



# Experimental investigation of ultra-fast heating annealing cycles on Ti-stabilized IF steels

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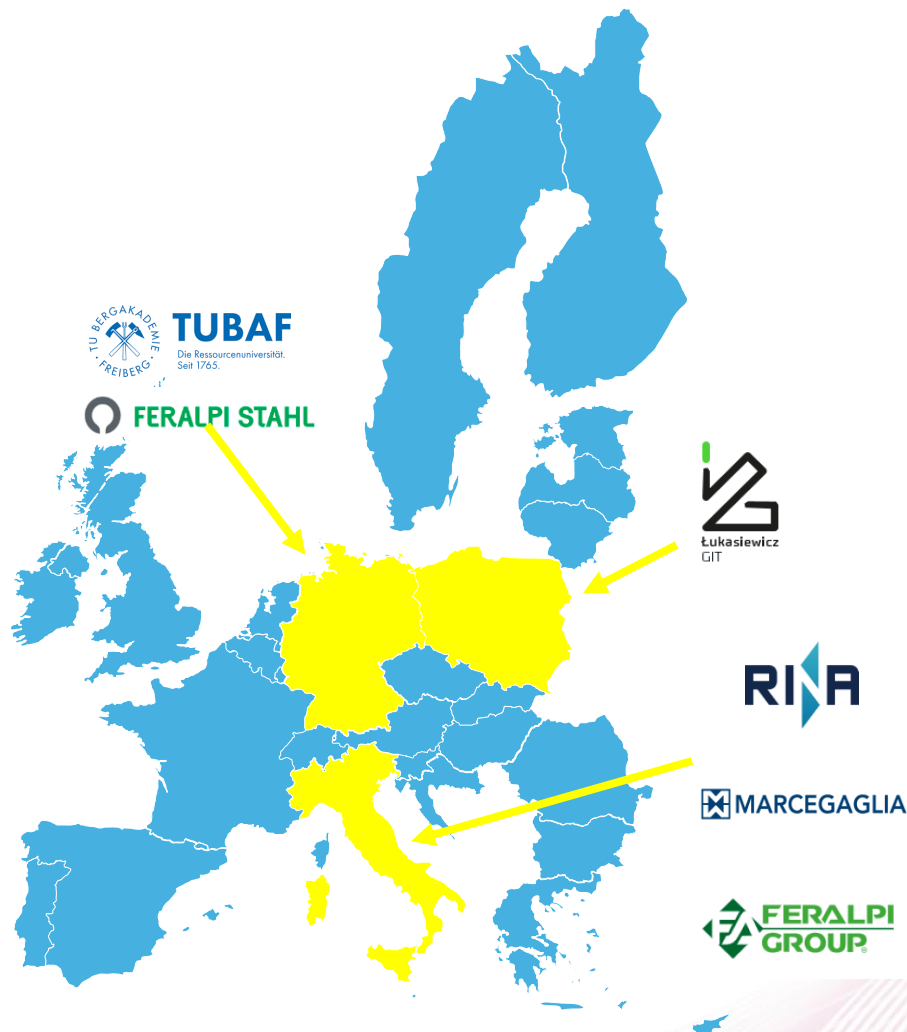
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il futuro tra ricerca e innovazione

## MODIPLANT project (1)



## MODIPLANT

Modular hybrid technology in the steel plant production

- Coordinator: RINA-CSM
- Call: RFCS-2022-CSP
- Start date: 01/03/2023
- End date: 29/02/2028
- Total costs: €14.390.797,35

## MODIPLANT project (2)

MODIPLANT aims to demonstrate the industrial feasibility of Renewable Energy Source (RES)-based electrification of downstream steel heating processes.

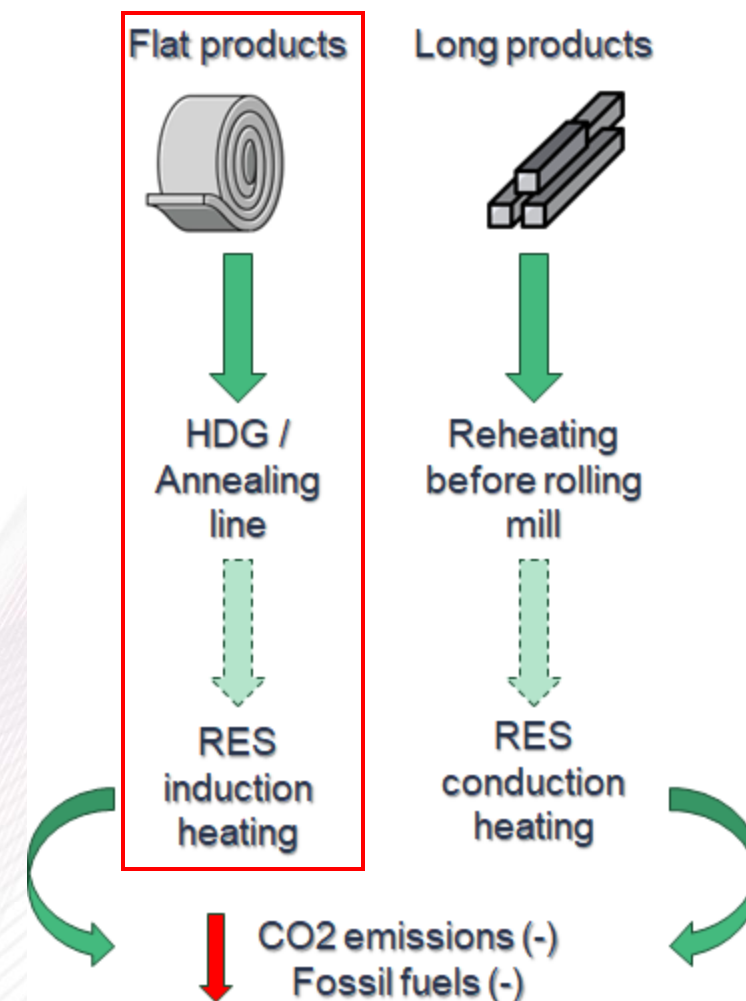
MODIPLANT targets a significant reduction of CO<sub>2</sub> emissions while preserving productivity, product quality, and economic viability.

MODIPLANT has a hybrid and modular electrification strategy, combining mature and emerging electrical heating technologies within real industrial constraints.

*“Uncertainty on metallurgical/surface effects of fast electrical heating”*

- Electrical heating can imply very high heating rates ( $>100$  °C/s) compared to conventional furnaces
- Industrial concerns related to:
  - Temperature uniformity
  - Microstructural evolution
  - Final mechanical and surface properties

### Downstream steel heating processes

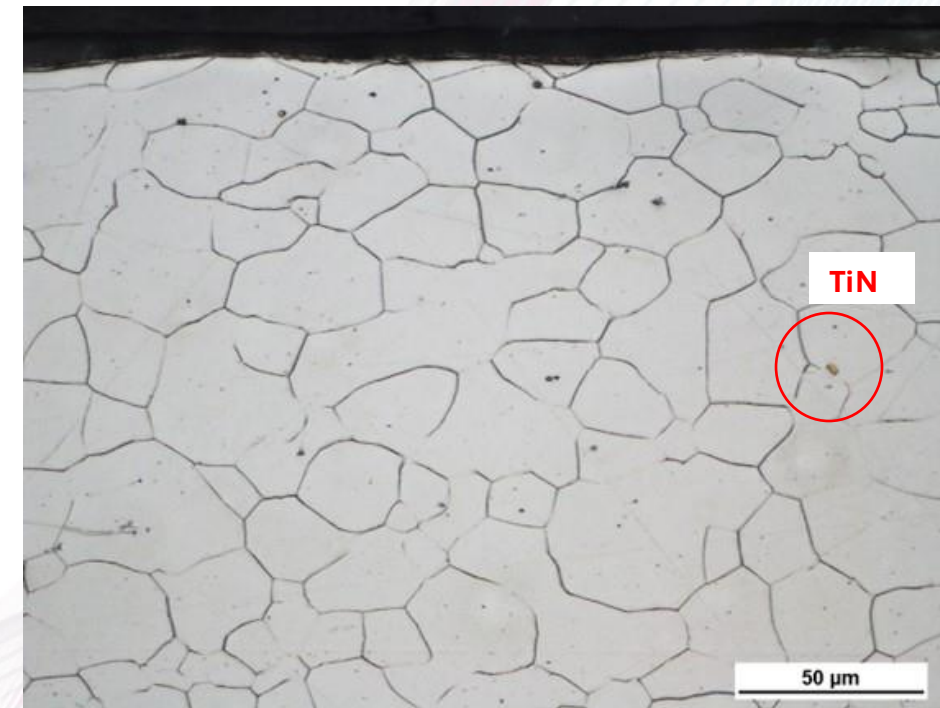


## Introduction: Interstitial Free (IF) steels

- Contain very low levels of C and N (typically 30-40 ppm).
- Contain elements as Ti or Nb, forming carbides and nitrides (stabilizers), to obtain a matrix completely free from interstitial elements.
- Typically processed through continuous annealing.
- Tensile properties: low YS (~140 MPa), high elongation ( $\geq 41\%$ ),  $r \geq 2$ .
- Applications: extra-deep drawing steel sheets.

$$Ti_{(STAB)} = 4C + 3.42N + 1.5S$$

$$Ti^* = Ti_{total} = (4C + 3.42N + 1.5S)$$

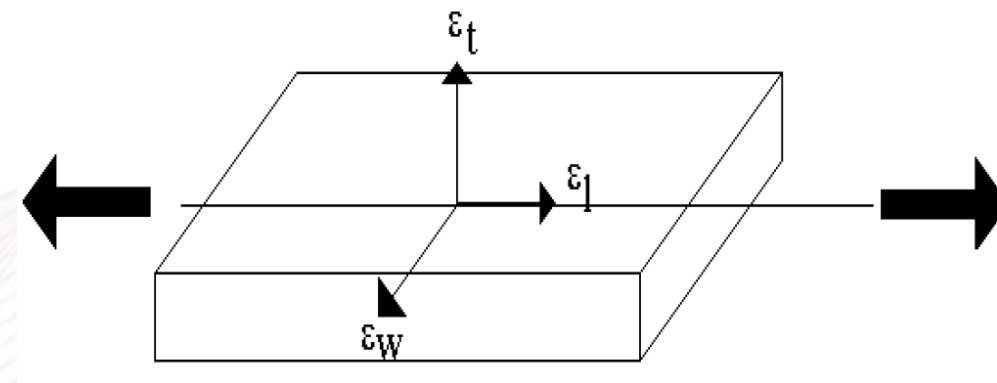


## Introduction: plastic anisotropy (*r-value*)

- Plastic anisotropy is defined as the ratio of the width strain to the thickness strain and is very important for formability (drawing).
- In an isotropic material this would be 1.0 (the length strain is accommodated by both thickness and width equally).
- This ratio is known as *r-value* or *Lankford coefficient*. Typical values for EDDQ steels:  $\geq 2.0$

$$r = \frac{\text{true in-plane strain}}{\text{true through thickness strain}} = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln \frac{w}{w_0}}{\ln \frac{t}{t_0}}$$

$$\frac{t}{t_0} = \frac{(w - l)}{(w_0 - l_0)}$$



## IF steels formability and the $\gamma$ -fiber

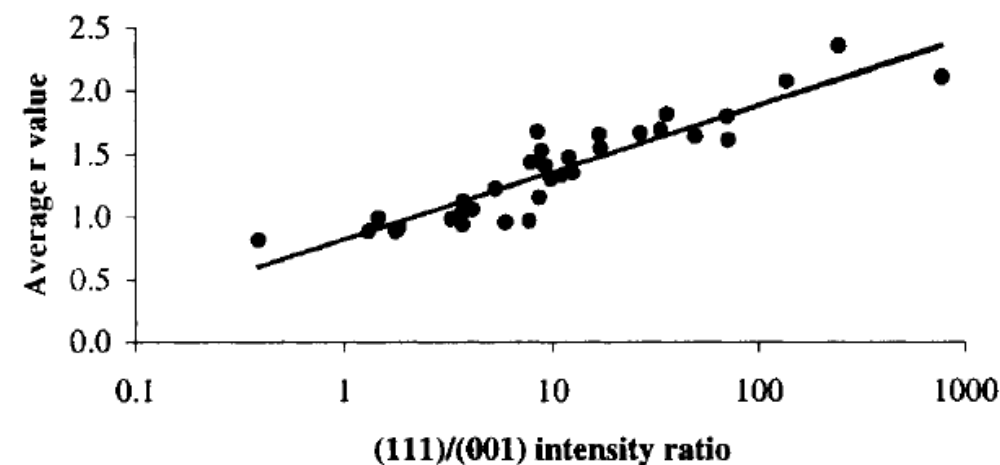
- IF steels owe their deep-drawing performance to a strong  $\langle 111 \rangle // \text{ND}$  ( $\gamma$ -fiber) recrystallization texture.
- The  $\gamma$ -fiber maximizes and stabilizes the *r-value*, the key parameter governing sheet deformation during drawing.
- The annealing cycle determines the final properties (including anisotropy, not only the microstructure).

### $\gamma$ -fiber $\langle 111 \rangle // \text{ND}$

Favourable — high, stable *r-value*

### $\alpha$ -fiber $\langle 110 \rangle // \text{RD}$

Detrimental — depresses *r-value*



(F.J. Held, 1965)

## The ultra-fast induction annealing

- Induction heating is an alternative to combustion-based conventional heating for continuous annealing lines to raise productivity, reduce line length and energy use.
- Ultra-fast heating tend to reduce the role of recovery with respect to that of recrystallization.
- It also changes activation of deformation heterogeneities such as shear bands, and the evolution or dissolution of precipitates.
- **Can the favorable texture still develop with heating rates an order of magnitude above conventional practice?**

**$\approx 30$  °C/s**

Conventional continuous annealing

**40–120 °C/s**

Gleeble physical simulation

**160–220 °C/s**

Pilot induction annealing

*Conventional continuous annealing operates around 30 °C/s; induction units in this work reach 220 °C/s.*

## State of the art: some references

| Study                      | Conditions                                  | Reported effect of heating rate                                                                                   |
|----------------------------|---------------------------------------------|-------------------------------------------------------------------------------------------------------------------|
| Muljono et al. [1]         | 0.003–0.05 %C, 70% CR<br>50–1000 °C/s       | Faster anisothermal recrystallization, finer grain; $\langle 111 \rangle$ //ND intensity increases up to 200 °C/s |
| Park et al. [2]            | Non-oriented electrical steel<br>5–30 °C/s  | Annealing texture development sensitive to heating rate at low rates                                              |
| Senuma et al. [3]          | Extra-low C (0.0029 %)<br>up to 1000 °C/s   | Main recrystallization texture components weakened; effect located at the nucleation stage                        |
| Reis [4], Castro Cerda [5] | Cold-rolled ultra-low C sheet<br>wide range | {111} fiber maintained; negligible difference in grain size and texture vs conventional                           |

## Objectives of the study

- Characterize the metallurgical response of one Ti-stabilized IF steel across a continuous, wide range of heating rates
- Integrate Gleeble physical simulation (40–120 °C/s) with pilot-scale induction annealing (160–220 °C/s) on the same material
- Separate the role of annealing temperature from the role of heating rate

## Experimental: the material

Chemical composition (mass %)

| C      | Mn   | Si   | P     | S     | Al    | Ti    |
|--------|------|------|-------|-------|-------|-------|
| 0.0035 | 0.09 | 0.01 | 0.008 | 0.009 | 0.067 | 0.047 |

- Ultra-low carbon (35 ppm) fully stabilized by titanium — no free interstitials to pin recrystallization nuclei
- Samples taken from a single 1 mm sheet, 75% cold-rolled, ensuring an identical starting microstructure for every thermal cycle
- All comparisons therefore isolate the thermal cycle as the only process variable

## Experimental: heating devices



**a) Gleeble 3800 dedicated unit — L-GIT**

Resistance heating, specimens  $265 \times 15$  mm,  $40\text{--}120$  °C/s, peaks  $750 / 800 / 850$  °C



**b) Pilot induction unit — CSM**

Transverse flux, 100 kW over 100 mm, specimens  $500 \times 120$  mm,  $160\text{--}220$  °C/s, peaks  $700\text{--}1085$  °C

## Experimental: test matrix and characterization

| Platform              | Heating rate       | Peak temperature            | Specimen                         | Holding time |
|-----------------------|--------------------|-----------------------------|----------------------------------|--------------|
| Gleeble 3800 (L-GIT)  | 40 / 80 / 120 °C/s | 750 / 800 / 850 °C          | 265 × 15 mm                      | 0 s nominal  |
| Pilot induction (CSM) | 160–220 °C/s       | 700 – 1085 °C               | 500 × 120 mm, longitudinal to RD | 0 s nominal  |
| Reference             | ≈ 30 °C/s          | Conventional full annealing | —                                | conventional |

- Microstructure — recrystallized fraction by metallographic assessment
- Mechanical response — tensile testing for Rp0.2, Rm, At%, Agt%, n and r-value
- Crystallographic texture — ODF sections at  $\phi_2 = 45^\circ$ , giving direct access to  $\alpha$ - and  $\gamma$ -fiber intensities

## Tensile results — Gleeble 3800 (40–120 °C/s)

| T (°C) | HR (°C/s) | Rp0.2 (MPa) | Rm (MPa) | At % | Agt % | r(90°) | n    | RX fraction |
|--------|-----------|-------------|----------|------|-------|--------|------|-------------|
| 750    | 40        | 286         | 415      | 15.2 | 10.0  | –      | 0.21 | 0.31        |
| 750    | 80        | 227         | 358      | 17.6 | 10.3  | –      | 0.22 | 0.45        |
| 750    | 120       | 244         | 365      | 19.4 | 9.0   | –      | 0.20 | 0.43        |
| 800    | 40        | 144         | 296      | 36.4 | 22.2  | 1.81   | 0.20 | 0.91        |
| 800    | 80        | 148         | 310      | 37.8 | 22.3  | 2.25   | 0.28 | 0.89        |
| 800    | 120       | 162         | 311      | 35.2 | 21.4  | 2.05   | 0.28 | 0.91        |
| 850    | 40        | 178         | 316      | 38.2 | 22.5  | 1.95   | 0.23 | 0.99        |
| 850    | 80        | 151         | 295      | 45.0 | 23.5  | 2.05   | 0.30 | 0.95        |
| 850    | 120       | 140         | 291      | 45.0 | 24.7  | 2.90   | 0.30 | 0.99        |

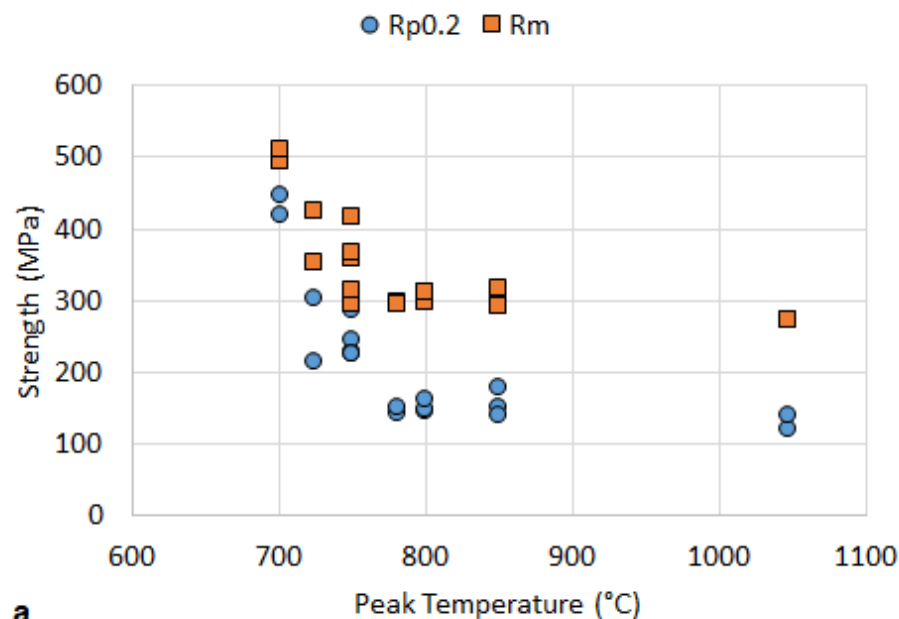
*At 750 °C recrystallization is incomplete and no r-value can be measured; from 800 °C the material is essentially fully recrystallized.*

## Tensile results — pilot induction heating (167–220 °C/s)

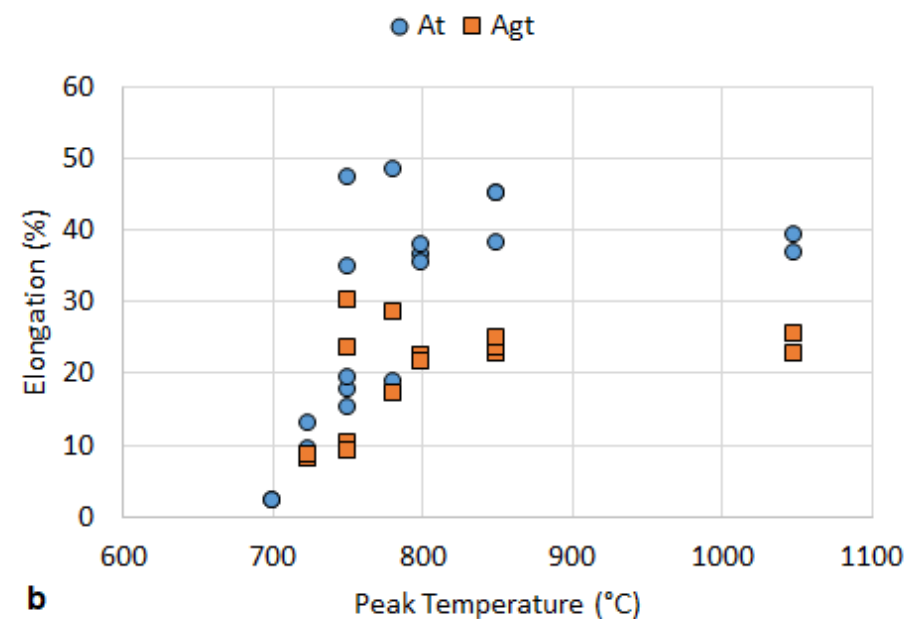
| T (°C) | HR (°C/s) | Rp0.2 (MPa) | Rm (MPa) | At % | Agt % | r(0°) | n    | RX fraction |
|--------|-----------|-------------|----------|------|-------|-------|------|-------------|
| 701    | 220       | 418         | 493      | 2.1  | —     | —     | —    | 0.10        |
| 701    | 220       | 447         | 509      | 2.1  | —     | —     | —    | 0.10        |
| 724    | 180       | 214         | 352      | 9.3  | 8.0   | —     | —    | 0.20        |
| 724    | 180       | 301         | 423      | 13.0 | 8.5   | —     | —    | 0.25        |
| 750    | 195       | 225         | 295      | 47.3 | 30.0  | 1.68  | 0.28 | 0.90        |
| 750    | 195       | 226         | 313      | 34.9 | 23.5  | 1.01  | 0.23 | 0.90        |
| 781    | 204       | 142         | 298      | 18.7 | 17.0  | 1.20  | 0.21 | 1.00        |
| 781    | 204       | 150         | 293      | 48.3 | 28.5  | 1.62  | 0.27 | 1.00        |
| 1048   | 167       | 121         | 272      | 36.7 | 25.5  | 1.44  | 0.26 | 1.00        |
| 1048   | 167       | 138         | 271      | 39.3 | 22.5  | 1.01  | 0.22 | 1.00        |

*Full recrystallization is reached — yet r-values stay between 1.01 and 1.68, well below the Gleeble values at comparable RX fraction.*

## Tensile properties, annealing temperature and heating rate



Rp0.2 and Rm vs peak temperature

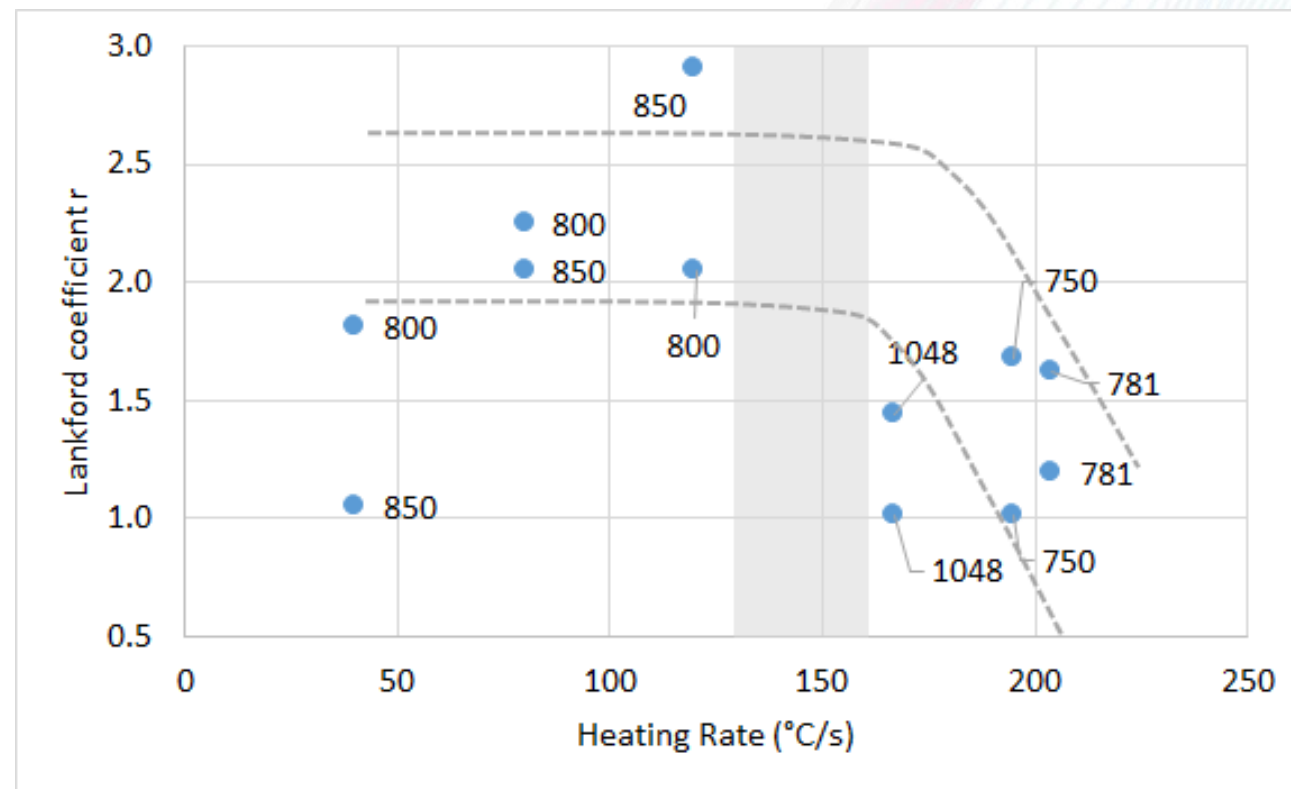


Total and uniform elongation vs peak temperature

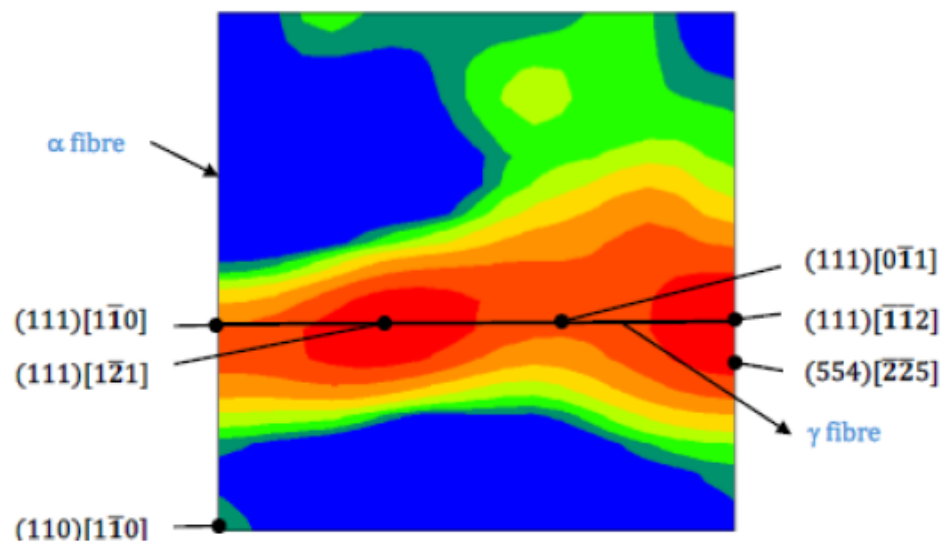
- Strength falls and ductility rises with peak temperature, approaching asymptotic values — the signature of the transition from partially to fully recrystallized microstructure
- Once full recrystallization is achieved, strength and ductility become largely independent of heating rate

## Evolution of $r$ -value

- Considering only specimens with recrystallized fraction  $\geq 0.9$ ,  $r$ -value stays relatively high with scatter up to roughly 130–160 °C/s
- Beyond that band,  $r$ -values drop sharply into the 1.0–1.5 range — below the level required for extra-deep drawing applications
- High- $r$  and low- $r$  points occur over overlapping peak-temperature ranges, so temperature cannot explain the split
- Heating rate is therefore the dominant variable controlling  $r$ -value



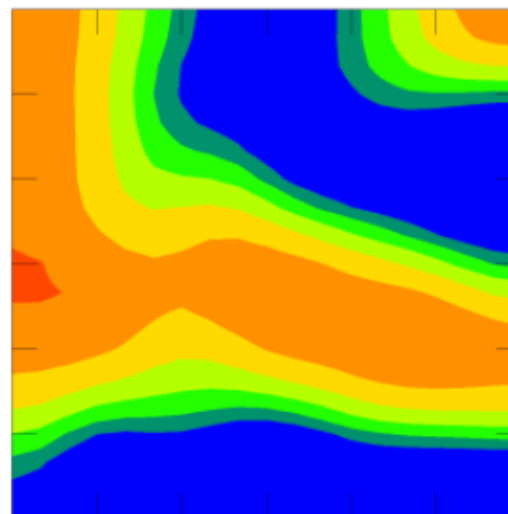
## Texture evidence: ODF sections at $\phi_2 = 45^\circ$



**HR = 80 °C/s**

$I_{\max} = 7.0$   $r = 2.25$

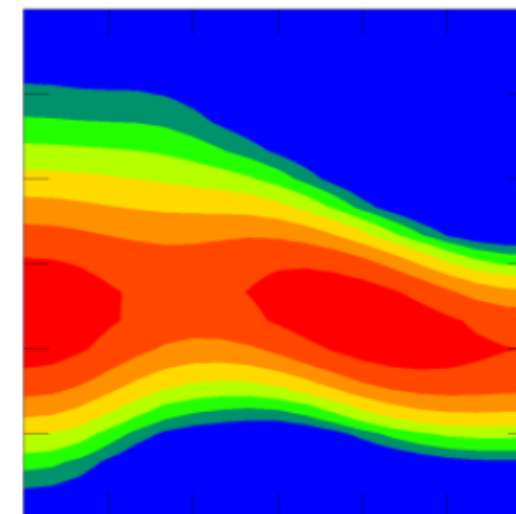
*Strong  $\gamma$ -fiber,  $\alpha$ -fiber weakened*



**HR = 167 °C/s**

$I_{\max} = 3.1$   $r = 1.01$

*Weak  $\gamma$ -fiber,  $\alpha$ -fiber persists*



**Conventional ( $\approx 30$  °C/s)**

$I_{\max} = 5.1$   $r = 1.90$

*Reference deep-drawing texture*

*Low  $r$ -values at high heating rate coincide with persistence of the  $\alpha$ -fiber  $\langle 110 \rangle // RD$  alongside a weak  $\gamma$ -fiber, both at low overall intensity.*

## Discussion (1)

### Observation

- Comparable recrystallized fractions ( $\geq 0.9$ ) are reached at both low and high heating rate
- Yet final textures and r-values differ substantially

### If growth-controlled

- Similar recrystallized fractions would imply similar selective-growth history
- Final textures should therefore converge — they do not

### Conclusion

- Heating rate acts on which nuclei form, and thus which orientations survive into the final microstructure
- The critical effect occurs during nucleation

*The final recrystallization texture is set largely by the nature and distribution of the nuclei formed under each thermal condition.*

## Discussion (2)

### Low heating rate

Recovery proceeds before  
recrystallization starts

→ Stored energy redistributes  
selectively

→  $\gamma$ -fiber nuclei favoured → high r-  
value

### Ultra-fast heating

Recovery is progressively  
suppressed

→ Many highly strained regions  
stay active as nucleation sites

→ Non-selective nucleation,  $\alpha$ -  
fiber survives → low r-value

*The 150–200 °C/s transition marks where loss of nucleation selectivity becomes severe enough to prevent full  $\gamma$ -fiber development.*

## Conclusions

- Full recrystallization is achieved from peak temperatures of about 780–800 °C; under these conditions strength and ductility are largely independent of heating rate.
- The r-value behaves differently: high values are maintained at low and moderate heating rates, while formability deteriorates markedly under ultra-fast heating.
- The deterioration is tied to a changed recrystallization texture — weaker  $\gamma$ -fiber  $\langle 111 \rangle // ND$  with persistent  $\alpha$ -fiber  $\langle 110 \rangle // RD$  components.
- Heating rate acts through nucleation conditions and orientation selection, not through the final recrystallized fraction or selective grain growth.
- A gradual transition region spans roughly 130–160 °C/s — there is no single critical heating rate, only progressively reduced nucleation selectivity.

***Next-generation induction annealing must balance the productivity gains of high heating rates against preservation of the deep-drawing texture.***



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tra ricerca  
e innovazione

# THANK YOU!

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