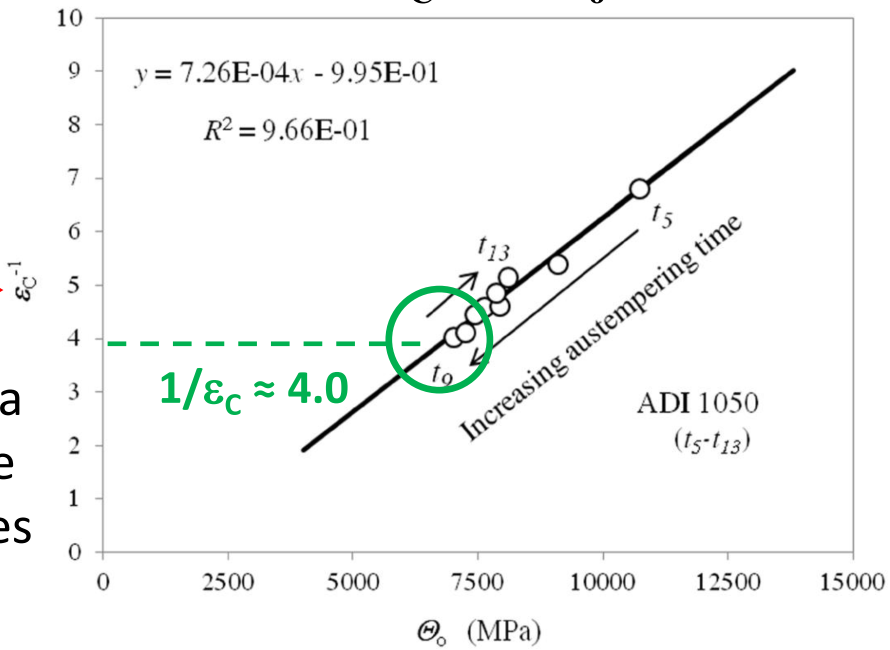
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} = \Theta_o - \frac{1}{\varepsilon_C} \cdot \sigma$$

Matrix Assessment Diagram (MAD):

$1/\varepsilon_C$ vs. Θ_o



If we zoom on data from intermediate austempering times $t_5 - t_{12}$

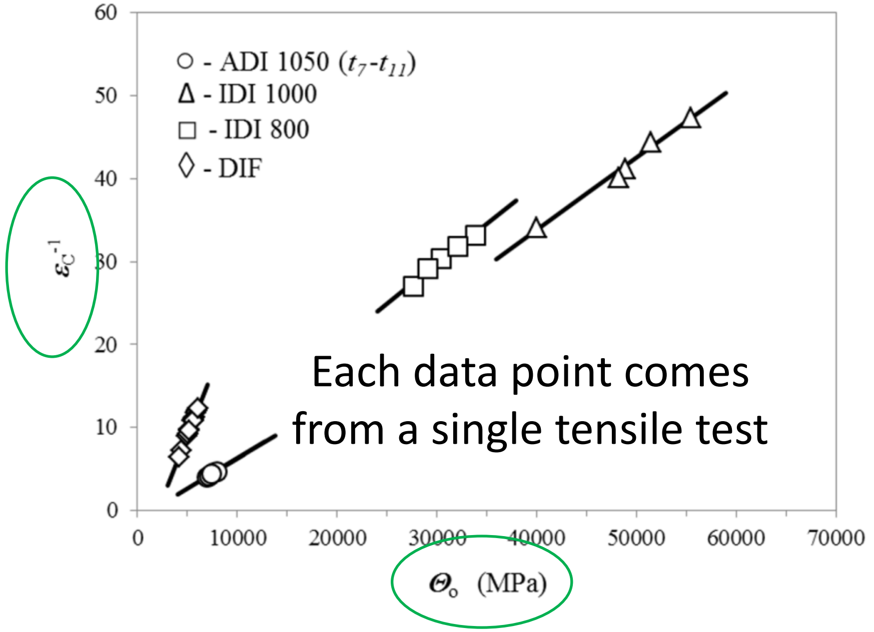


The representative data points move along a single line, identifying a minimum for $t = t_9$, the <u>**optimal austempering condition time**</u>.

Best ADI: $1/\varepsilon_C \approx 4.0$

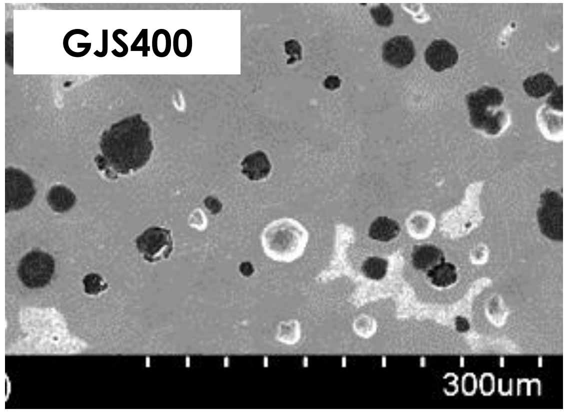
Refinement of Dorazil method

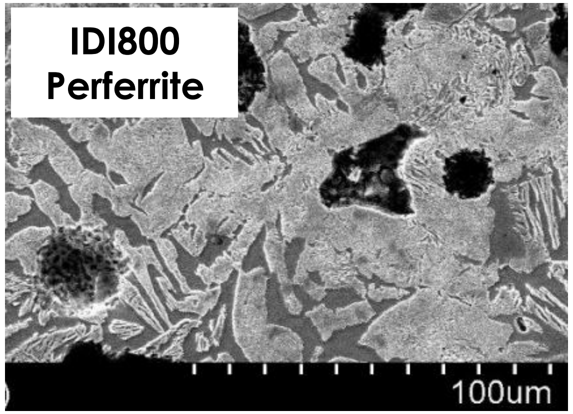
$$\frac{d\sigma}{d\varepsilon} = \Theta_o - \frac{1}{\varepsilon_C} \cdot \sigma$$

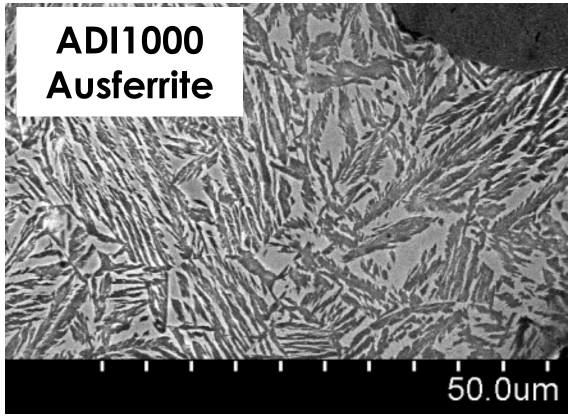


Voce tensile data from **different chemical** composition samples and **different heat treatments** lay on distinct lines.

Best ADI:	**$1/\varepsilon_C \approx 4.0$**
GJS 400:	$1/\varepsilon_C = 10\text{-}15$
IDI 800:	$1/\varepsilon_C = 25\text{-}35$
IDI 1000:	$1/\varepsilon_C = 35\text{-}50$







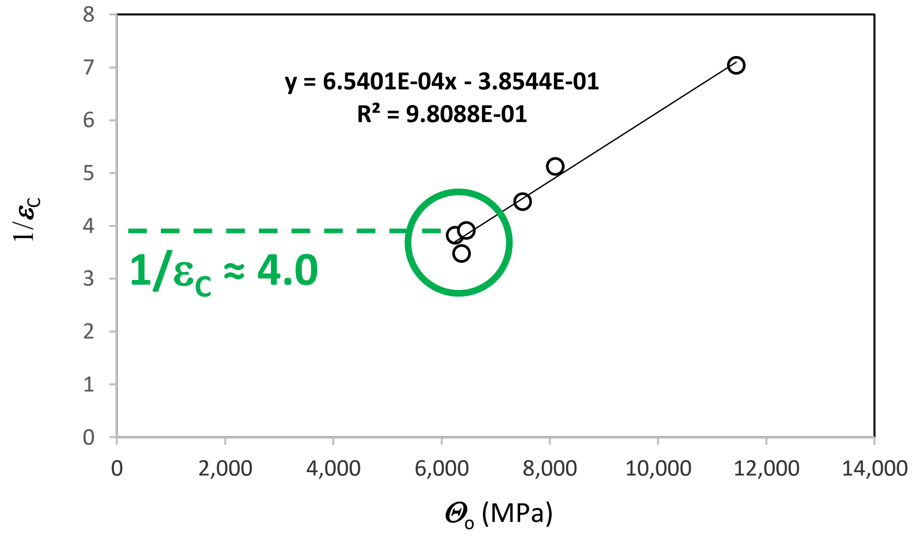
- R. Donnini, F. Vettore, F. Zanardi, G. Angella. ***Materials Science Forum***, 925, 2017, pp. 342-349.
- G. Angella, F. Zanardi. ***Metals,*** 2019, 9(8), 837.

Refinement of Dorazil method

Ni ≈ 2.5wt.%

Different $T\gamma$ values

T_{Aust} = 370°C



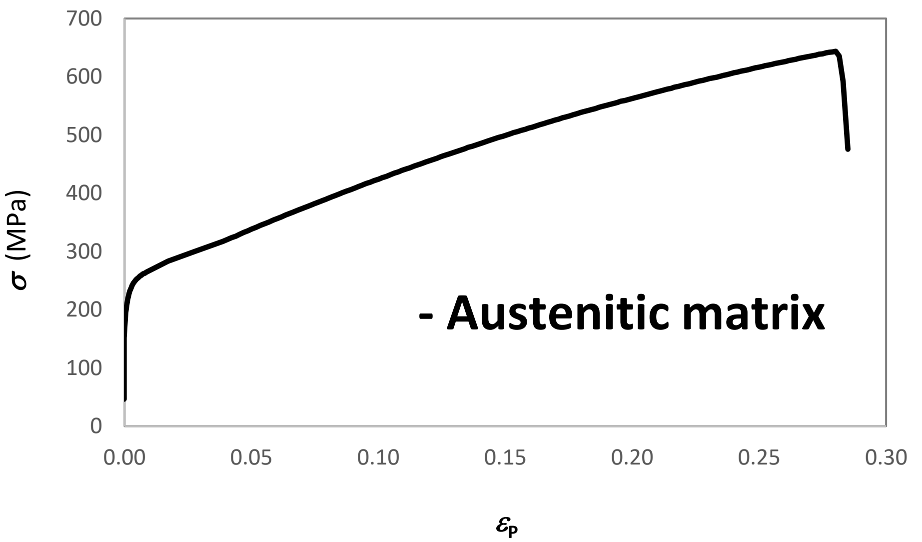
Best ADI: **$1/\varepsilon_C \approx 4.0$**

Higher **$1/\varepsilon_C$** :
unstable ausferrite
or
Fe-Ce carbides

The representative data points move along a single line, identifying the **<u>optimal austenitization conditions</u>** with the minima.

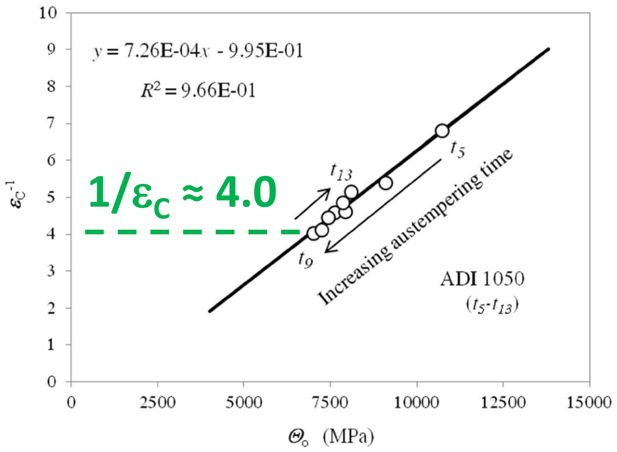
The most mechanically “stable” unstable austenite: the lowest $1/\varepsilon_C$

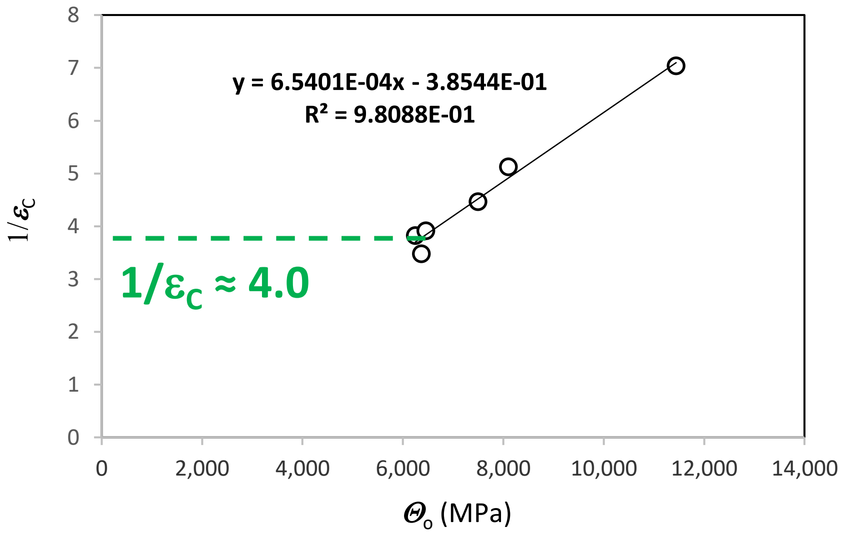
Nickel resist DI (21%wt. Ni)



Austenitic matrix: $1/\varepsilon_C \approx 3.1$

Best ADI : $1/\varepsilon_C \approx 4.0$





In **undertreated**/unstable ausferrite, TRIP effect increases strain hardening because of martensite transformation ($1/\varepsilon_C > 4$)

In **overtreated** ausferrite strain hardening is increased by Fe-C carbides ($1/\varepsilon_C > 4$).

The **best** austenitization/austempering treatment produces the most “stable” metastable austenite (**$1/\varepsilon_C$ as low as possible**).

Thank you!