Review of existing aluminium material tests at post-fire conditions against full scale fire test scenarios

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University of Hertfordshire UH

STRUCTURES IN FIRE FORUM

Motivation

Aluminium

Production increased between 2002-2022 [1]

25% is used in the construction industry [2]

- Good corrosion resistance
- Low density
- High strength-to-weight ratio
- High specific modulus
- Good recyclability

Arvida bridge, Quebec, Canada [5]

Motivation

Aluminium

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- Low density
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- High specific modulus
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Design codes for fire design

EN 1999-1-1:
General rules (RT) [3]

EN 1999-1-2:
Structural fire design [4]

Post-fire ?

Phd project

Multi-scale structural behaviour of aluminium alloys at sub-zero and elevated temperatures

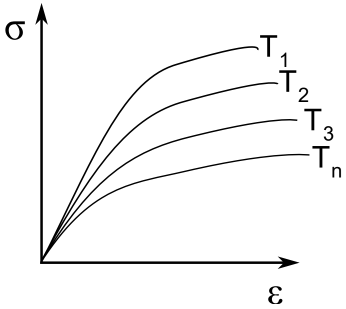
Stage 1
Mechanical properties

Stage 2
Microstructure

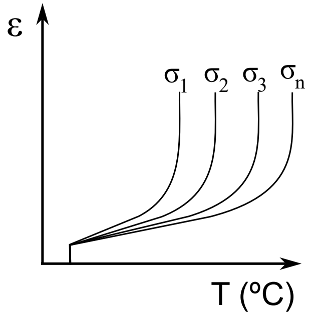
Stage 3
Connections

Stage 4
Structural level

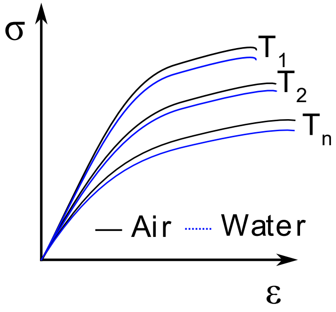
Steady tests



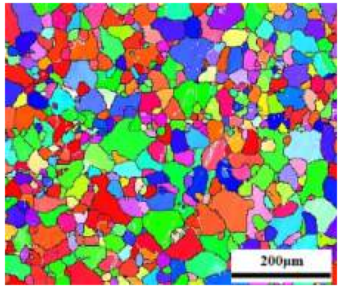
Transient tests



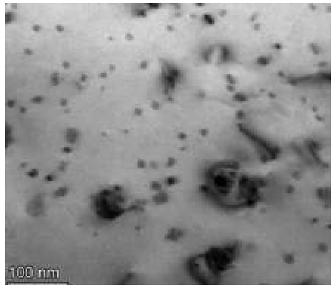
Post-fire tests

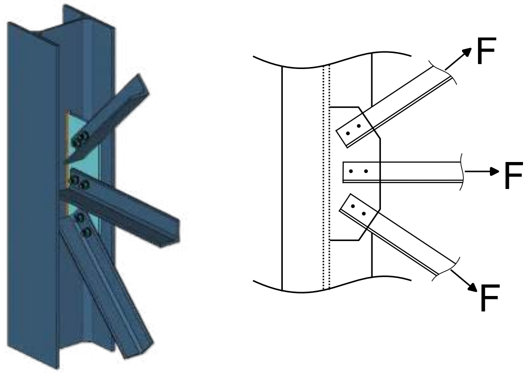


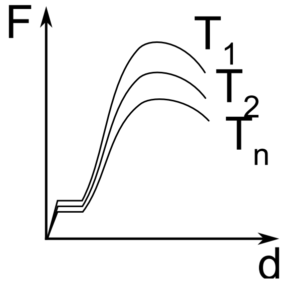
SEM+EBSD

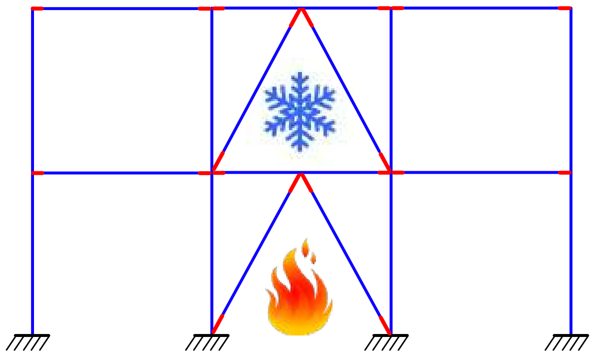


TEM







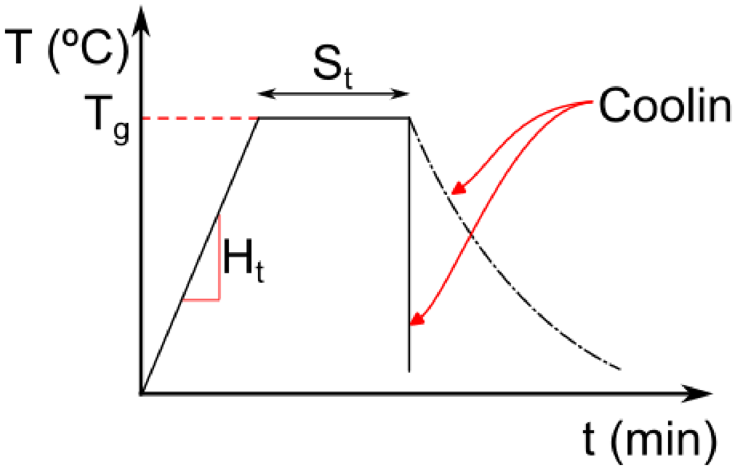


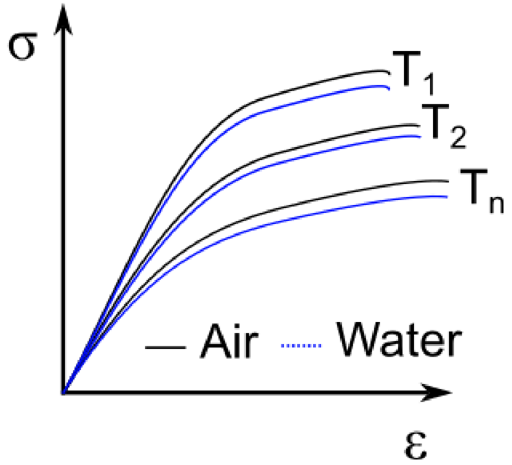
Literature review

University of Hertfordshire UH

Post-fire tests

- To simulate the mechanical properties after a fire.
- Mechanical properties after exposure to high temperature and subsequent cooling by one or more methods.





Variables:

- T_g = Target temperature
- H_t = Heating rate
- S_t = Soaking time

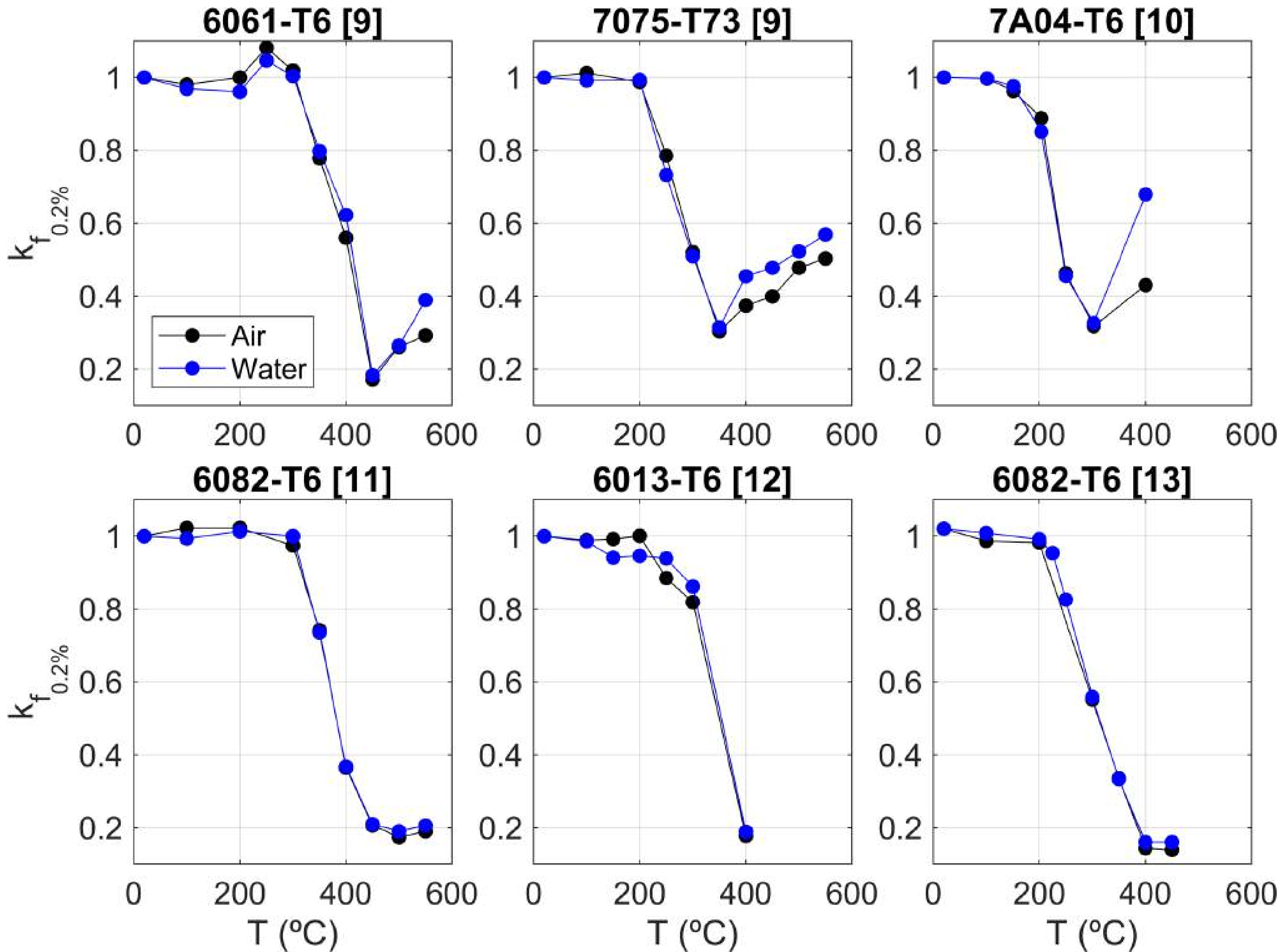
Usually used in literature:

- T_t = 20-550ºC
- H_t = 15-20 ºC/min
- S_t = 15-30 min
- Cooling environment: Water, air

How do these variables relate to real fires?

What is the effect on mechanical properties?

Previous studies
Effect of cooling method on mechanical properties



Cooling methods show a minor effect except for 7A04-T6 at 400ºC

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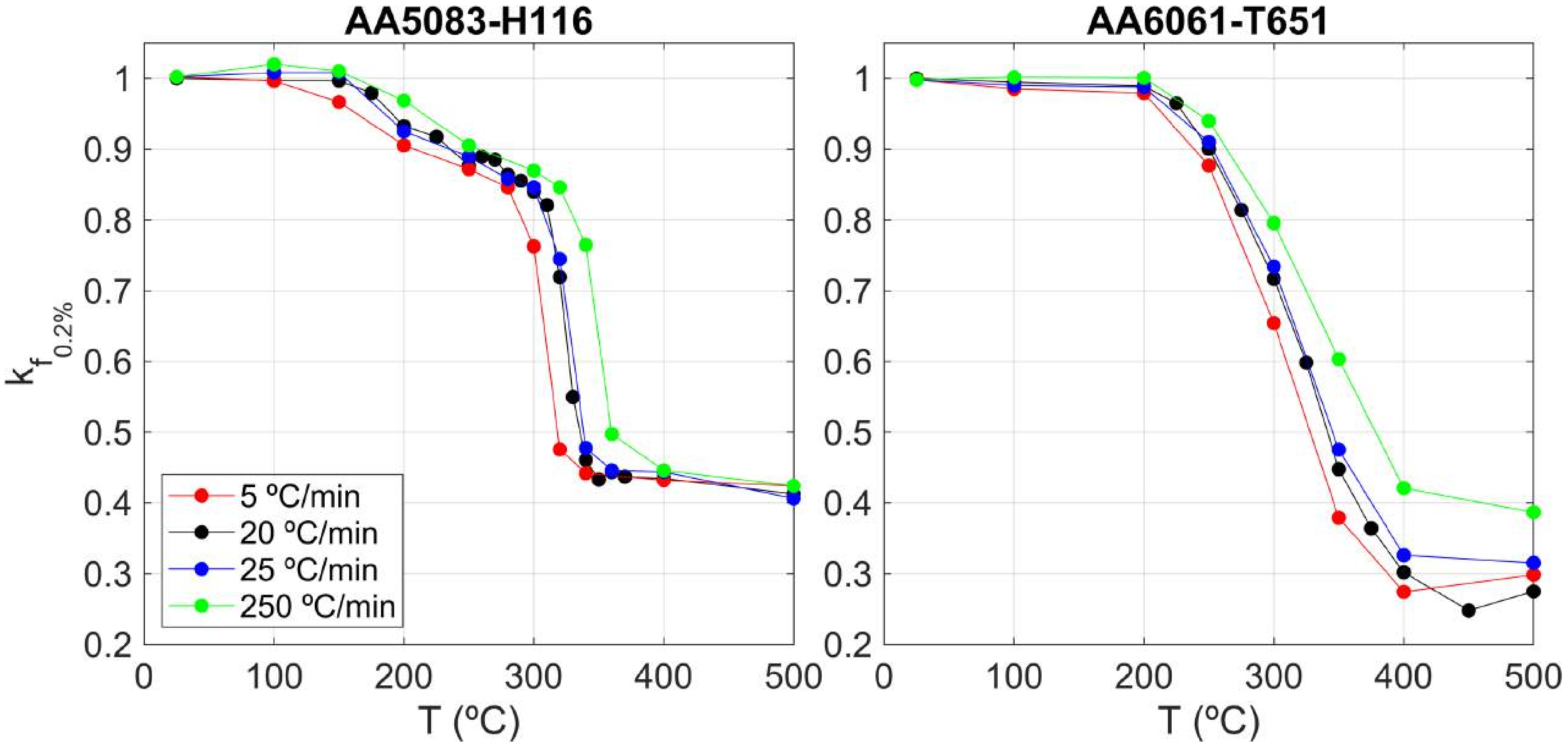
Aluminium remains unaltered up to 200-300ºC

↓

Strength recovery is observed in some alloys

Previous studies
Effect of heating rate on mechanical properties

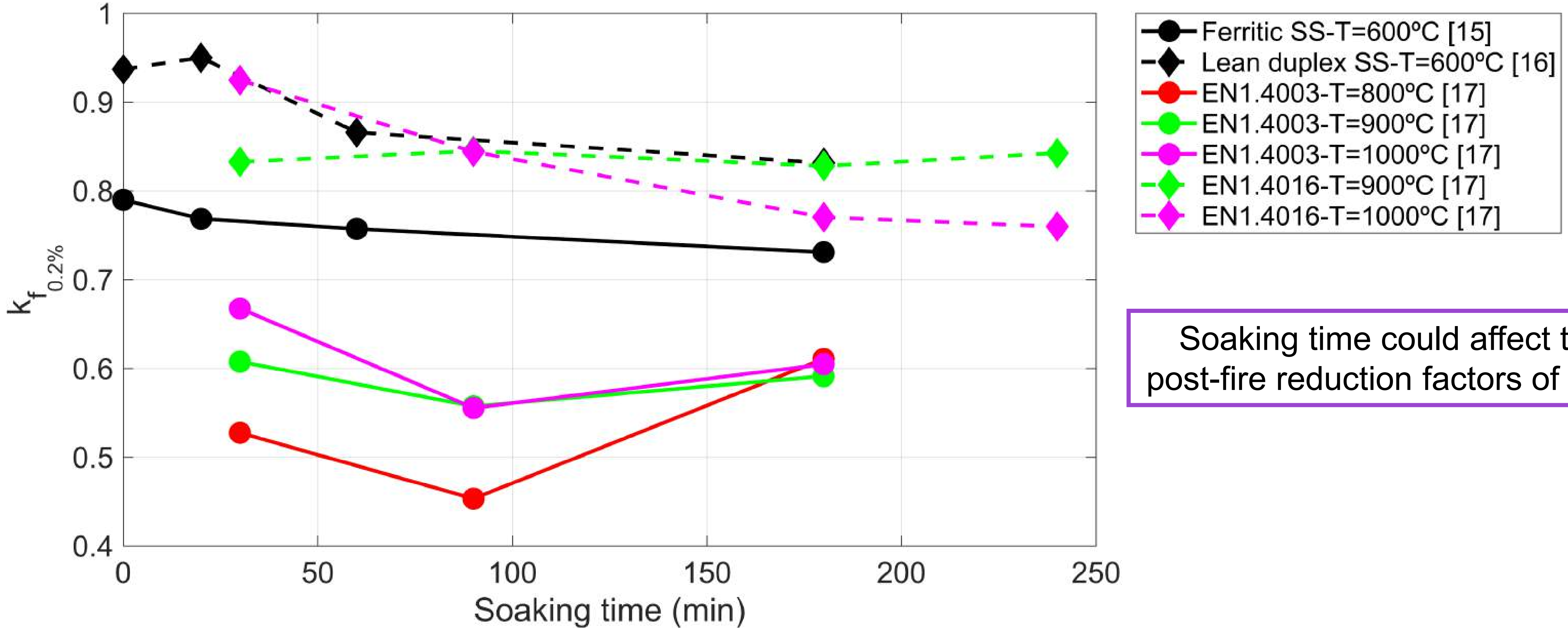


Heating rate affects different alloys differently, as reported by [14]

Higher heating rates produce a lower reduction in proof strength

Previous studies
Effect of the soaking time on mechanical properties

Research on the effect of soaking time on the post-fire mechanical properties of aluminium appears to be limited



Soaking time could affect the post-fire reduction factors of steel

Fire tests

1996 – Cardington [18]
- Steel frames
- Composite floors
- Corner tests + large compartment

2010 – MOKRSKO [19]
- Steel frames with cellular beams
- Composite floors

2011 – COSSFIRE [20]
- Steel frames
- Composite floors
- Emphasis on connections

2012 – FICEB [21]
- Steel frames with cellular beams
- Composite floors

Fire tests

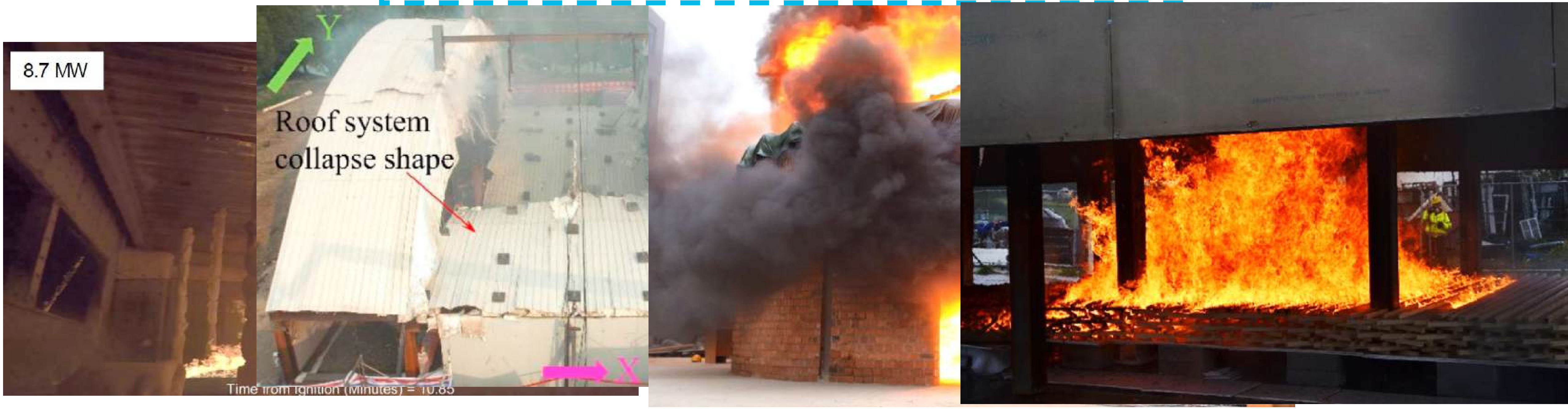
Aluminium structures

2021
NIST [22]
- Steel frames
- Composite floors

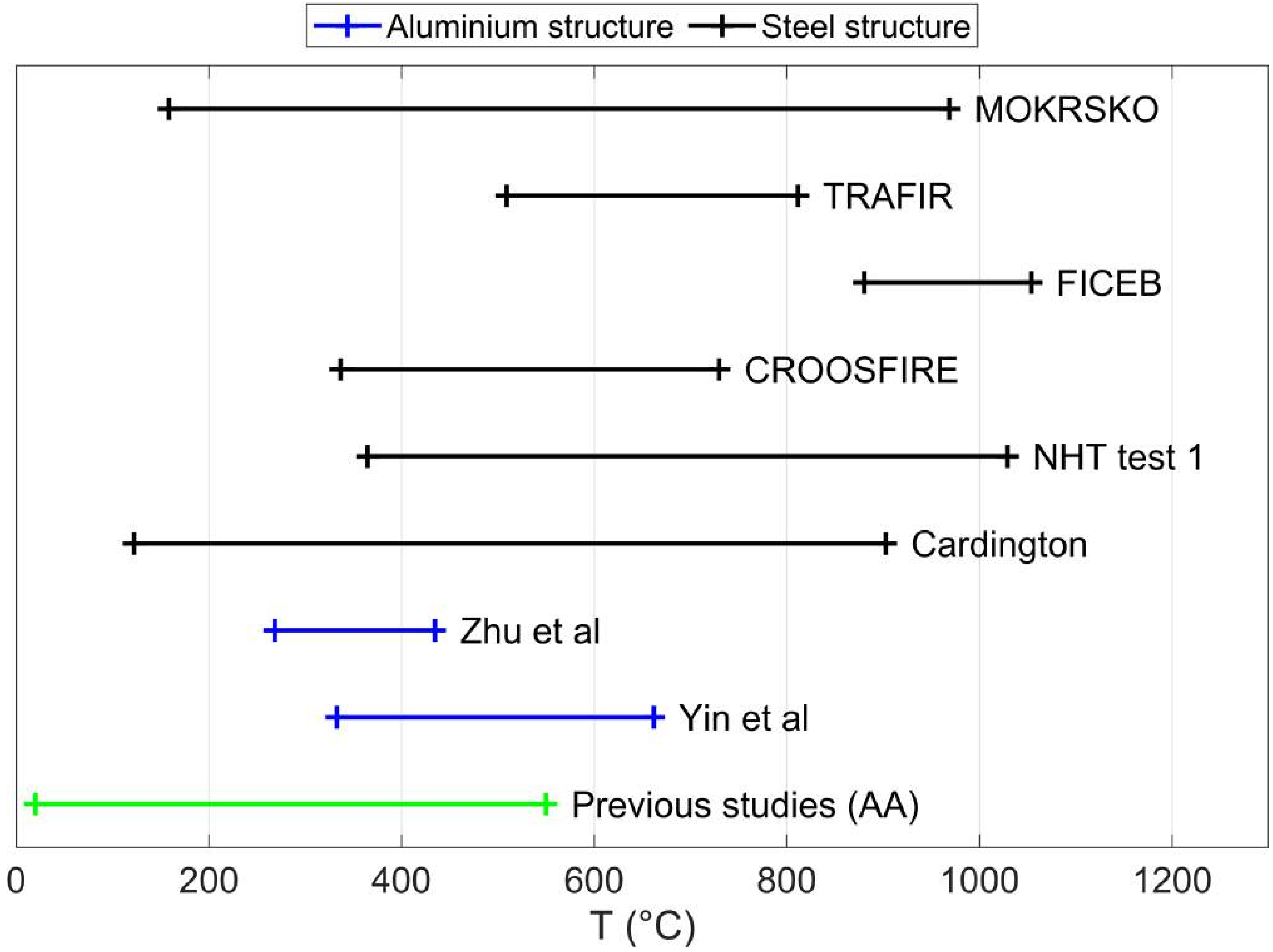
2021
Yin et al [23]
- Reticulated aluminium roof

2021
Zhu et al [24]
- Reticulated aluminium roof

2022
TRAFIR [25]
- Steel frames
- Travelling fire scenario



Fire tests



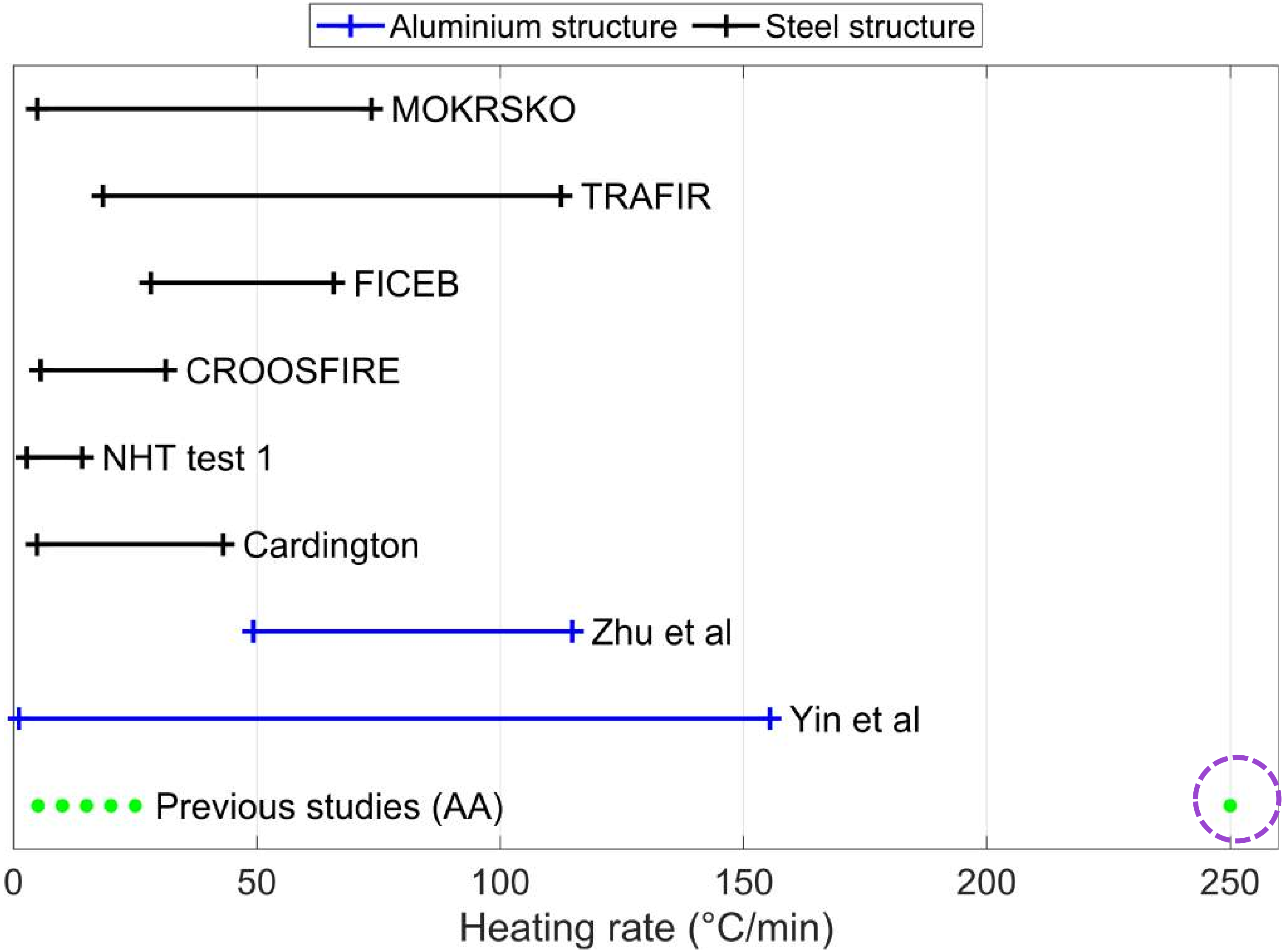
Temperature range

Measured at members

Max temperature observed for FICEB and NHT (1053 and 1029ºC)

Steel structures tipically reach higher temperatures than aluminium

Fire tests



Heating rate (Ht)

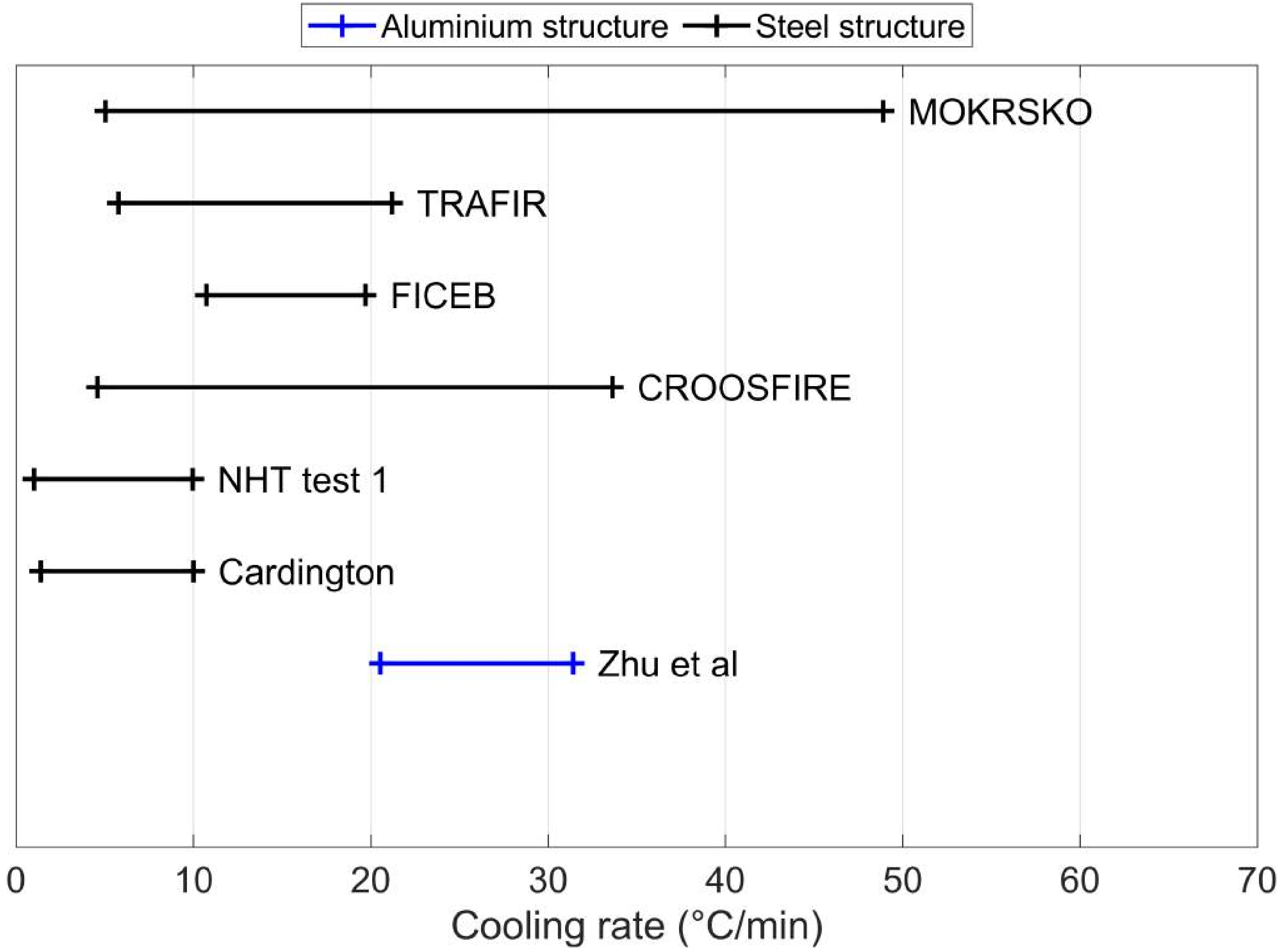
Measured at members

Depends on fire load and openings

Aluminium experiences higher heating rates than steel (difference in thermal properties of materials)

Ht>50ºC/min only covered by one study

Fire tests



Cooling rate

↓

Measured at members

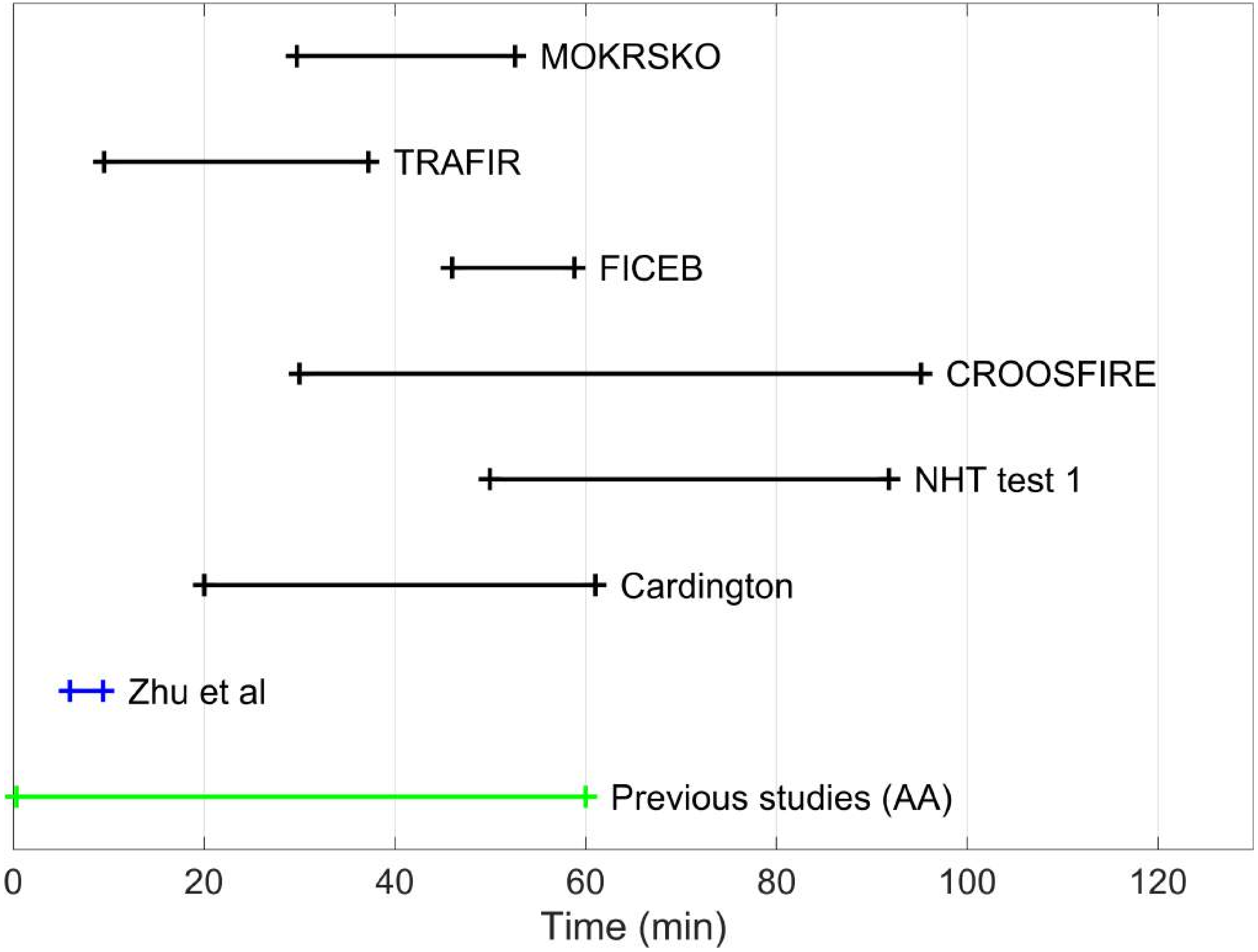
↓

Cooling rate usually range between 5-25ºC/min except MOKRSKO

↓

There is a need to study the effect of a wider range of cooling rates

Fire tests



Soaking time

↓

Time from T>200ºC to the start of the cooling process

↓

Depends on fire load

↓

Longer exposure times are expected for higher fire loads

Experimental programme

University of Hertfordshire UH

Experimental programme

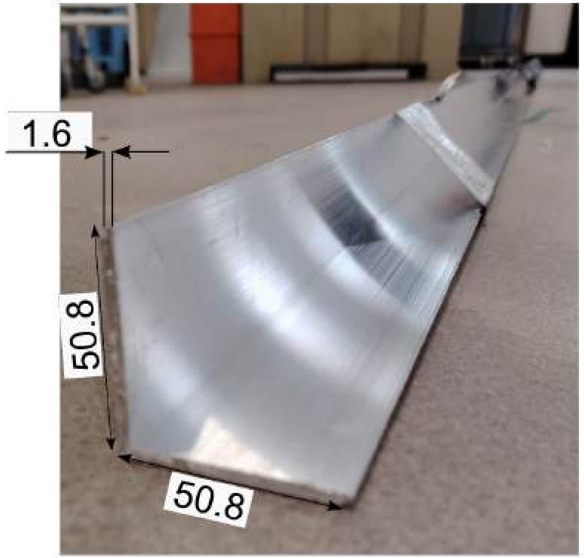
Programme 1		
Aluminium alloy	AA	6082-T6
Temperature	T	20, 100, 200, 300, 350, 400, 450 and 500ºC
Heating rate	Ht	15ºC/min
Soaking time	St	20 min
Cooling method	C	Inside furnace and water quenching

Programme 2		
Aluminium alloy	AA	6082-T6
Temperature	T	400ºC
Heating rate	Ht	15, 80 and 135 ºC/min (St=20min, C=water quenching)
Soaking time	St	20, 60 and 120 min (Ht=15ºC/min, C=water quenching)
Cooling method	C	Inside furnace, outside furnace and water quenching (Ht=15ºC/min, St=20min)

W=water
AF=Air inside furnace
A=Air outside furnace

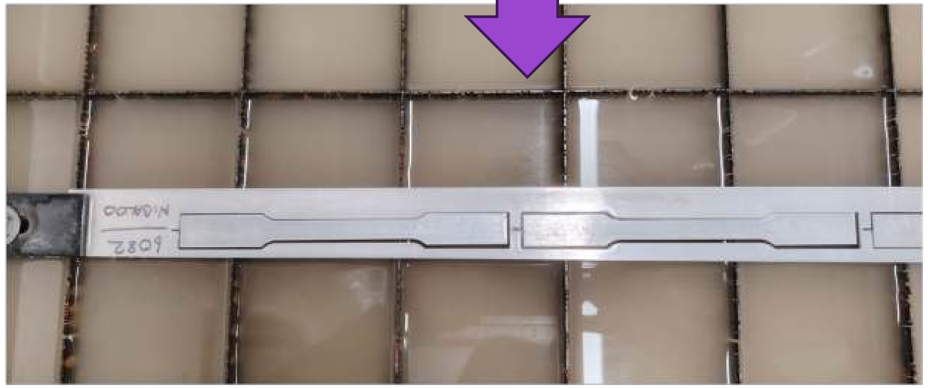
Sample cutting

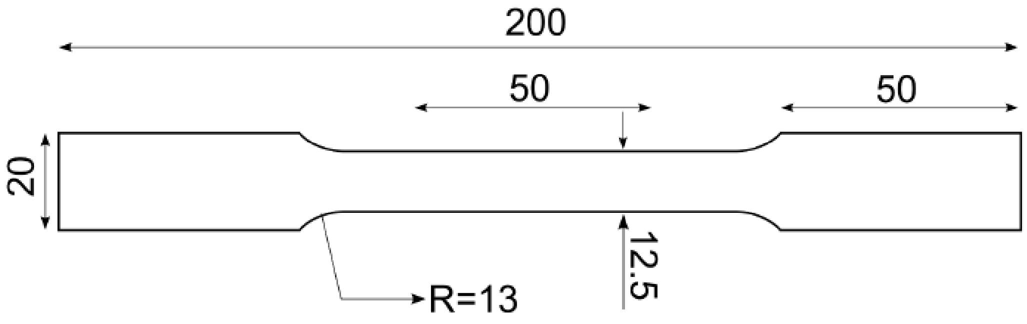
Angle 50.8x50.8x1.6mm



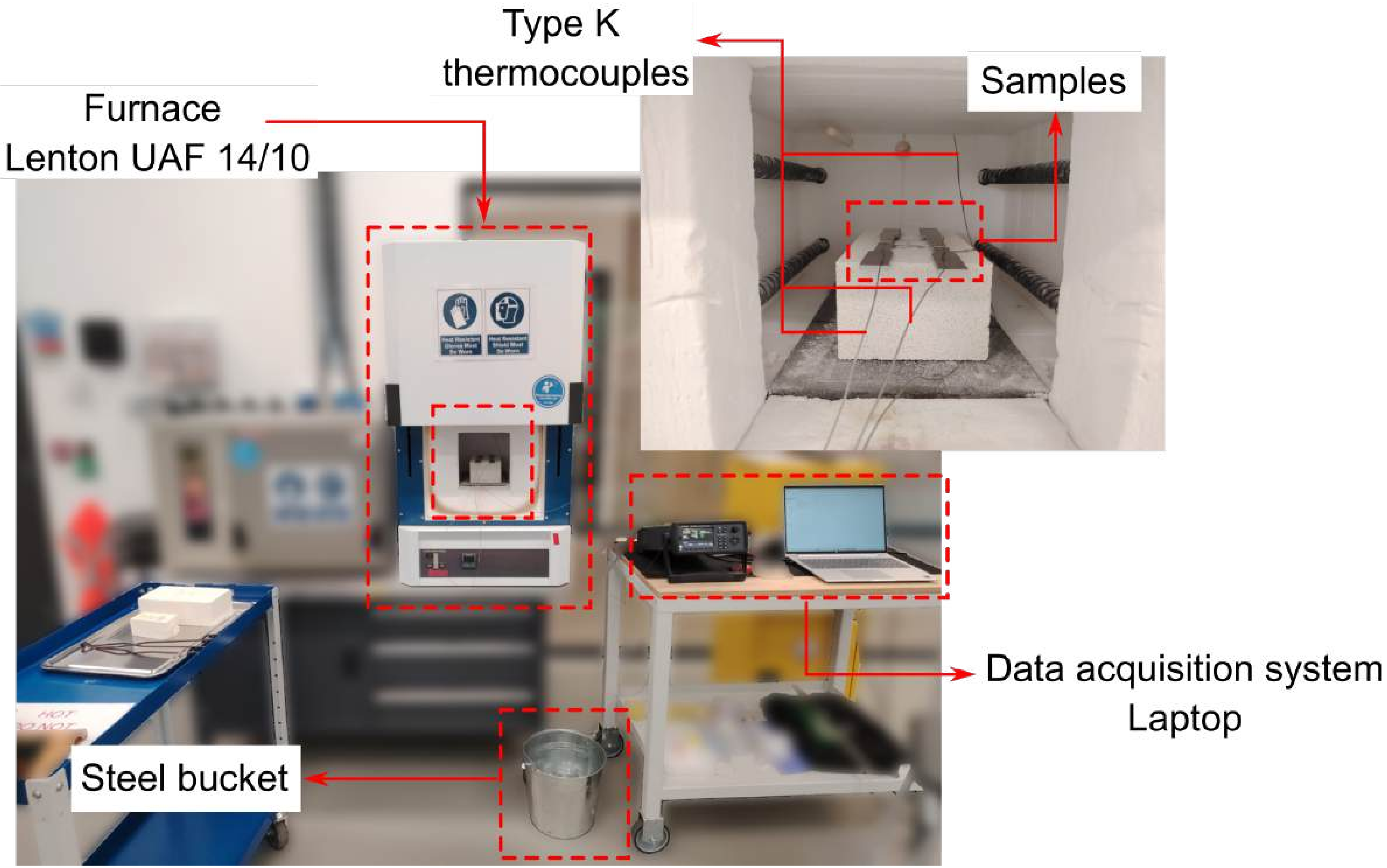
Cut into flat faces

Water-Jet cutting
(Water-jet WardJet Series A-1212)

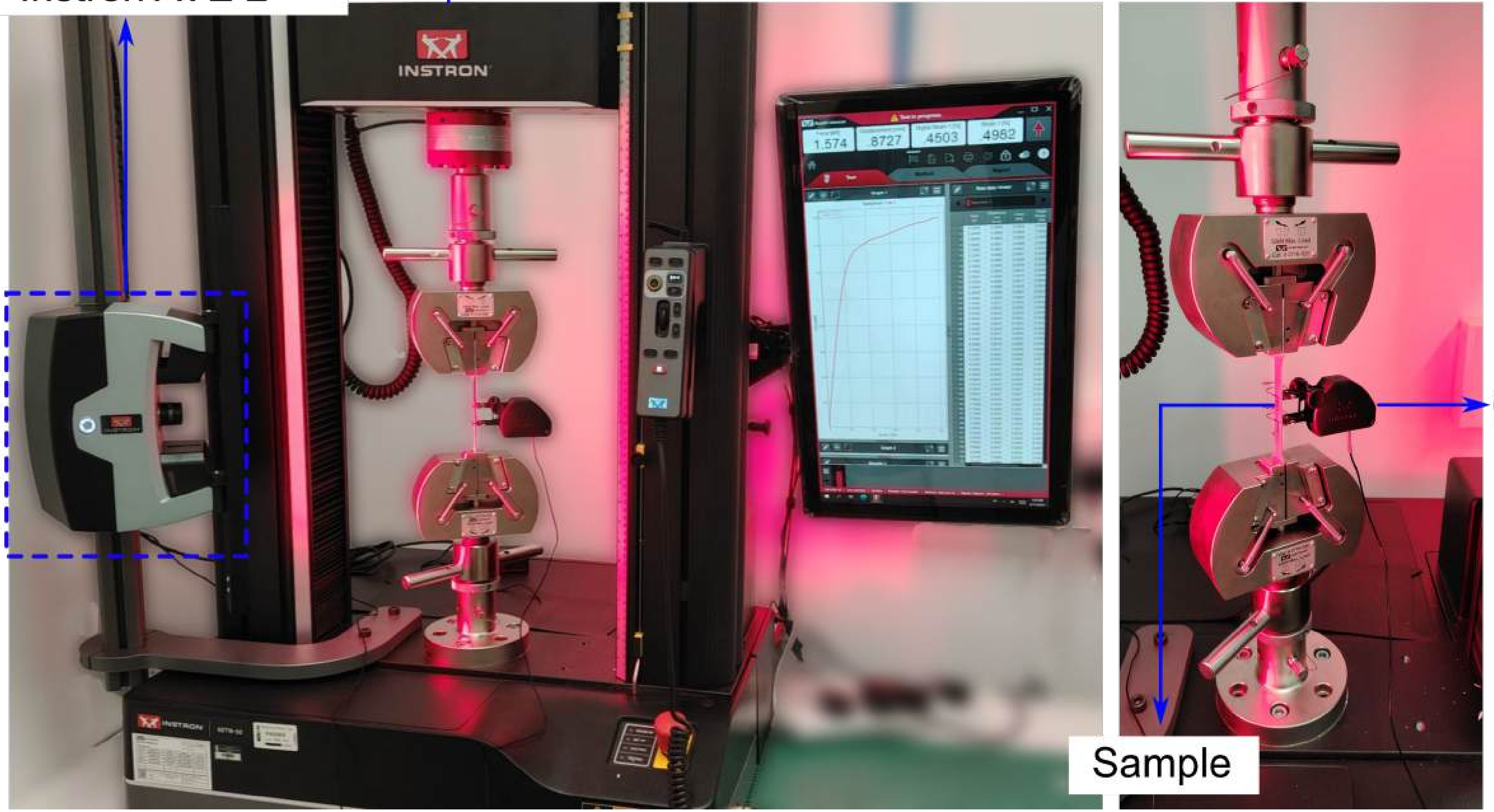




Set-up


Type K
thermocouples
Furnace
Lenton UAF 14/10
Samples
Data acquisition system
Laptop
Steel bucket

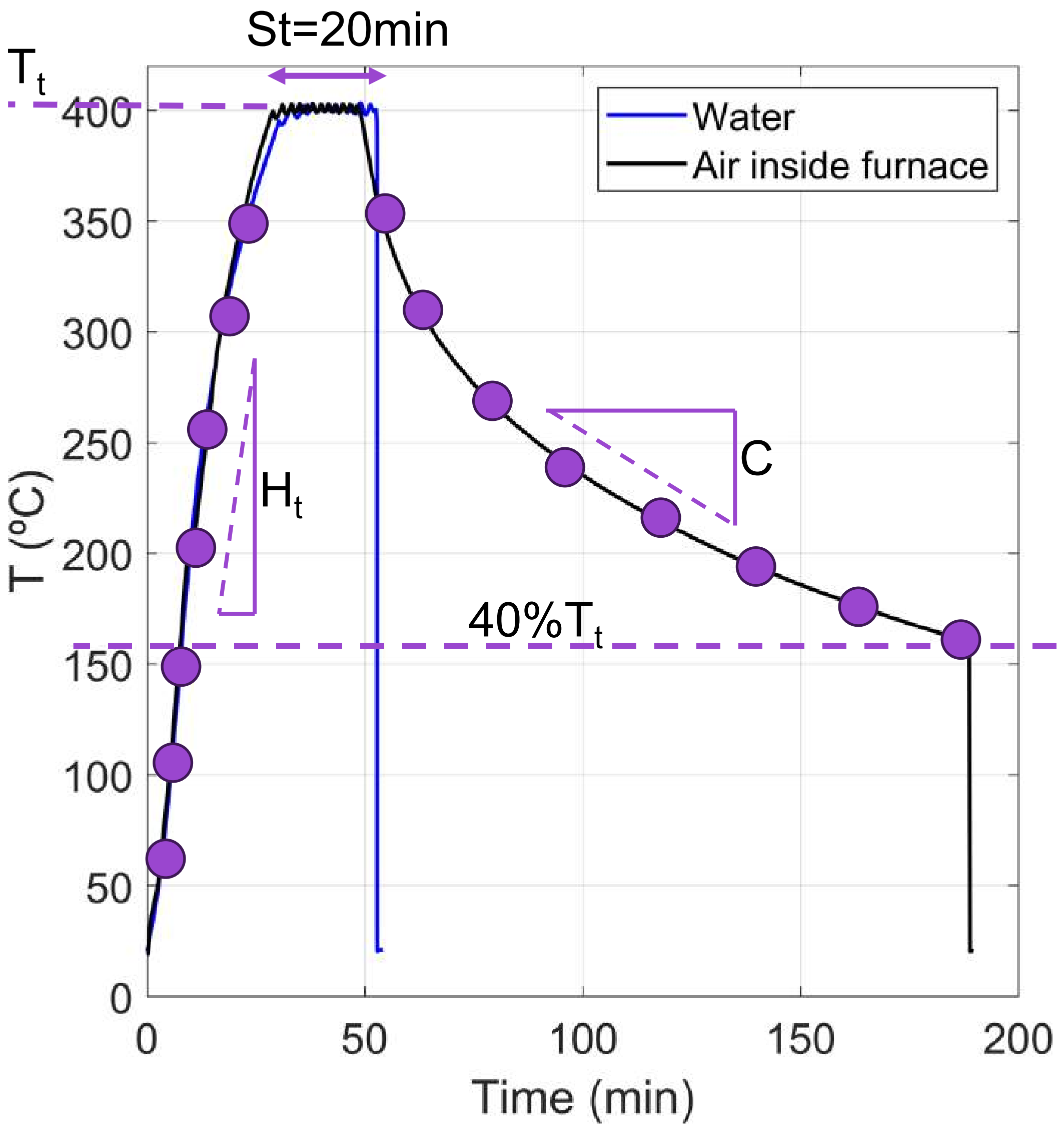
Set-up


Video extensometer
Instron AVE 2
Universal testing machine
Instron 68TM-50
Clip extensometer
Sample

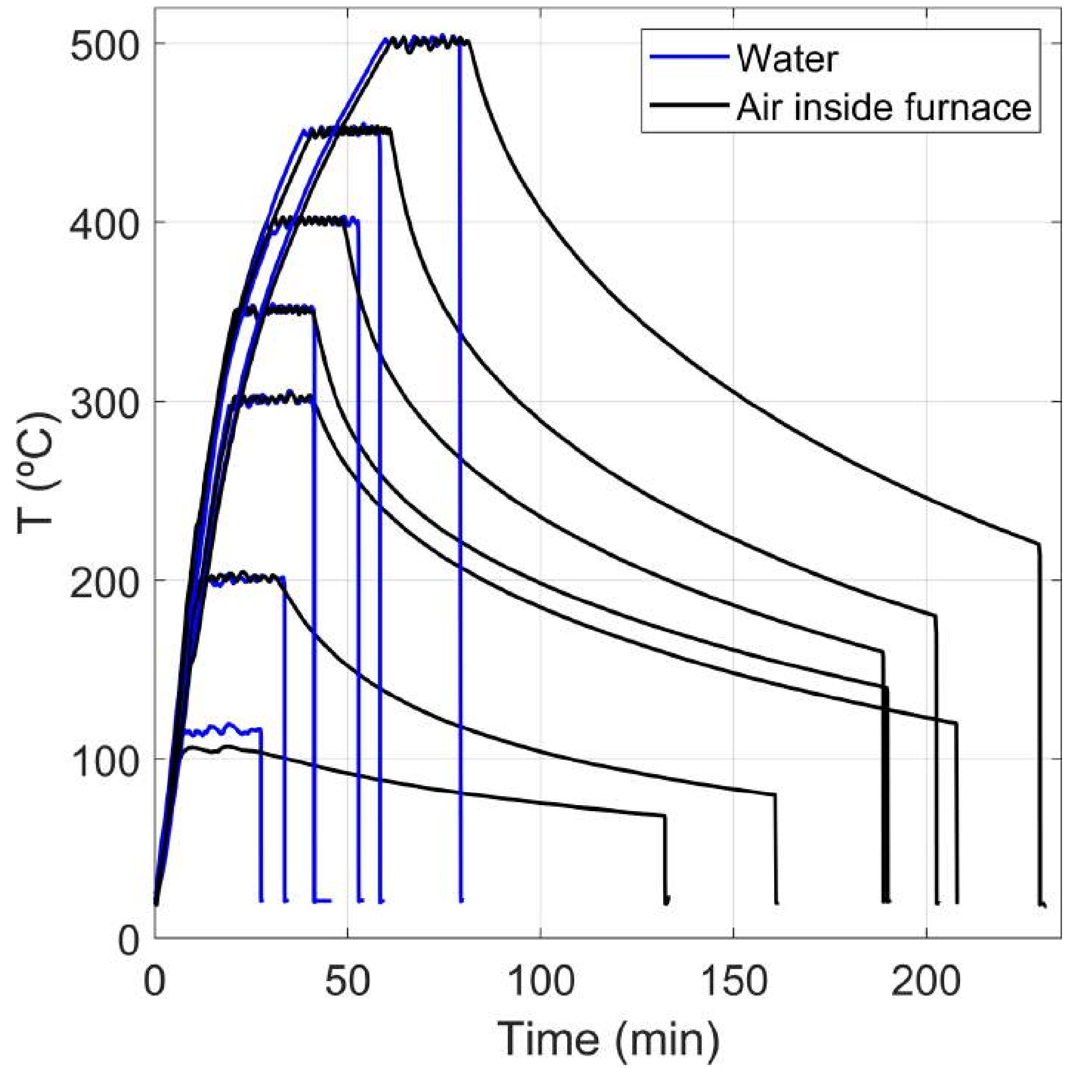
Test results

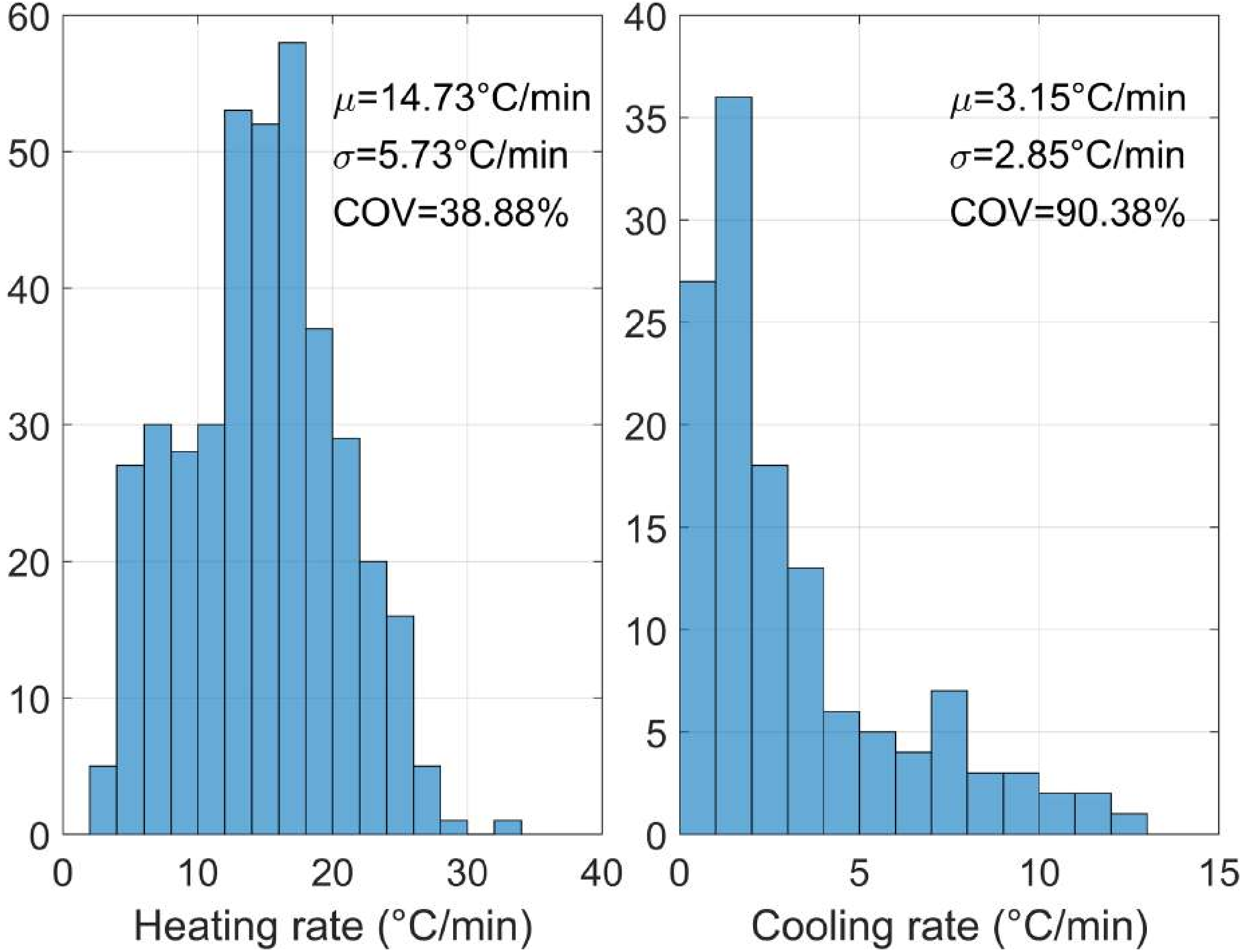
Programme 1

Sample exposure

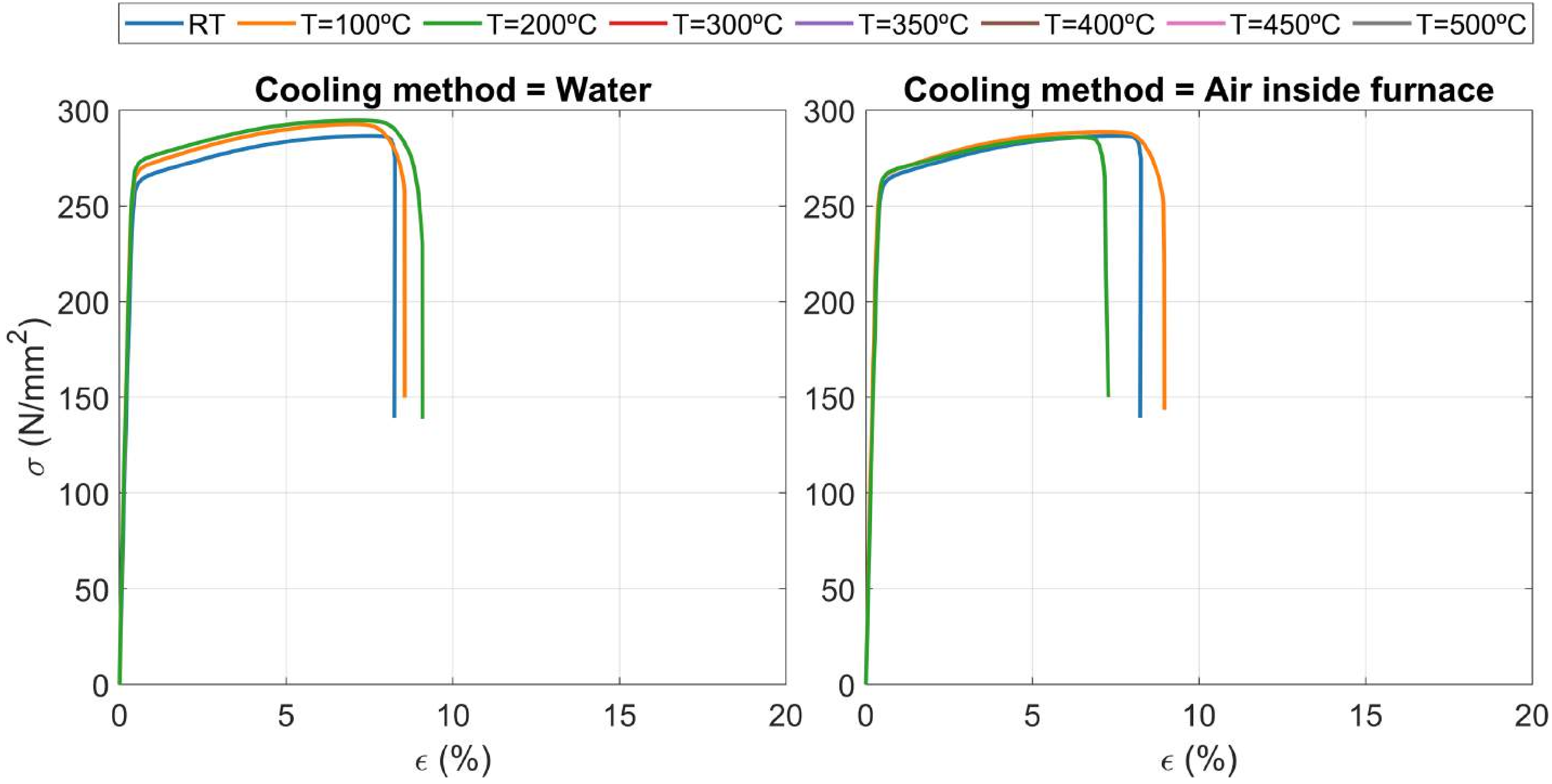


Temperature vs time curves



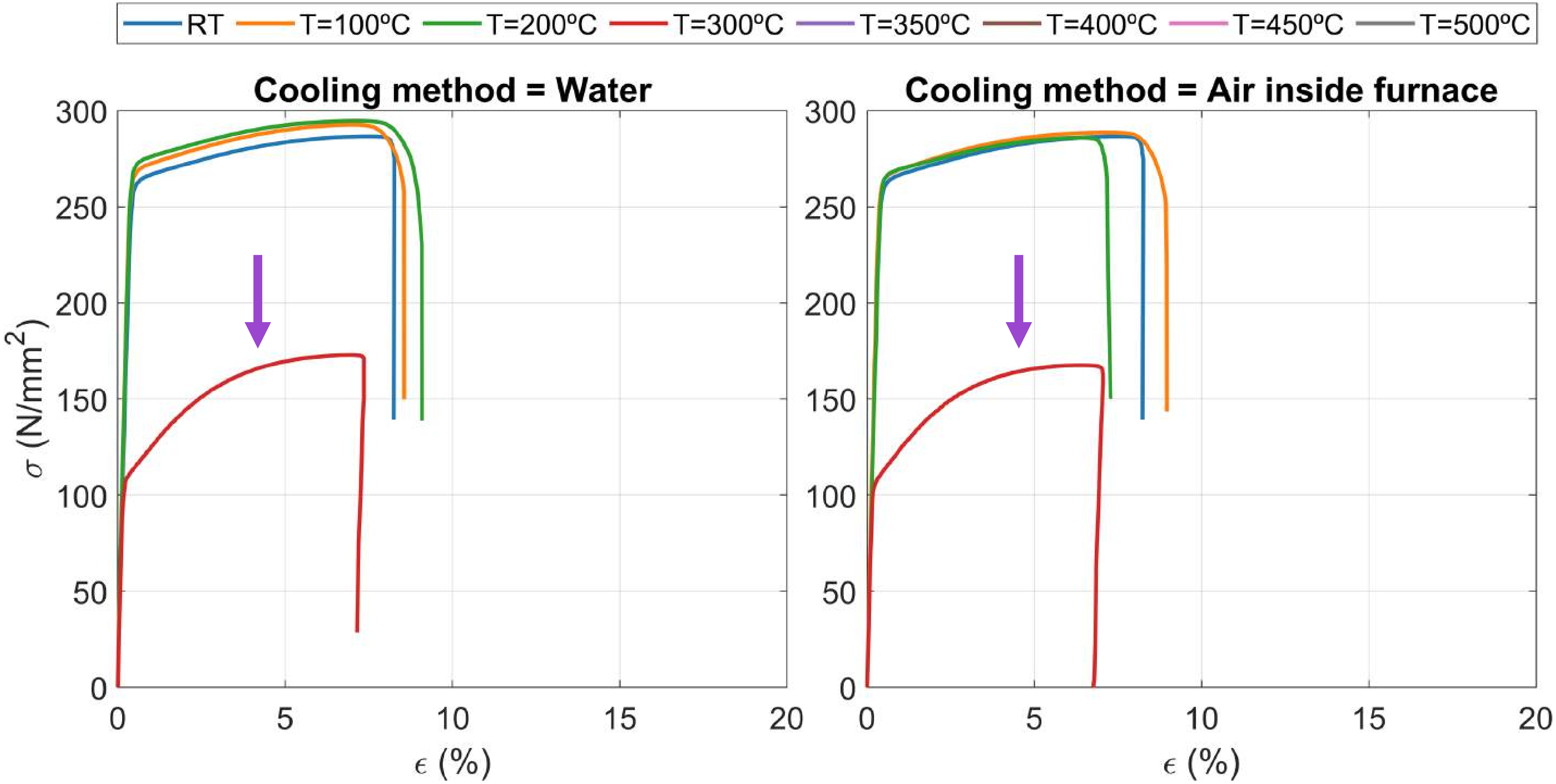


Stress-strain curves



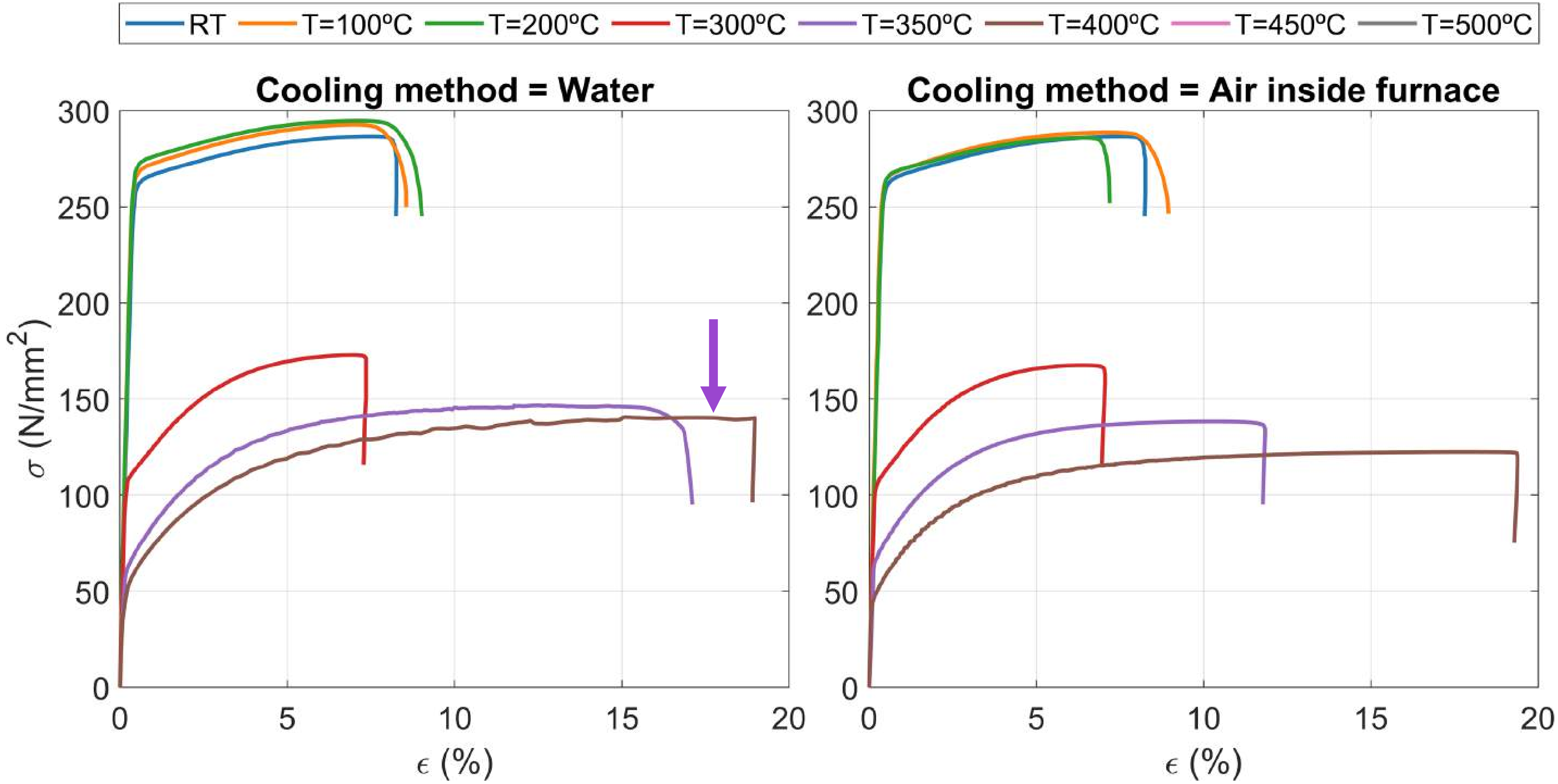
Very little effect up to T=200ºC

Stress-strain curves



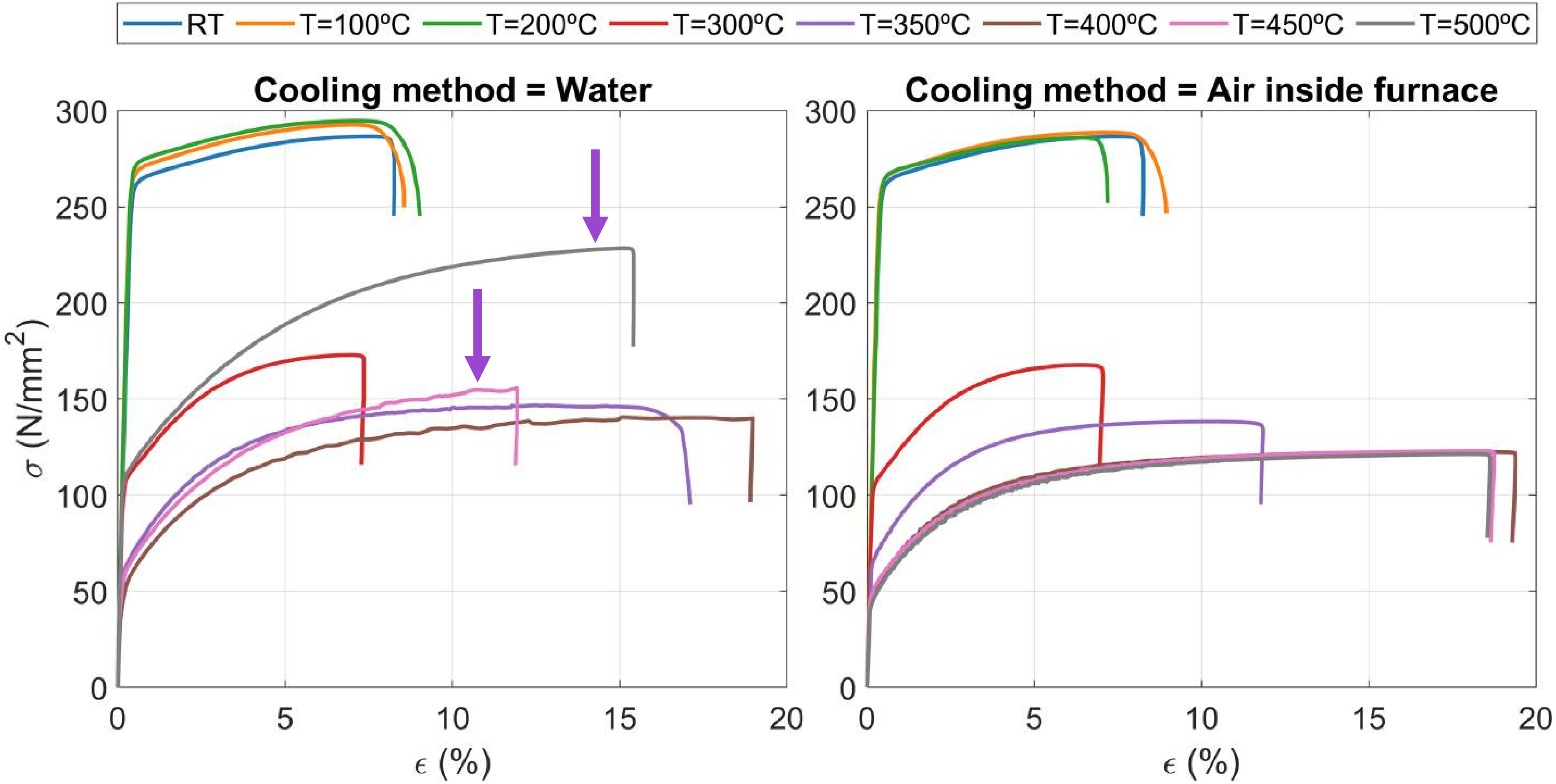
At 350ºC, a significant decrease in strength is observed

Stress-strain curves



For the water cooling method, strength is lower at 400ºC

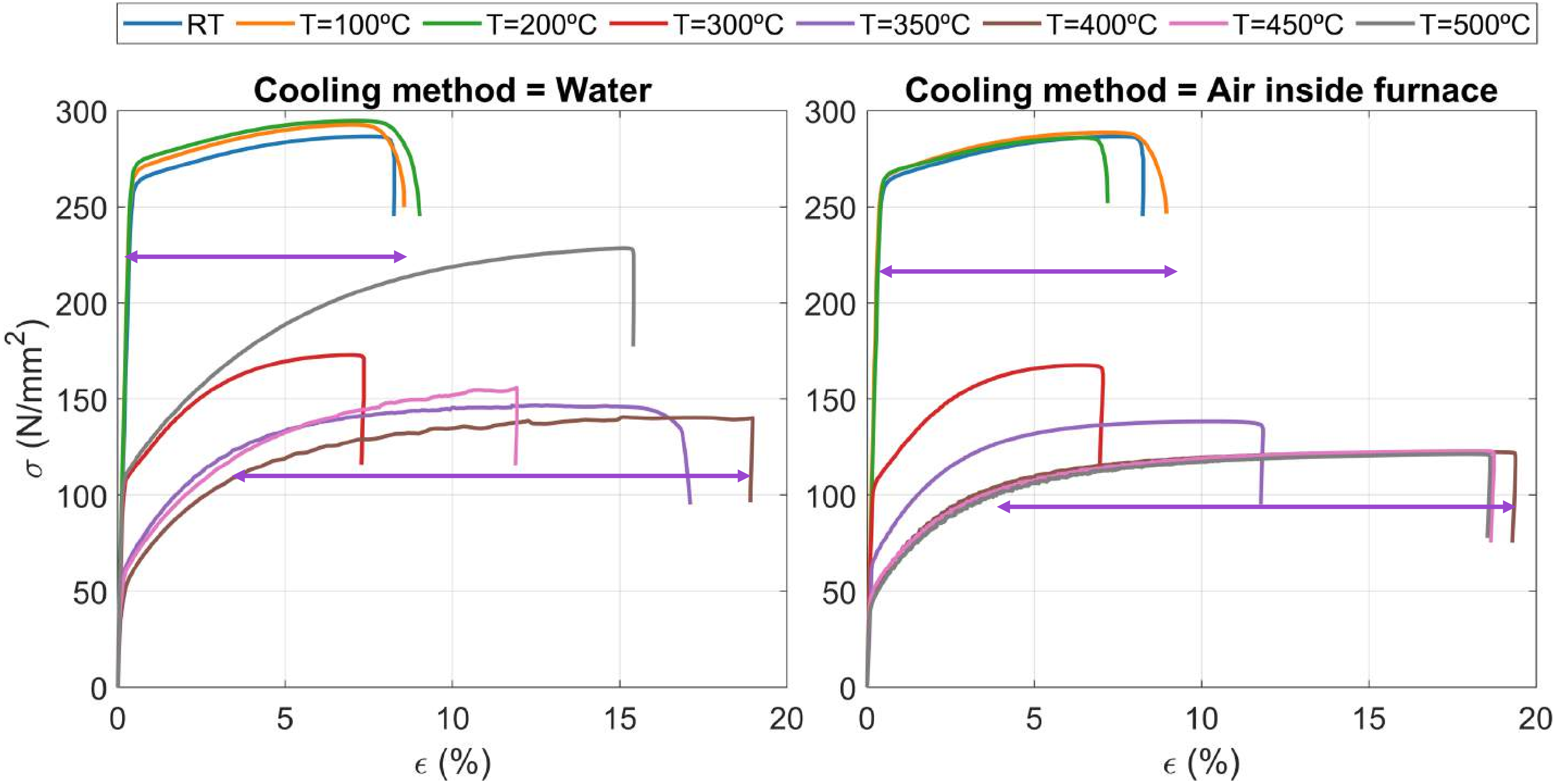
Stress-strain curves



Cooling=water: a strength recovery is observed at 450ºC and 500ºC

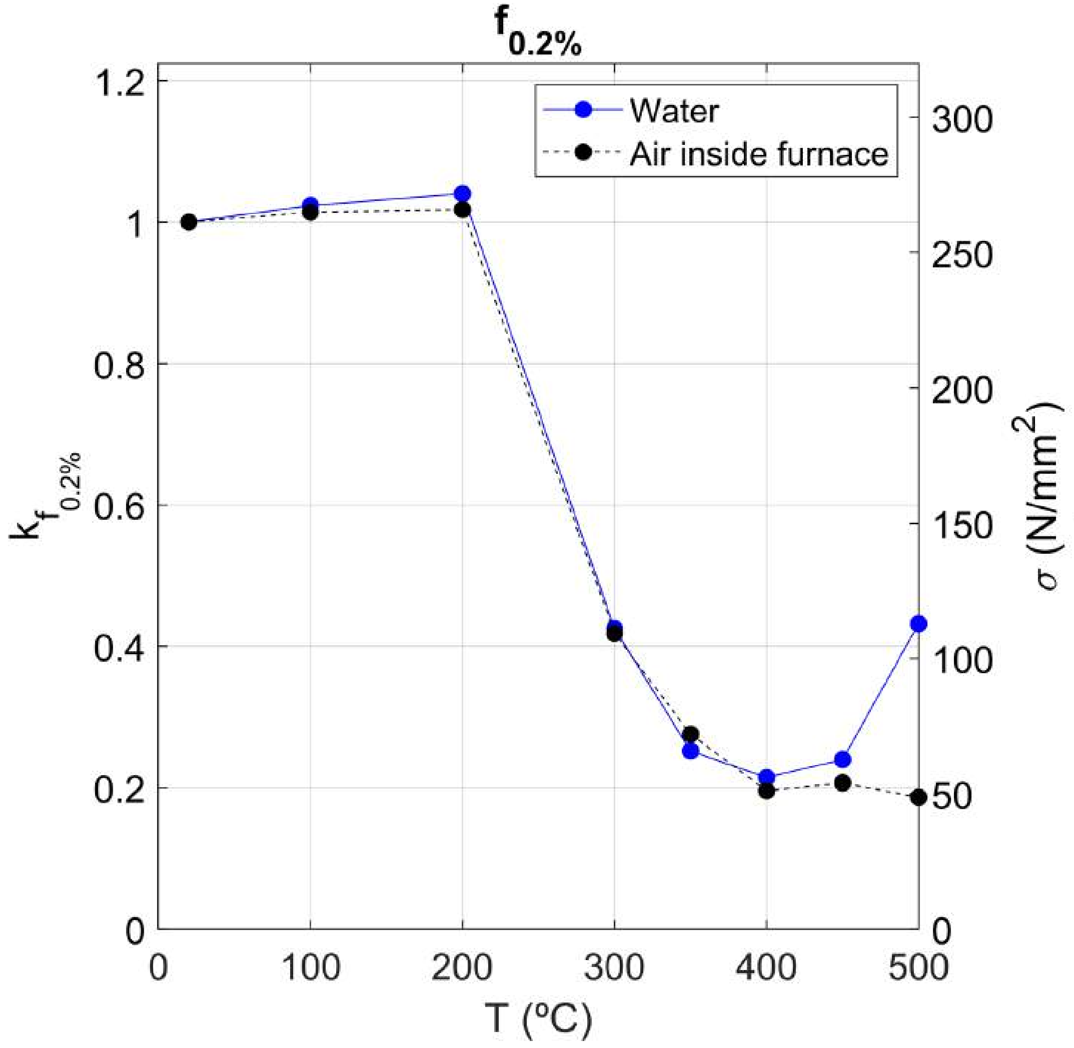
Cooling=air inside furnace: strength recovery is not observed

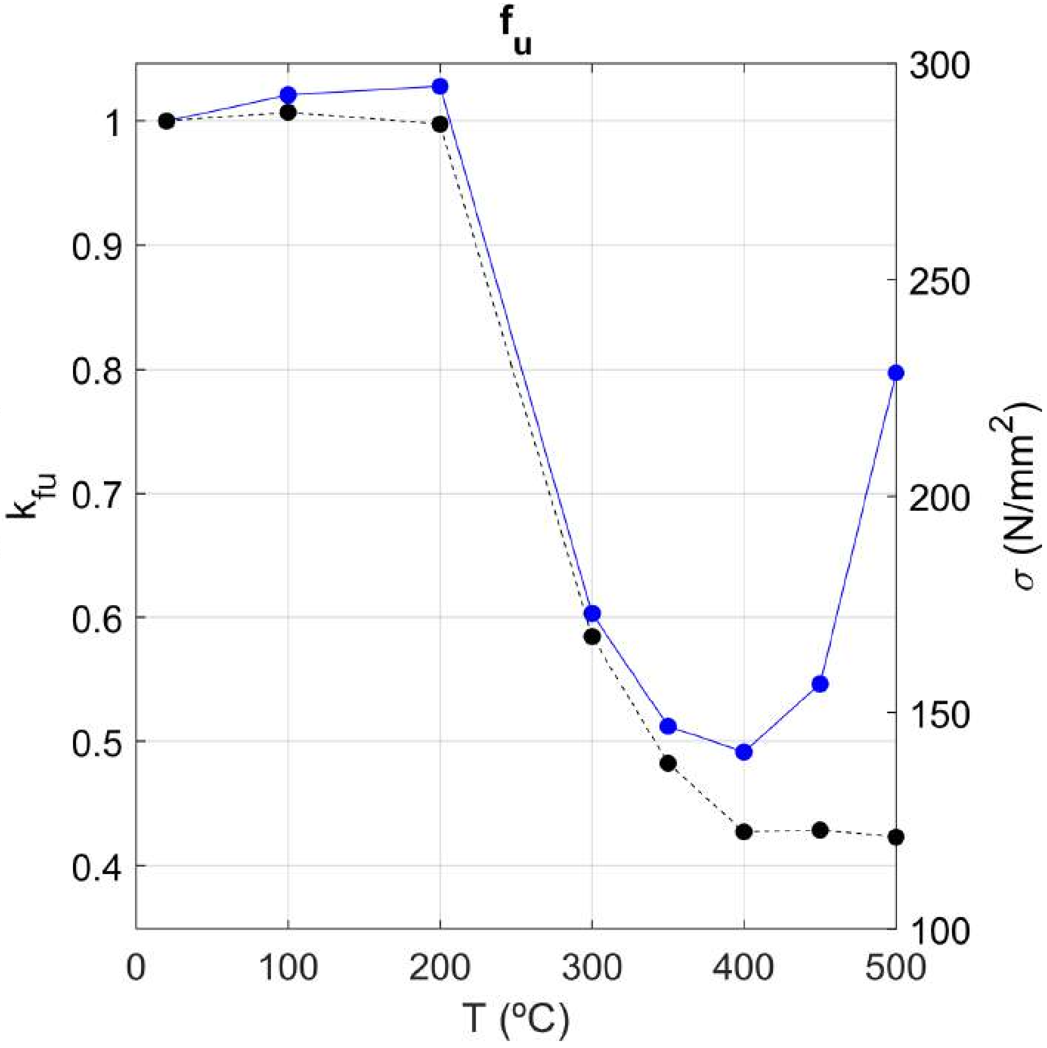
Stress-strain curves



An increase in ductility is observed for T≥350ºC

Reduction factors

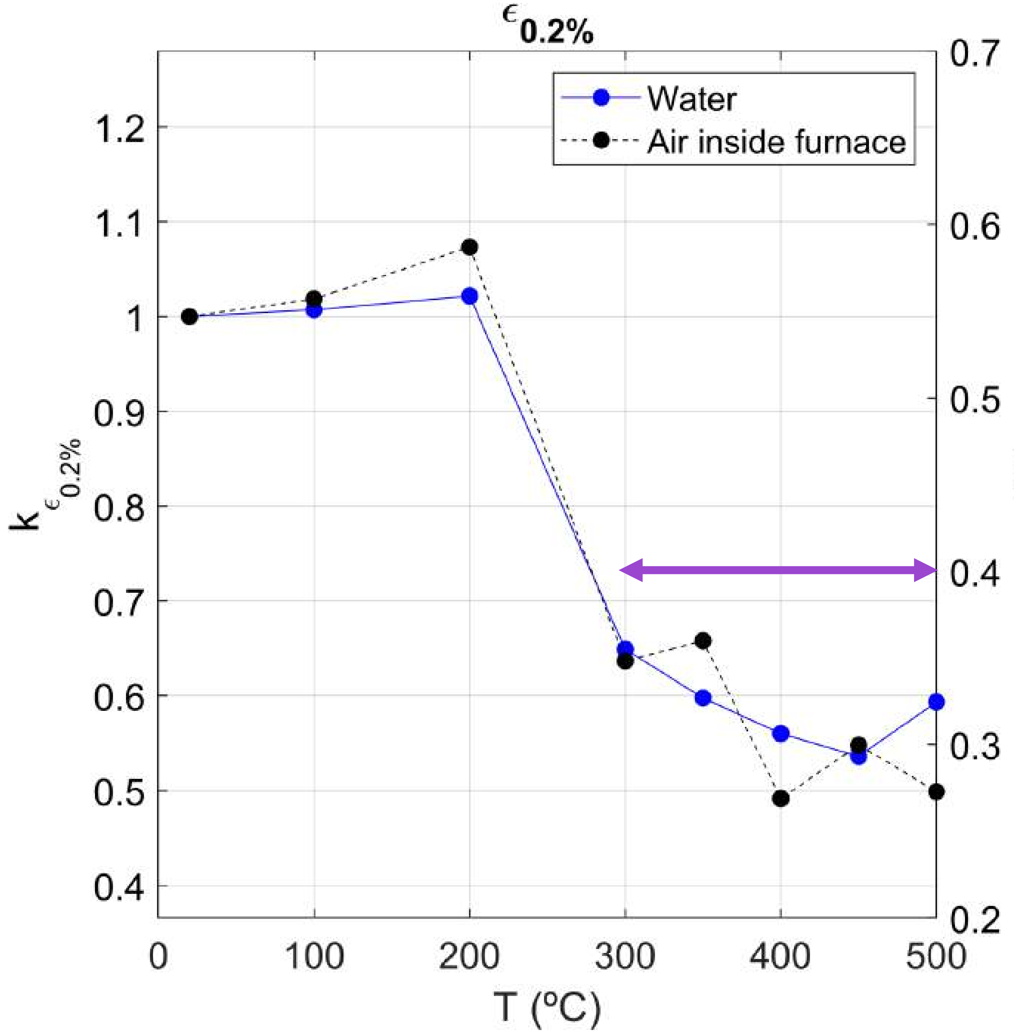


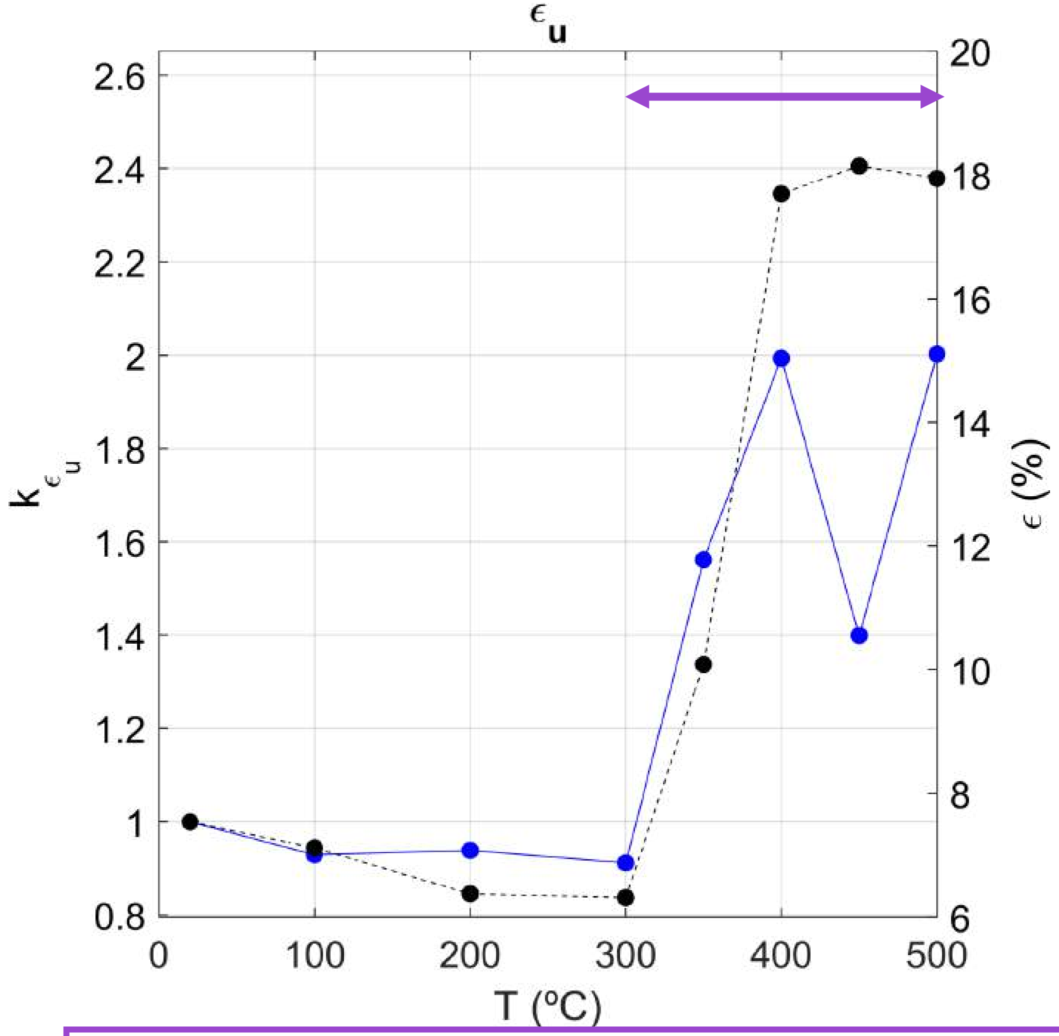


T=20-200ºC: $f_{0.2\%}$ and f_u remain unaltered

T>300ºC: significant loss of strength

Reduction factors

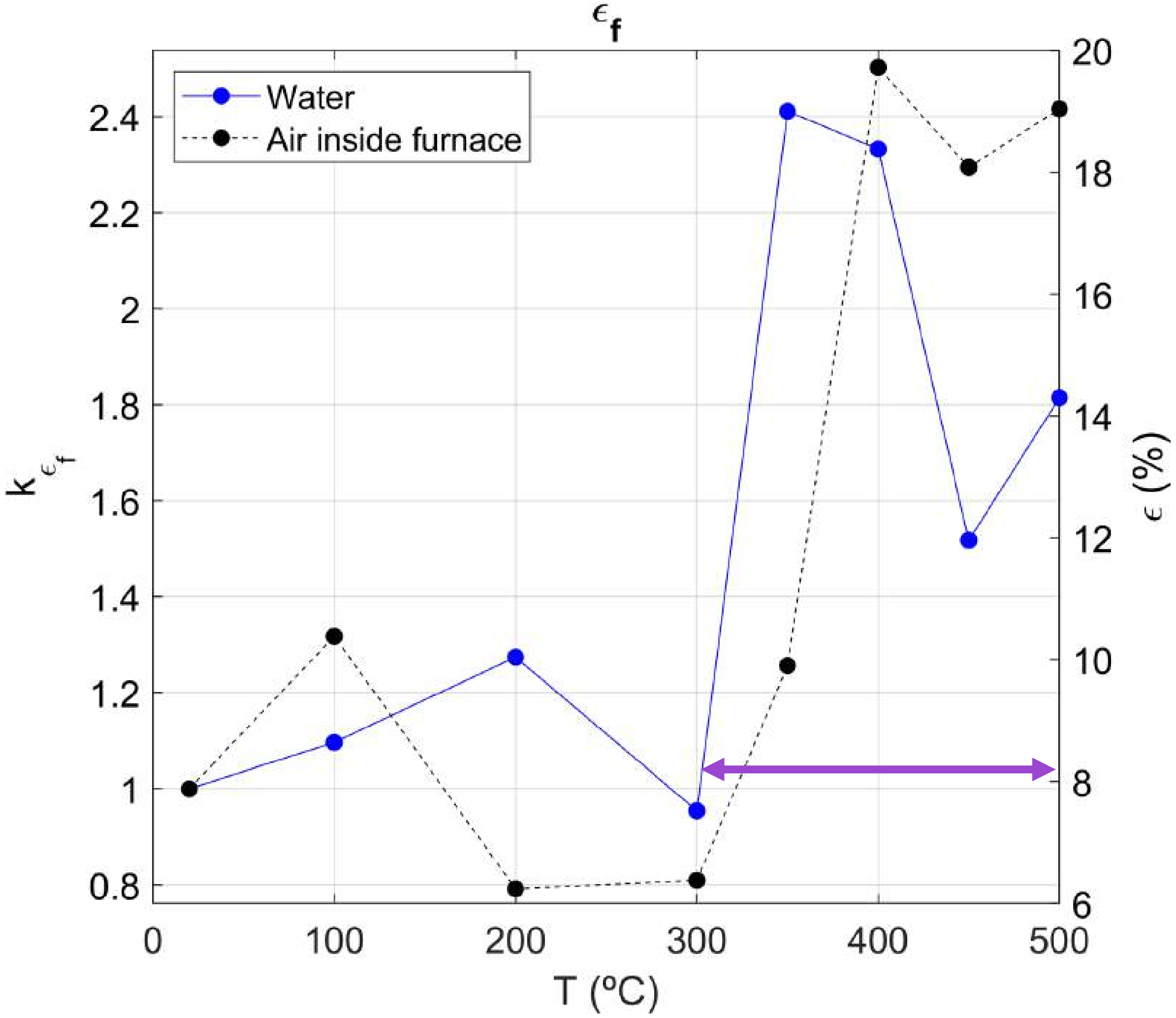




T=20-200ºC: $\varepsilon_{0.2\%}$ and ε_u remain unaltered

T=300-500ºC: $\varepsilon_{0.2\%}$ decrease and ε_u increases, resulting in increased ductility

Reduction factors



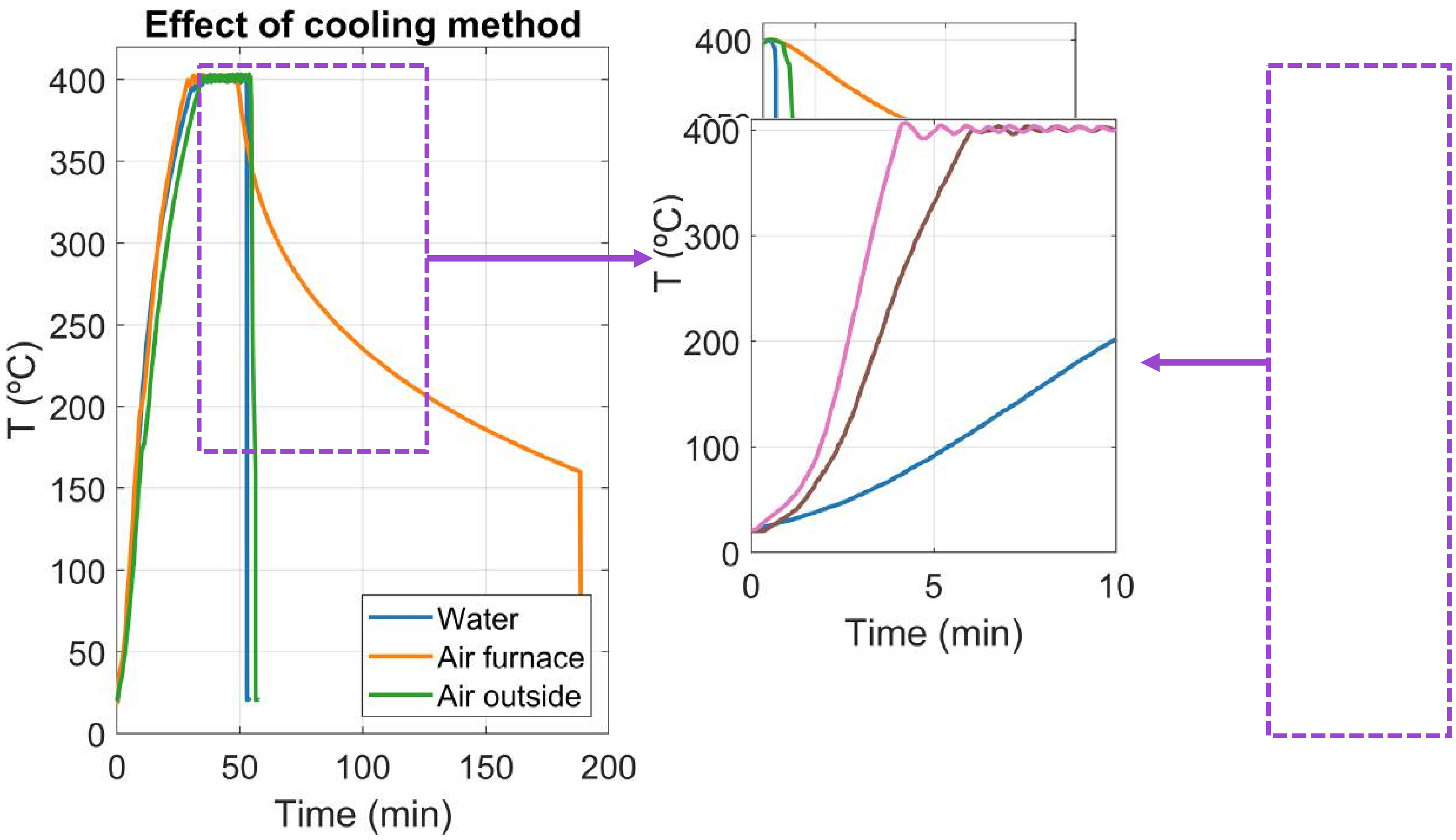
The increase in ductility is also observed in terms of fracture strain (elongation)

Test results

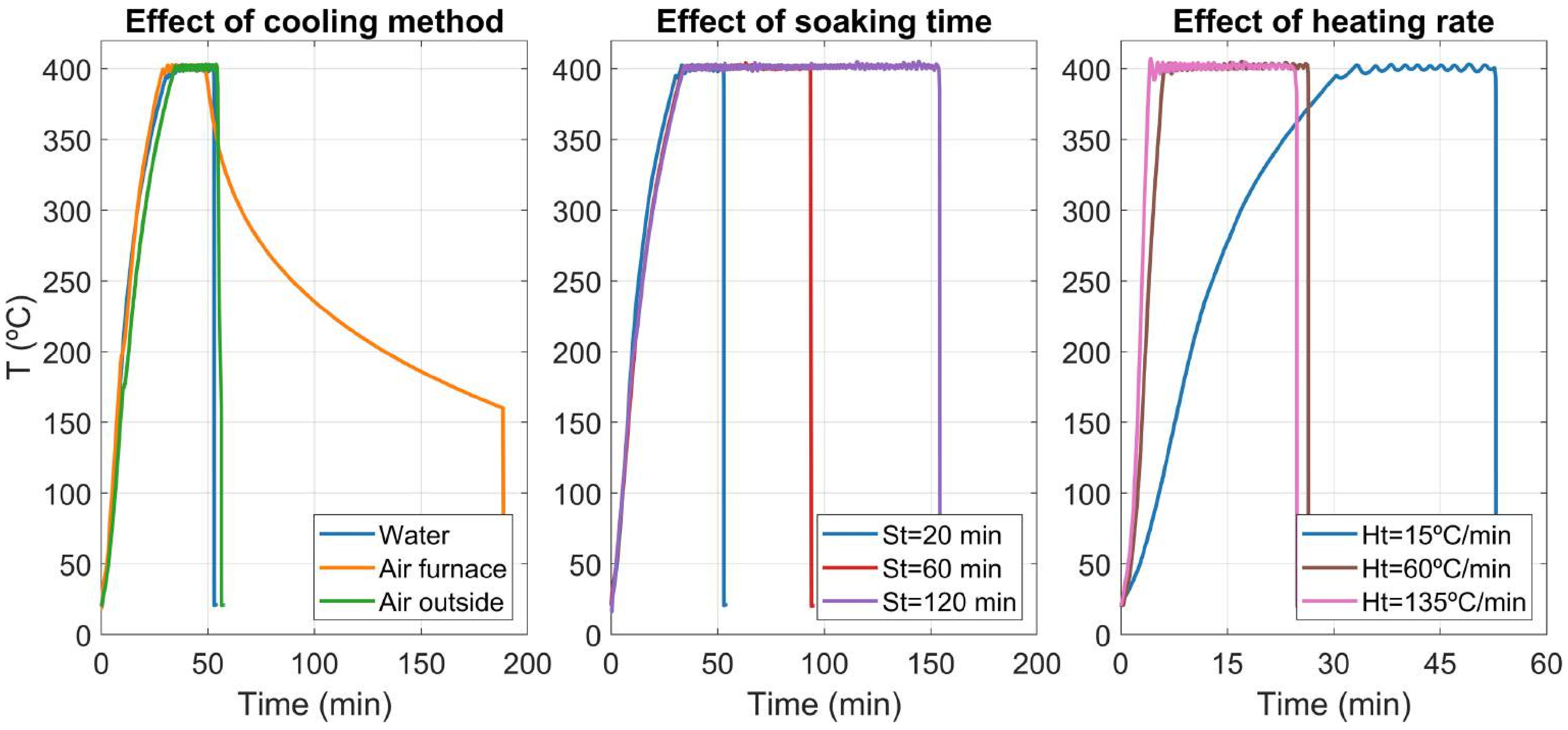
Programme 2

University of Hertfordshire UH

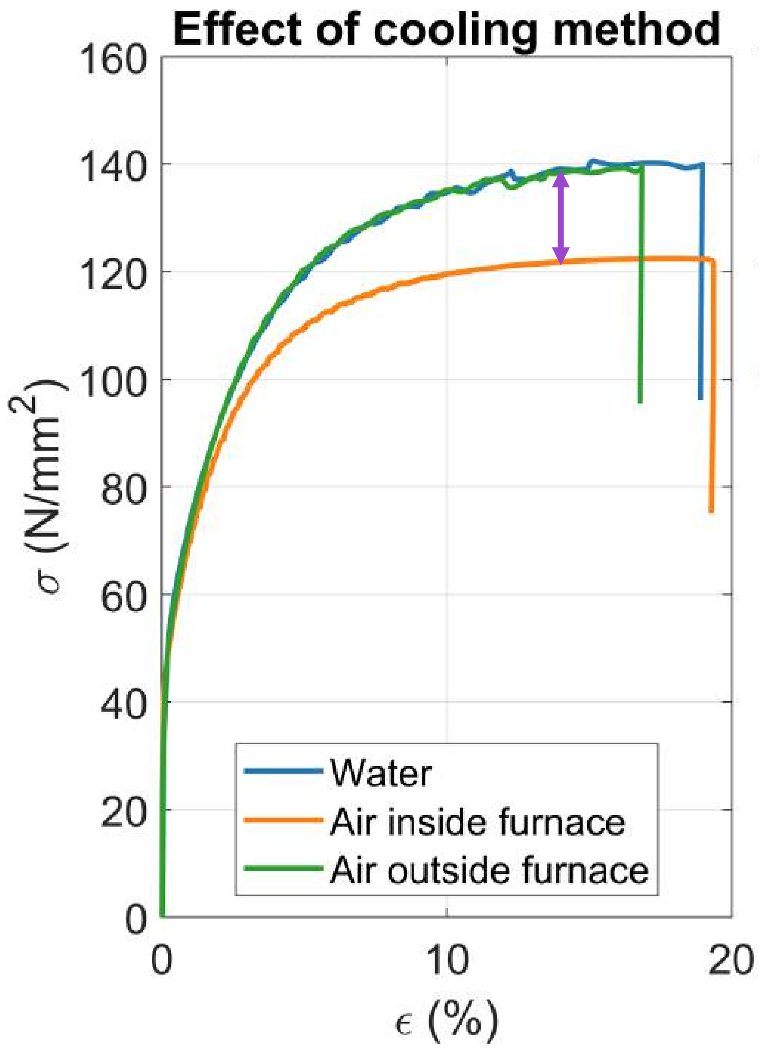
Effect of cooling method, soaking time and heating rate



Effect of cooling method, soaking time and heating rate

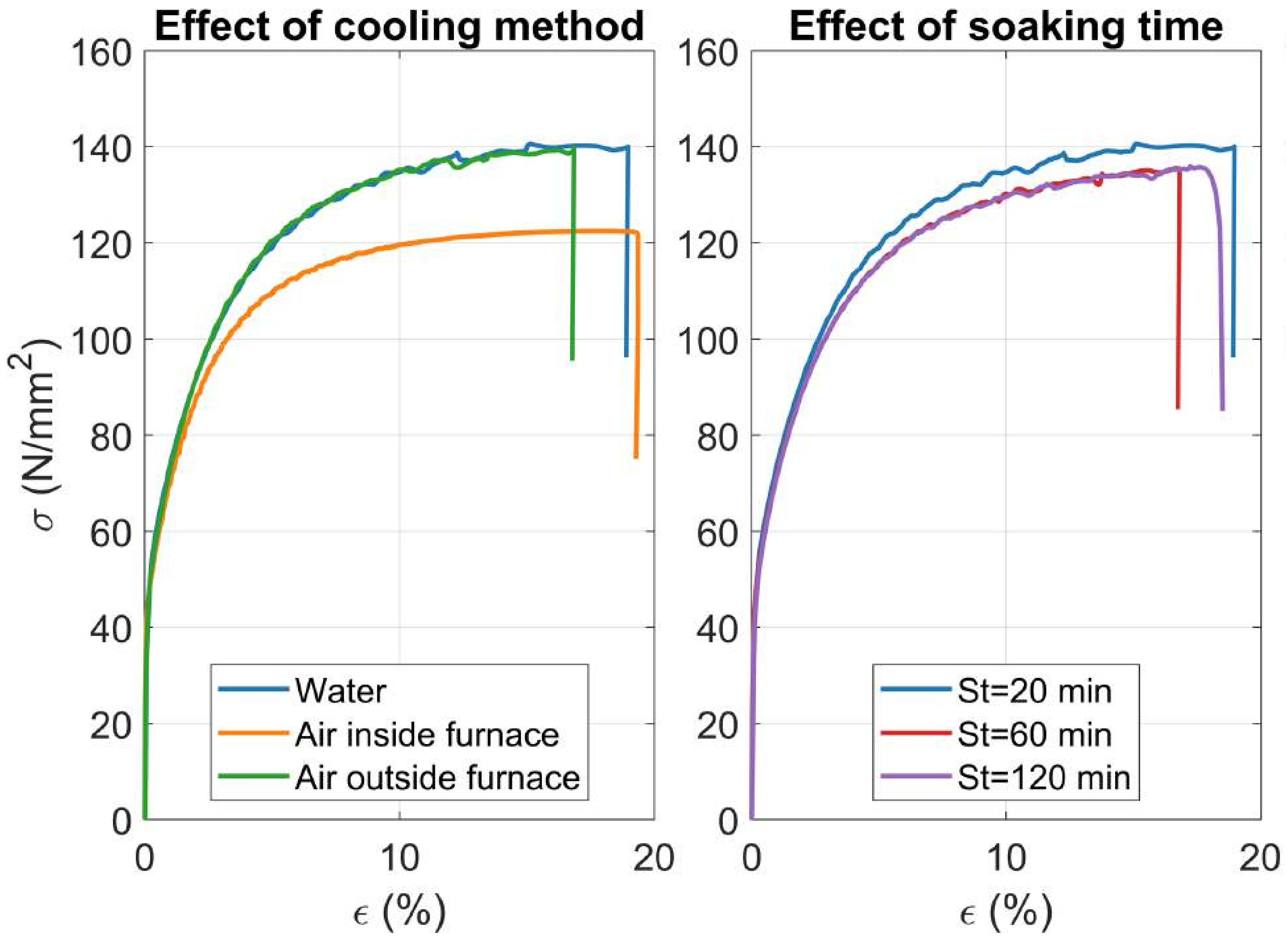


Effect of cooling method, soaking time and heating rate



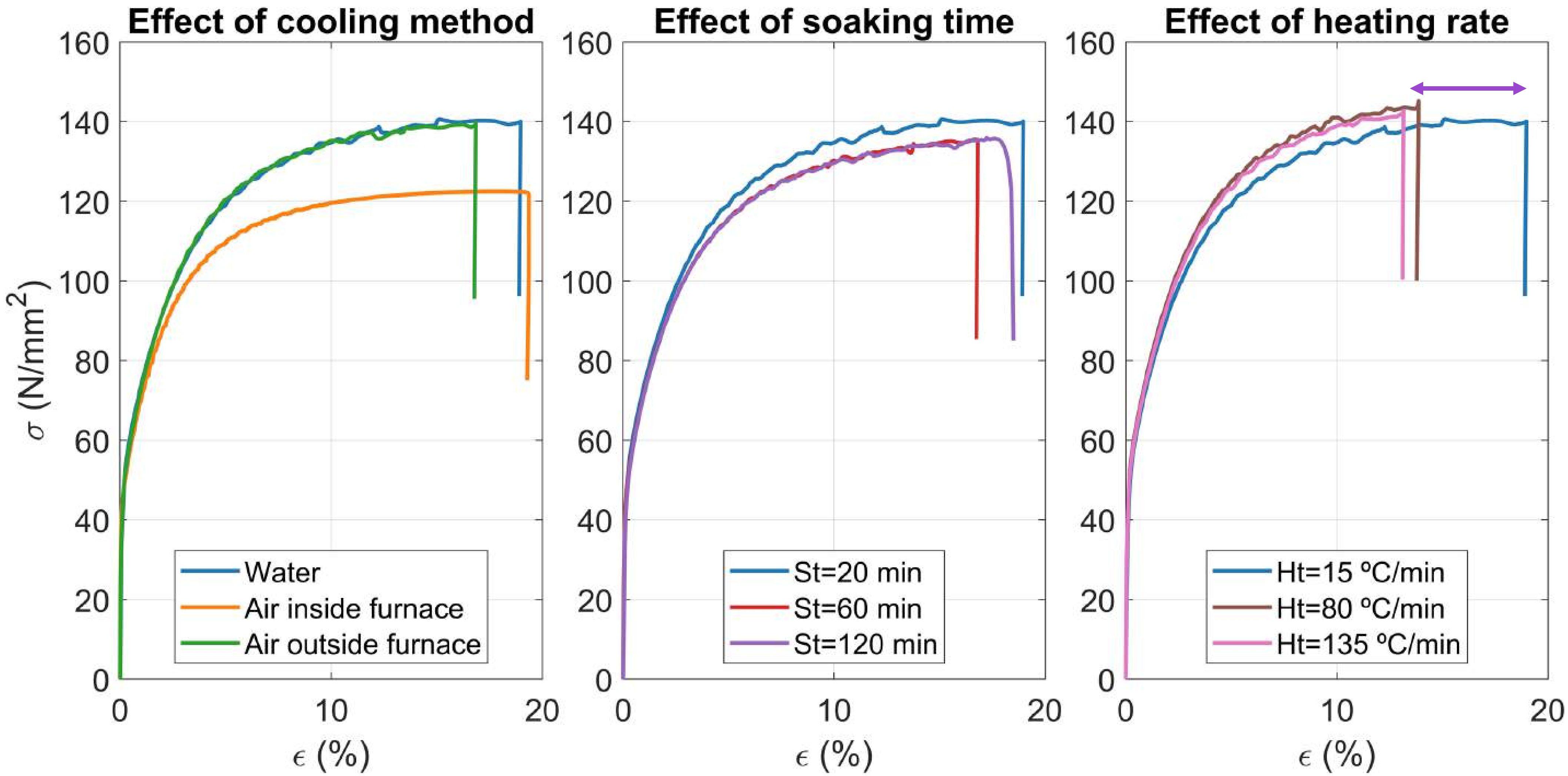
A 13% decrease in ultimate strength for cooling=air inside furnace

Effect of cooling method, soaking time and heating rate



A slight decrease in ultimate strength (4%) when St=60 and 120min

Effect of cooling method, soaking time and heating rate



A slight increase (4%) in ultimate strength is observed as the heating rate increases

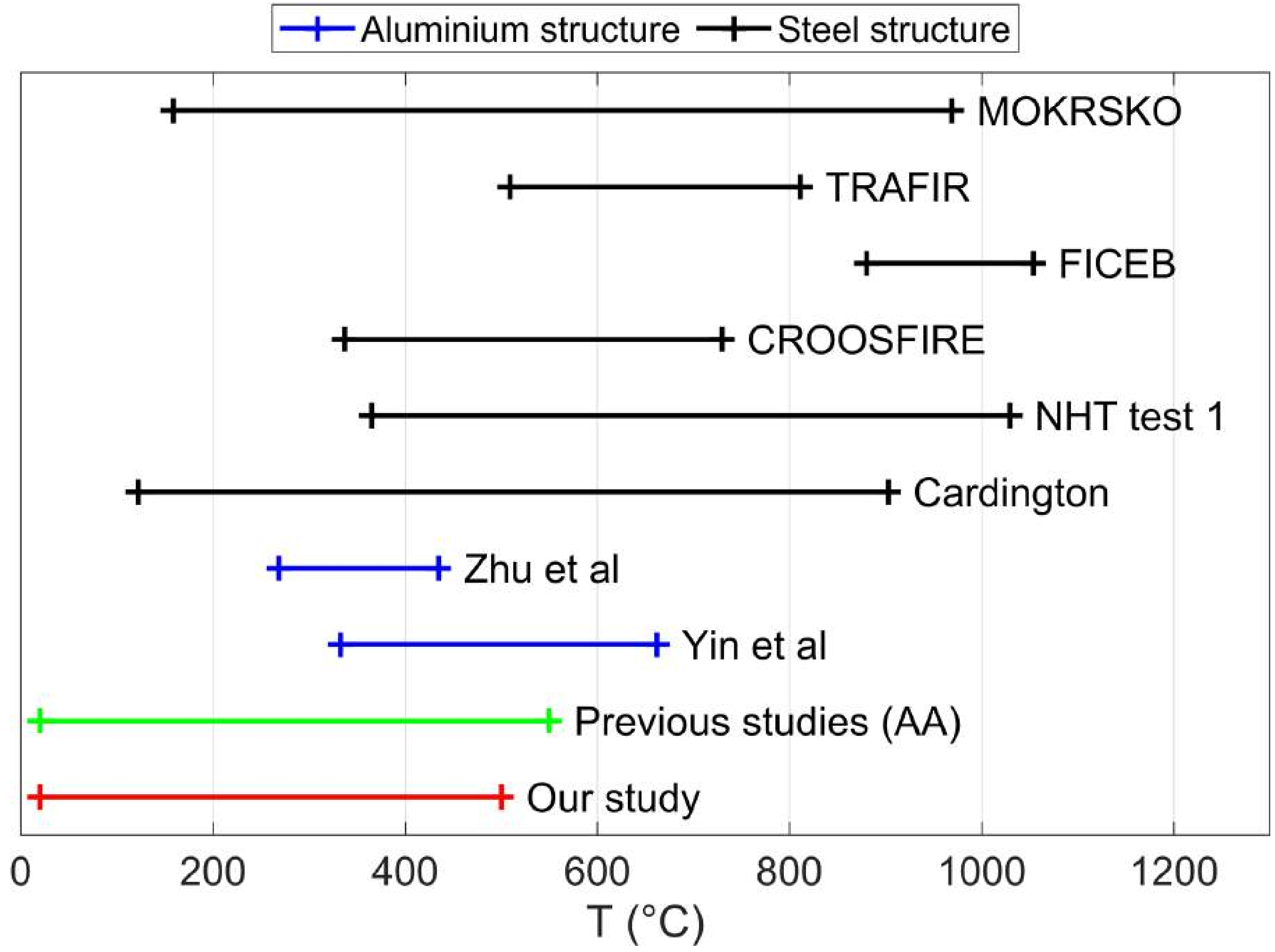
A 23% decrease in ultimate strain is observed as the heating rate increases

Conclusions

Post-fire mechanical properties of AAs

→ Effect of Tº

- $f_{0.2\%}$ and f_u decreases for T>200ºC
- Ductility increases for T>300ºC

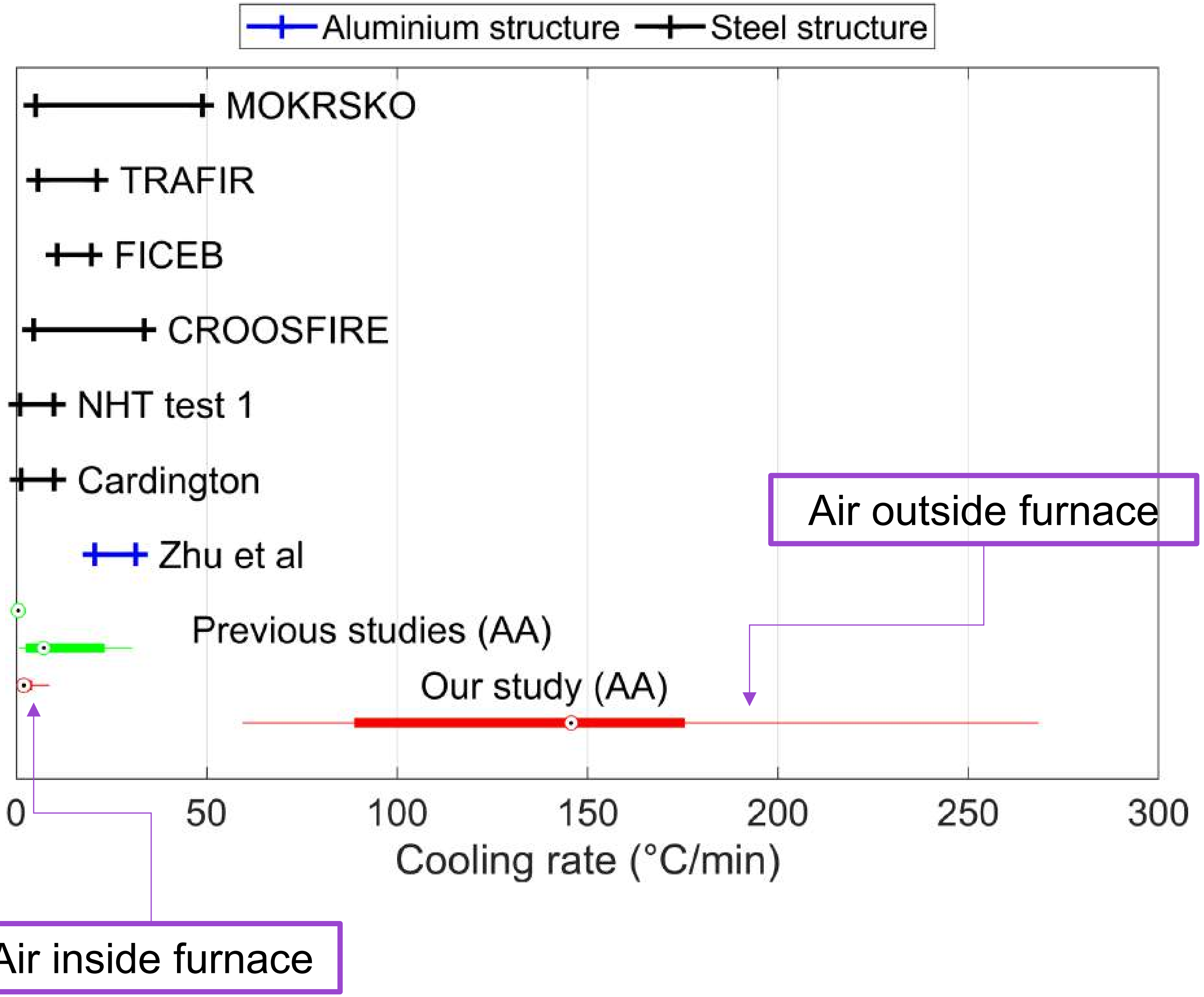


Conclusions

Post-fire mechanical properties of AAs

Effect of cooling method

- No significant effect for T<350ºC
- For T>400ºC, water cooling method produces higher reduction factors ($f_{0.2\%}$ and f_u)
- For T> 400ºC, water cooling method produces lower ductility

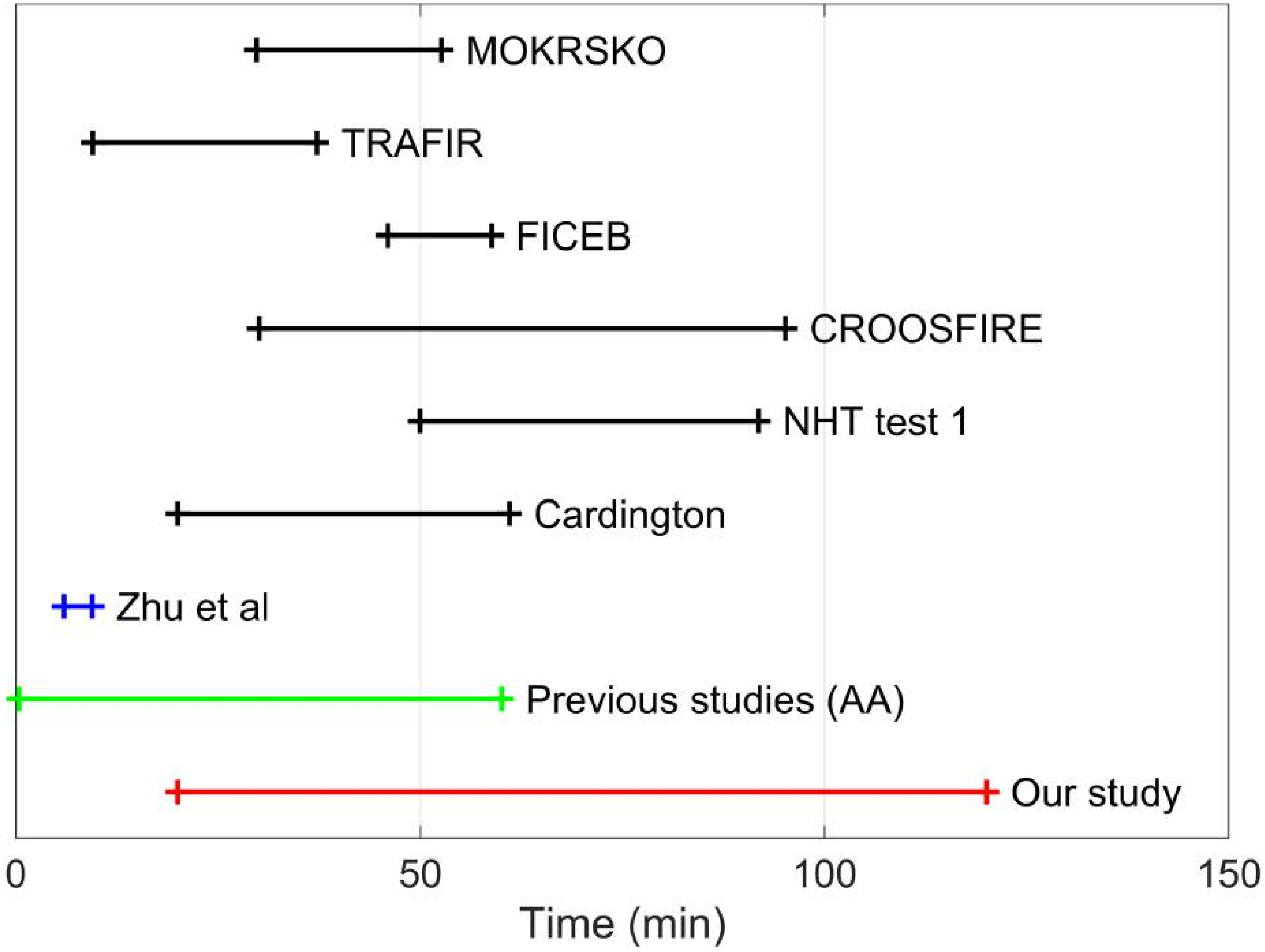


Conclusions

Post-fire mechanical properties of AAs

Effect of soaking time

Soaking time has minor effect on mechanical properties



Conclusions

Post-fire mechanical properties of AAs

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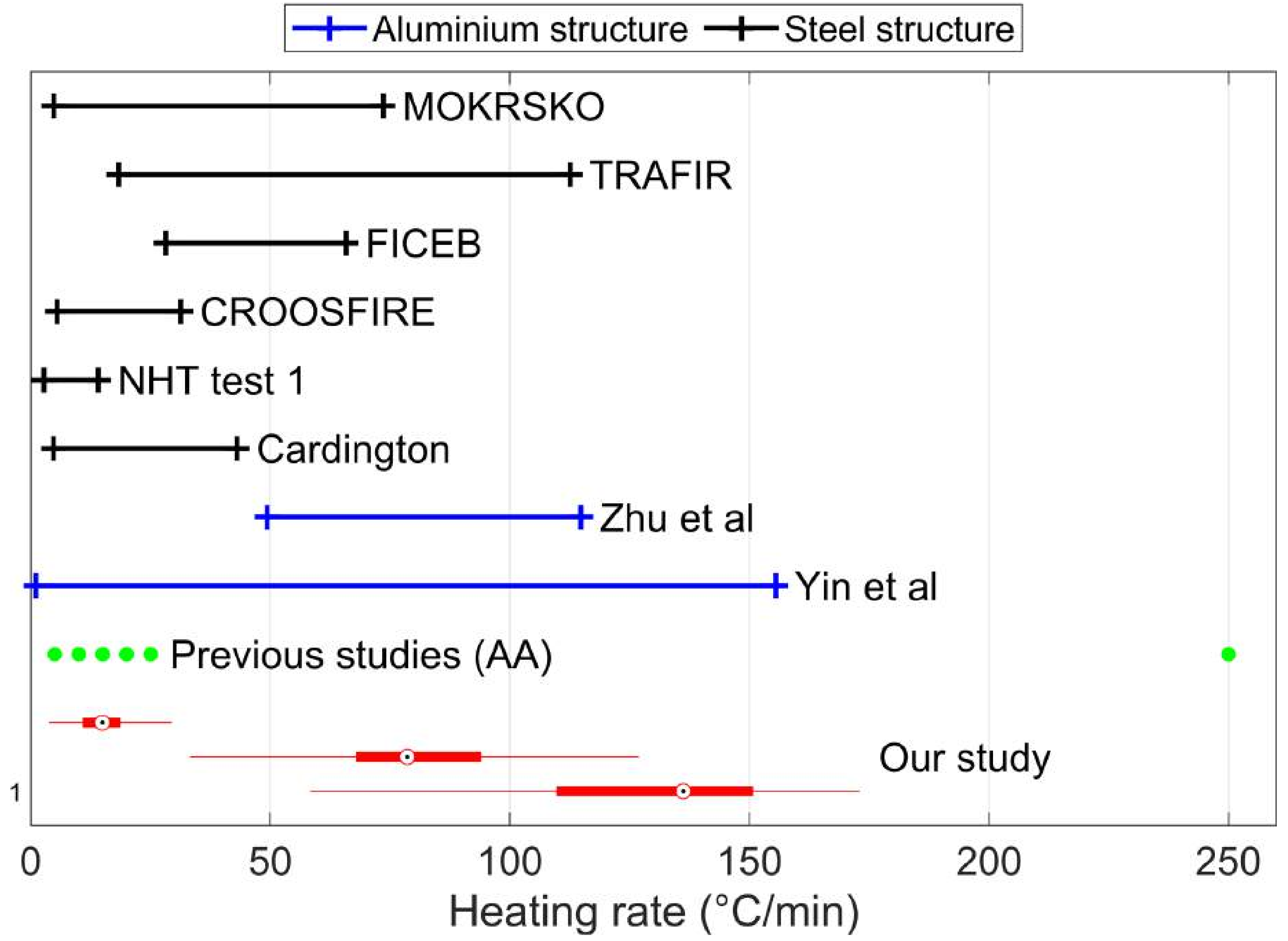
Effect of heating rate

- Heating rate has a minor effect on ultimate strength
- A decrease in ductility is observed as heating rate increases



Next stages

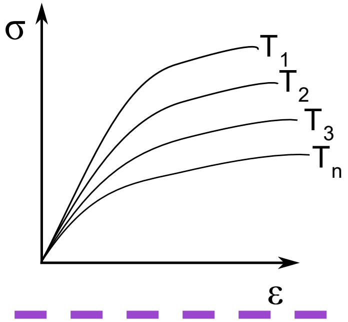
Stage 1
Mechanical properties

Stage 2
Microstructure

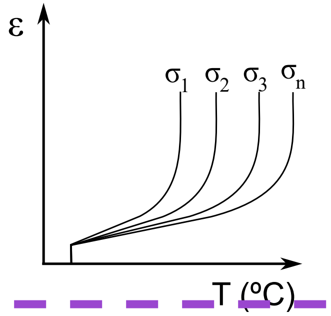
Stage 3
Connections

Stage 4
Structural level

Steady tests



Transient tests



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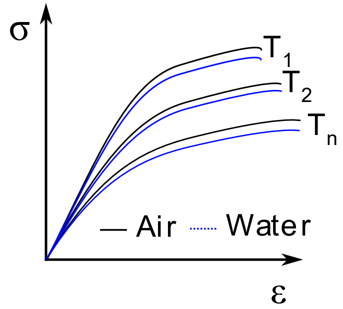
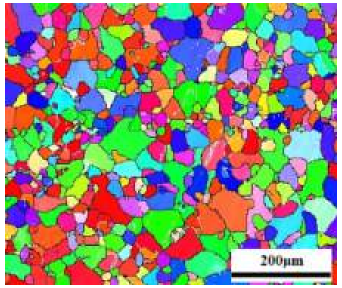


AA6005A-T6 and 7020-T6

SEM+EBSD



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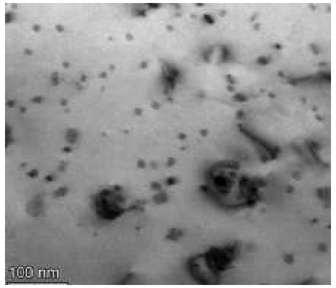

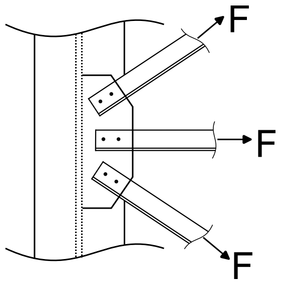

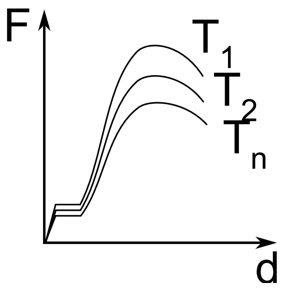

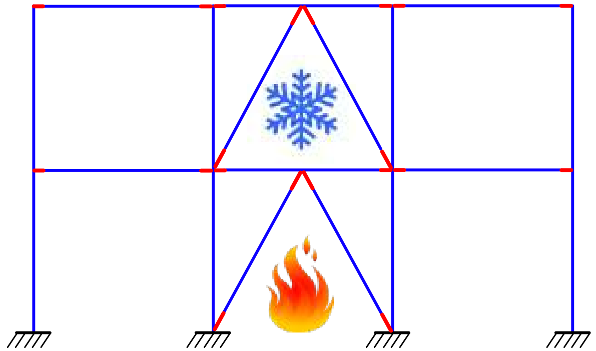

Thank you

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STRUCTURES IN FIRE FORUM

References

[1] Y. Sun, "The use of aluminum alloys in structures: Review and outlook," *Structures*, vol. 57, 2023, doi: 10.1016/j.istruc.2023.105290.

[2] X. You *et al.*, "A review of research on aluminum alloy materials in structural engineering," 2024. doi: 10.1016/j.dibe.2023.100319.

[3] Uni En, "BS EN 1999-1-1: 2023 - Eurocode 9: Design of aluminium structures - Part 1-1: General Rules," 2023.

[4] Uni En, "BS EN 1999-1-2: 2023 - Eurocode 9: Design of aluminium structures - Part 1-2: Structural fire design," 2023.

[5] Z. Wang *et al.*, "Structural fire behaviour of aluminium alloy structures: Review and outlook," 2022. doi: 10.1016/j.engstruct.2022.114746.

[6] "WIENECKE." Accessed: Sep. 12, 2025. [Online]. Available: https://wienecke.cl/

[7] British Standards Institution, "ISO 6892-2:2018 Mettalic materials - Tensile testing - Part 2: Method of test at elevated temperature," *British Standard*, 2011.

[8] ASTM, "ASTM E21-2017 Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials," *ASTM Standards*, 2017.

[9] Z. Chen, J. Lu, H. Liu, and X. Liao, "Experimental investigation on the post-fire mechanical properties of structural aluminum alloys 6061-T6 and 7075-T73," *Thin-Walled Structures*, vol. 106, 2016, doi: 10.1016/j.tws.2016.05.005.

References

[10] Z. Wang, C. Ma, M. Li, Q. Han, H. T. Li, and D. Zhao, “Mechanical properties of 7A04-T6 high strength structural aluminium alloy at elevated temperatures and after cooling down,” *Thin-Walled Structures*, vol. 180, 2022, doi: 10.1016/j.tws.2022.109930.

[11] Y. Liu, H. Liu, and Z. Chen, “Post-fire mechanical properties of aluminum alloy 6082-T6,” *Constr Build Mater*, vol. 196, 2019, doi: 10.1016/j.conbuildmat.2018.10.237.

[12] H. Li, R. Feng, and C. Zhong, “Elevated-temperature and post-fire performance of 6063-T6 high-strength aluminum alloy: Experimental study, predictive equations and constitutive models,” *Constr Build Mater*, 2024.

[13] L. Yin *et al.*, “High-temperature mechanical properties of constructional 6082-T6 aluminum alloy extrusion,” *Structures*, vol. 48, 2023, doi: 10.1016/j.istruc.2023.01.043.

[14] P. T. Summers, S. W. Case, and B. Y. Lattimer, “Residual mechanical properties of aluminum alloys AA5083-H116 and AA6061-T651 after fire,” *Eng Struct*, vol. 76, 2014, doi: 10.1016/j.engstruct.2014.06.033.

[15] Y. Huang and B. Young, “Post-fire behaviour of ferritic stainless steel material,” *Constr Build Mater*, vol. 157, pp. 654–667, Dec. 2017, doi: 10.1016/j.conbuildmat.2017.09.082.

[16] Y. Huang and B. Young, “Mechanical properties of lean duplex stainless steel at post-fire condition,” *Thin-Walled Structures*, vol. 130, pp. 564–576, Sep. 2018, doi: 10.1016/j.tws.2018.06.018.

[17] L.-A. Xie *et al.*, “Post-fire stress-strain response of structural ferritic stainless steels,” *J Constr Steel Res*, vol. 196, p. 107389, Sep. 2022, doi: 10.1016/j.jcsr.2022.107389.

[18] T. Lennon and D. Moore, “The natural fire safety concept—full-scale tests at Cardington,” *Fire Saf J*, vol. 38, no. 7, pp. 623–643, Nov. 2003, doi: 10.1016/S0379-7112(03)00028-6.

References

[19] F. Wald *et al.*, “Fire test on an administrative building in Mokrsko,” *CTU in Prague*, 2010.

[20] C. of steel and composite structures under natural fire conditions (COSSFIRE) *et al.*, *Connections of steel and composite structures under natural fire conditions (COSSFIRE)*. Publications Office of the European Union, 2011.

[21] T. Gernay and J.-M. Franssen, “Fire resistance of long span cellular beam made of rolled profiles (FICEB) report: Ulster test numerical simulation,” 2009.

[22] L. Choe *et al.*, “Fire resilience of a steel-concrete composite floor system: full-scale experimental evaluation for U.S. prescriptive approach with a 2-hour fire-resistance rating (Test #1),” *Technical Note (NIST TN)-2203*, 2021.

[23] L. Yin, Z. Ni, F. Fan, P. Qiu, Q. Kan, and Y. Ou-yang, “Temperature field characteristics of cylindrical aluminum alloy reticulated roof system under localized fire,” *Fire Saf J*, vol. 121, p. 103267, May 2021, doi: 10.1016/j.firesaf.2020.103267.

[24] S. Zhu, X. Guo, S. Jiang, S. Zong, and C. Chen, “Experimental Study on the Fire-Induced Collapse of Single-Layer Aluminum Alloy Reticulated Shells with Gusset Joints,” *Journal of Structural Engineering*, vol. 146, no. 12, Dec. 2020, doi: 10.1061/(ASCE)ST.1943-541X.0002819.

[25] A. Nadjai *et al.*, “Large scale fire test: The development of a travelling fire in open ventilation conditions and its influence on the surrounding steel structure,” *Fire Saf J*, vol. 130, p. 103575, Jun. 2022, doi: 10.1016/j.firesaf.2022.103575.