# Development of formable steel grades through alternative steelmaking technologies

Hannah Clarke

Supervisors: Prof. Cameron Pleydell-Pearce, Dr Richard Curry, Martyn Dranfield

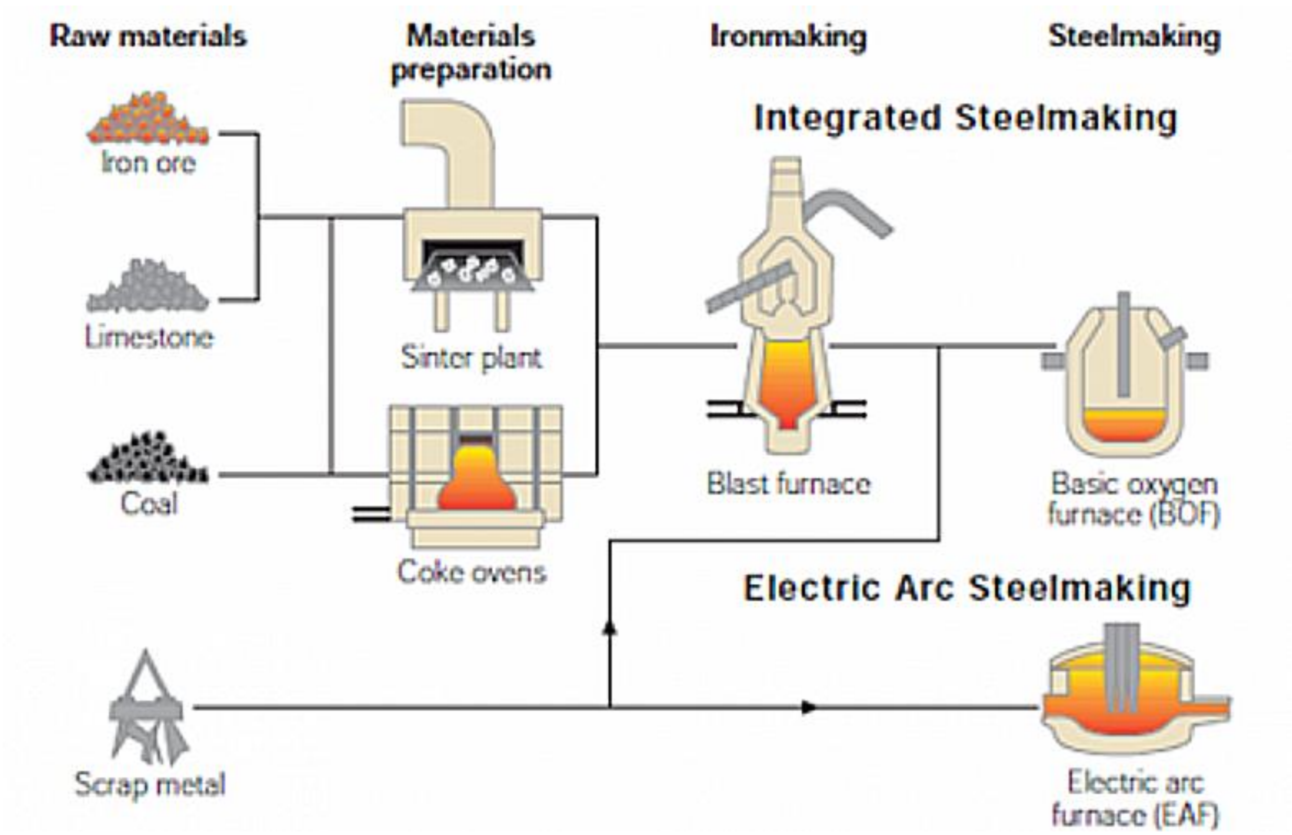
Prifysgol Abertawe Swansea University

TATA STEEL

UKRI Engineering and Physical Sciences Research Council

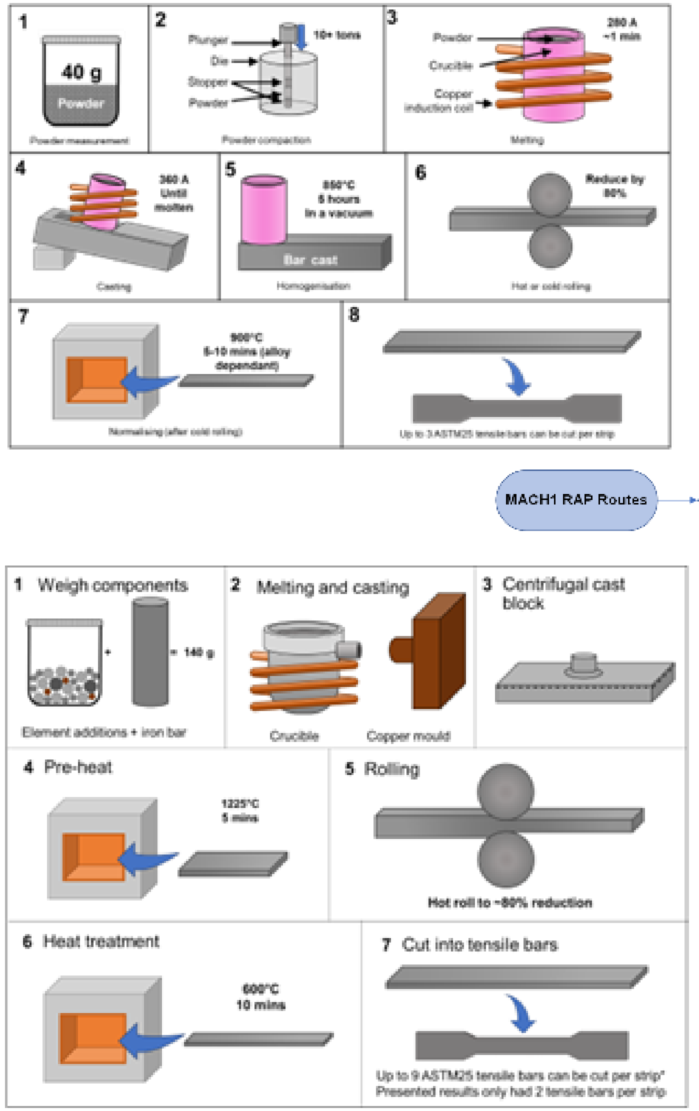
Undeb Ewropeaidd European Union
Llywodraeth Cymru Welsh Government
Cronfa Gymdeithasol Ewrop European Social Fund

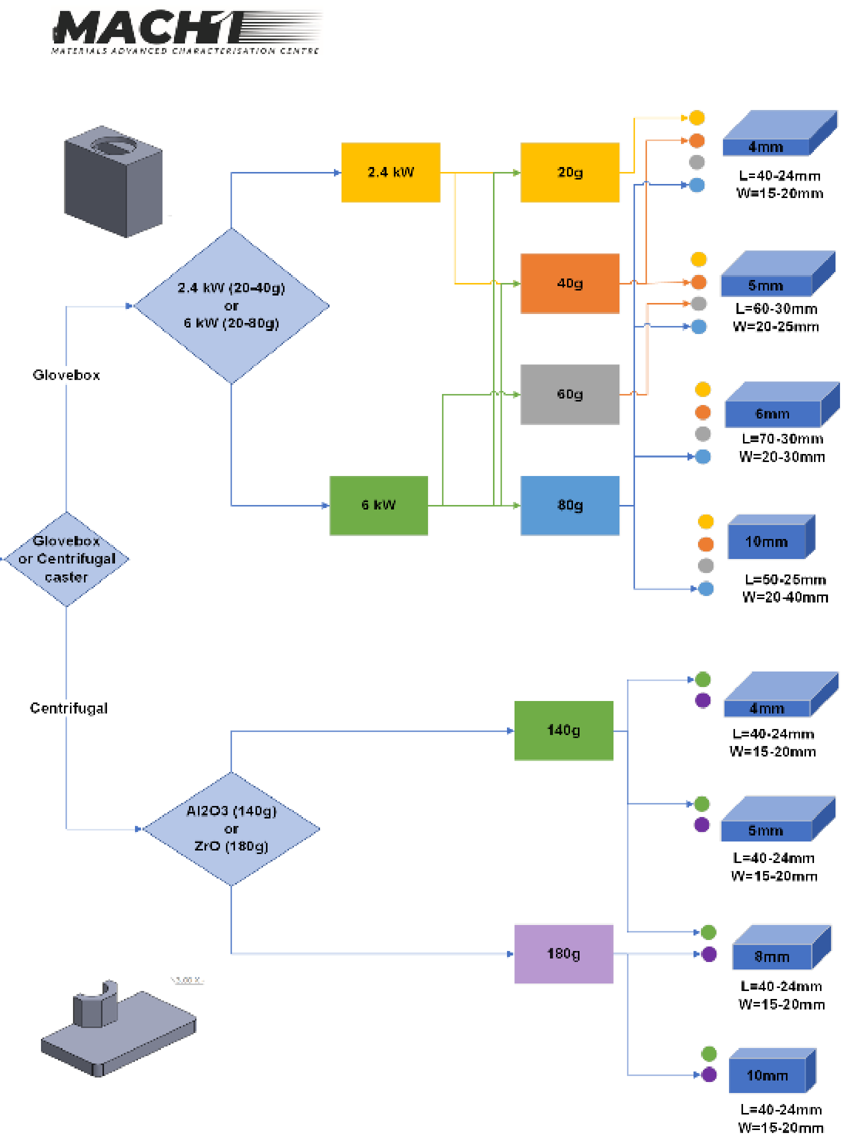
# Background to project

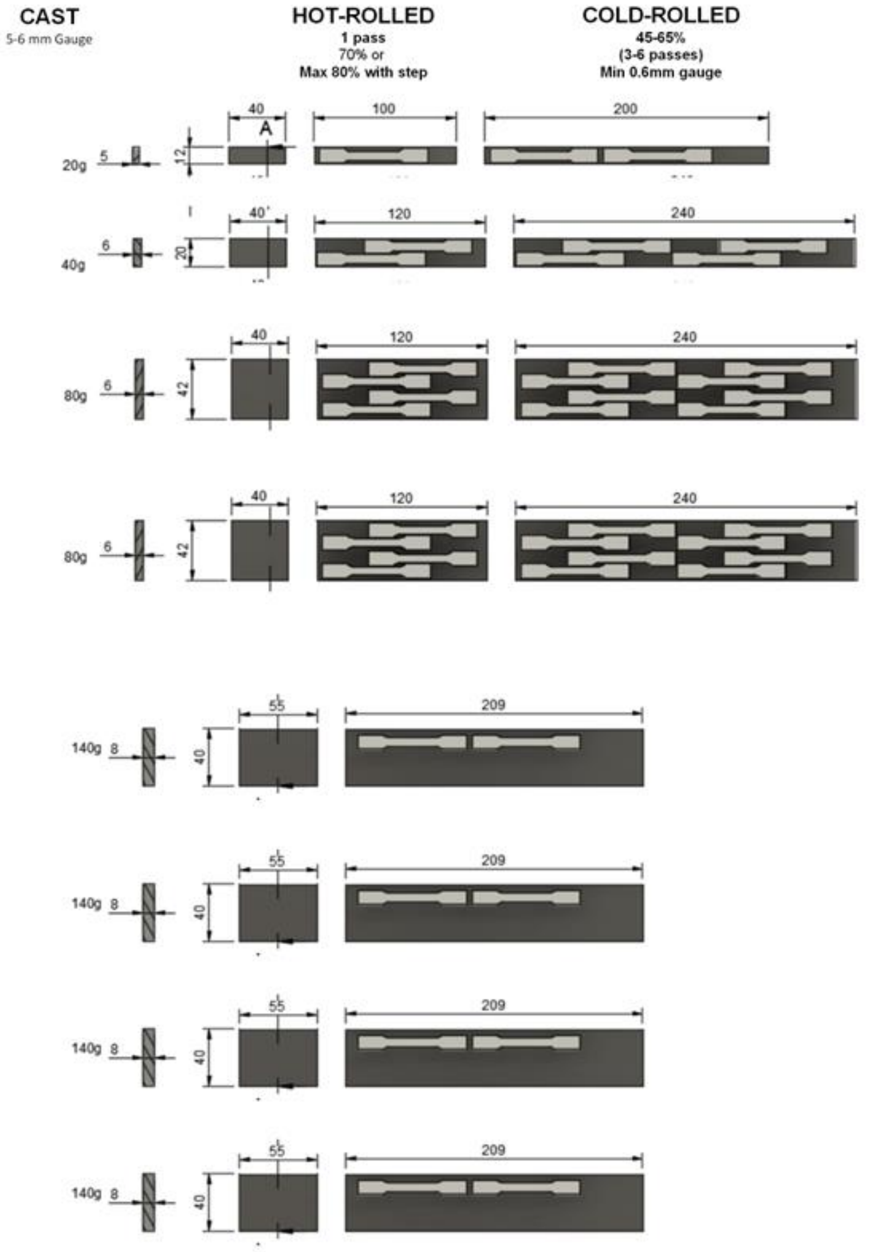



- Many environmental benefits of EAF steelmaking
- EAF steel typically contains higher carbon and nitrogen levels than BF/BOF route
- Very low levels of carbon and nitrogen needed for IF steel
- Aiming to understand capability of EAF steelmaking with regards to IF steel

# MACH1 RAP line



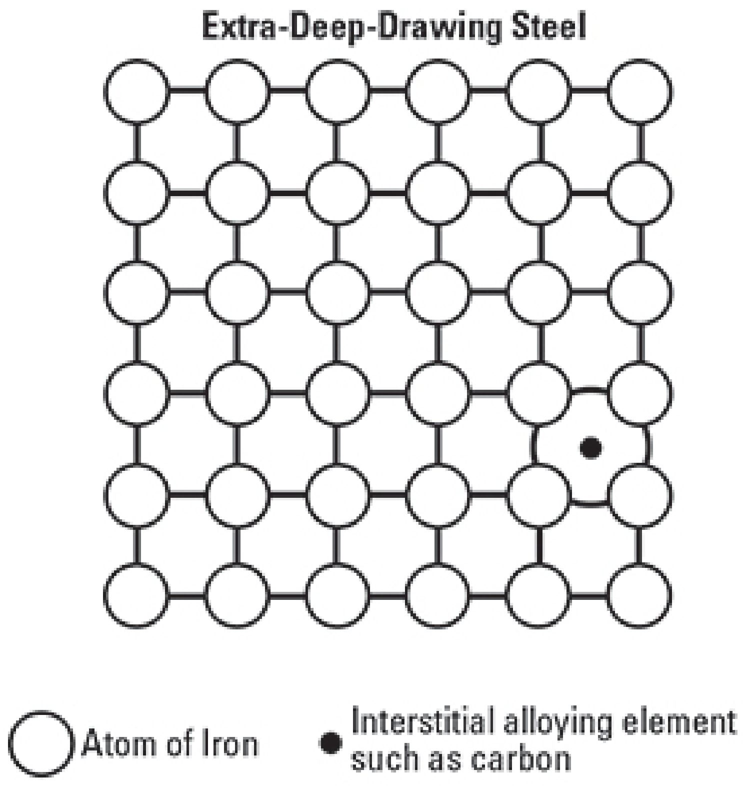



# Research Question

What is the effect of increasing nitrogen and carbon levels on the product performance of formable strip steels?

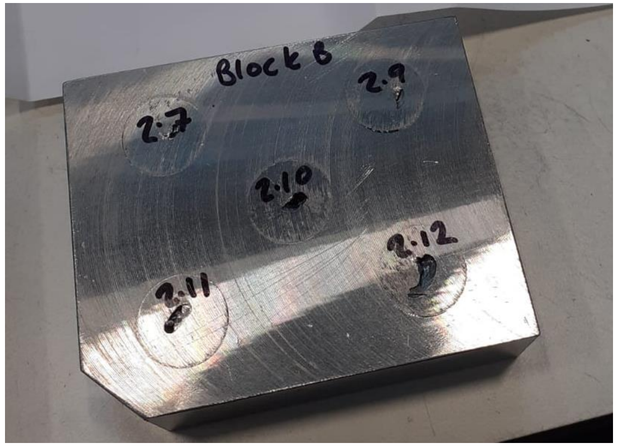
## Metallurgical principles

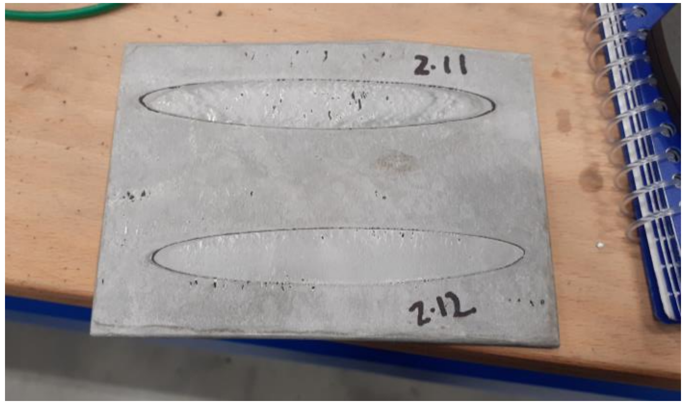
- Interstitial carbon and nitrogen strain the iron lattice and decrease the formability of steel
- Ti is added to scavenge interstitial atoms from the solid solution through the formation of precipitates
- Typical IF steels are highly formable and commonly used in automotive applications
- Ti and N react at high temperatures during steelmaking and continuous casting to form a stable compound, TiN, which will not decompose during subsequent treatments of the steel



# InTrap study

- Aiming to investigate effect of higher nitrogen levels in IF steels by making lab IF casts of fixed excess Ti (0.02 wt%) and different nitrogen levels.
- Following the InTrap route, the smaller lab scale casts (approx. 100g) were inserted into a larger transfer bar before further processing, allowing processing parameters more representative of those at an industrial scale.




# Summary of OES/Eltra/LECO results for InTrap casts

| | Fe | C | Mn | Al | Si | S | P | Ti | N eltra (ppm) | Excess Ti (wt%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Target (wt %) | 99.8 | 0.0019 | 0.080 | 0.045 | 0.004 | 0.007 | 0.010 | Variable | | |
| IF 2.1 | 99.723 | 0.0021 | 0.099 | 0.055 | 0.003 | 0.0007 | 0.0011 | 0.045 | 57.3 | 0.0164 |
| IF 2.3 | 99.727 | 0.0018 | 0.095 | 0.046 | 0.013 | 0.0008 | 0.0015 | 0.046 | 47.8 | 0.0205 |
| IF 2.4 | 99.739 | 0.0014 | 0.090 | 0.044 | 0.005 | 0.0009 | 0.0014 | 0.040 | 37.0 | 0.0180 |
| IF 2.5 | 99.68 | 0.0030 | 0.097 | 0.048 | 0.004 | 0.0013 | 0.002 | 0.066 | 56.0 | 0.0369 |
| IF 2.6 | 99.709 | 0.0039 | 0.098 | 0.051 | 0.002 | 0.0007 | 0.0018 | 0.066 | 60.3 | 0.0363 |
| IF 2.7 | 99.719 | 0.0009 | 0.101 | 0.038 | 0.004 | 0.0008 | 0.0015 | 0.062 | 35.3 | 0.0407 |
| IF 2.9 | 99.707 | 0.0009 | 0.102 | 0.048 | 0.004 | 0.001 | 0.002 | 0.051 | 37.3 | 0.0287 |
| IF 2.10 | 99.72 | 0.0031 | 0.091 | 0.046 | 0.006 | 0.001 | 0.0021 | 0.055 | 55.7 | 0.026 |
| IF 2.11 | 99.68 | 0.0043 | 0.107 | 0.061 | 0.006 | 0.0009 | 0.0022 | 0.062 | 39.3 | 0.0392 |
| IF 2.12 | 99.74 | 0.0012 | 0.097 | 0.042 | 0.004 | 0.0007 | 0.0023 | 0.046 | 19.7 | 0.0302 |

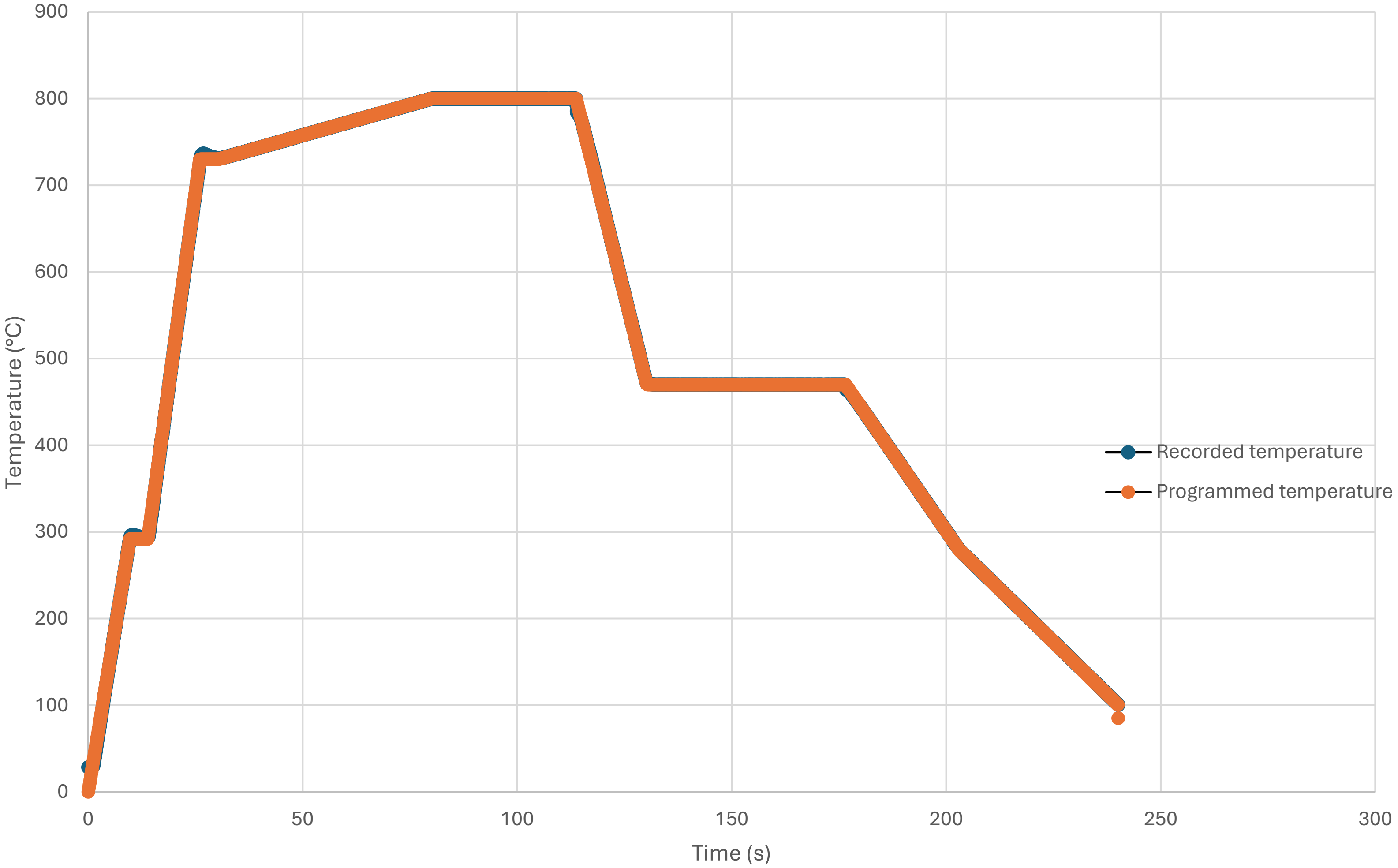
10 casts with varying N contents between 19.7ppm and 60.3ppm

Ti (excess) = Ti – (4C+ 3.42N + 1.5S)

# Gleeble cycle

- Each cast cut into 3 gleeble samples – M,L,R giving 30 gleeble samples

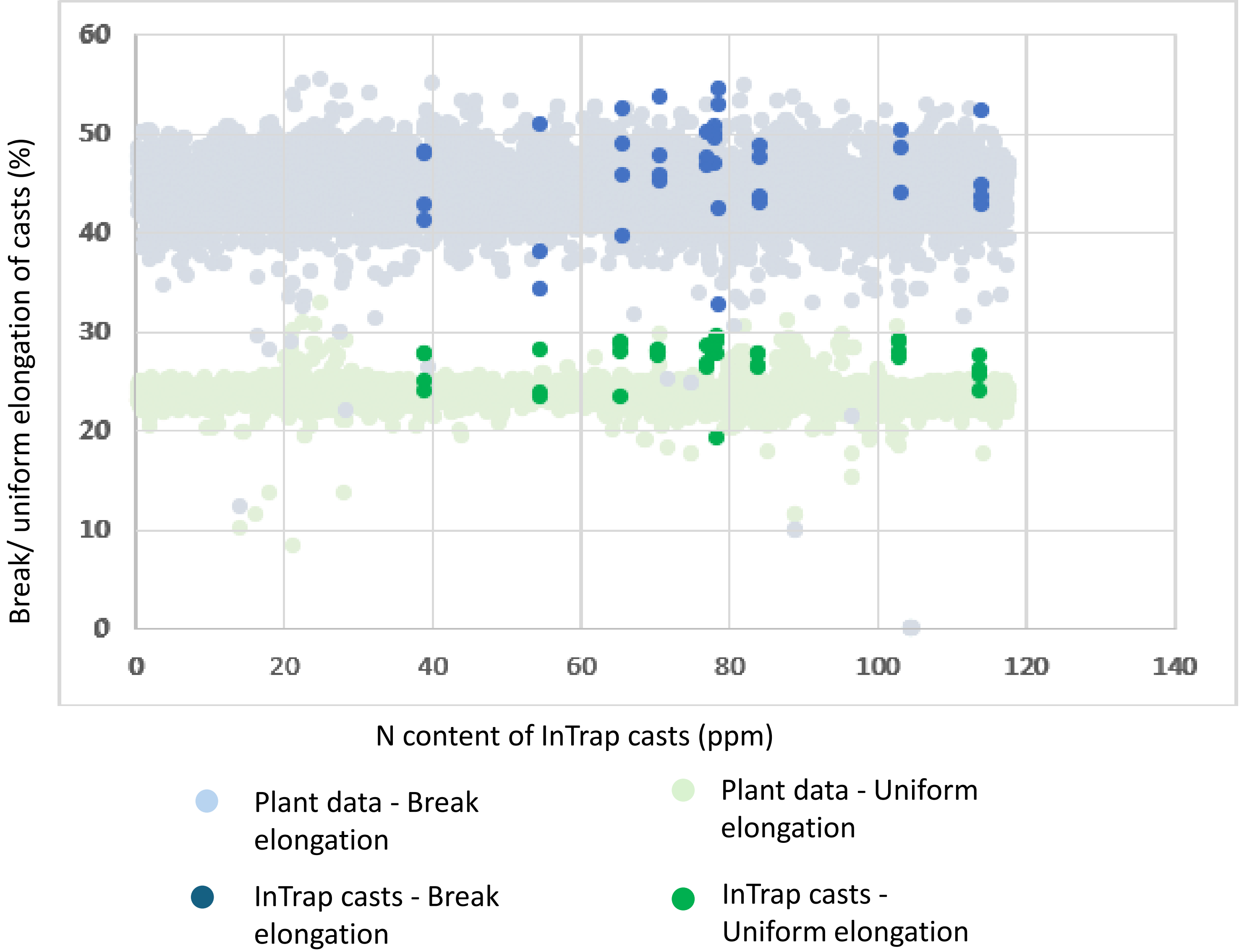
- Casts were annealed using the DX57 Zodiac cycle:




Gleeble cycle for IF 2.1L

# Tensile results – Break and Uniform elongation

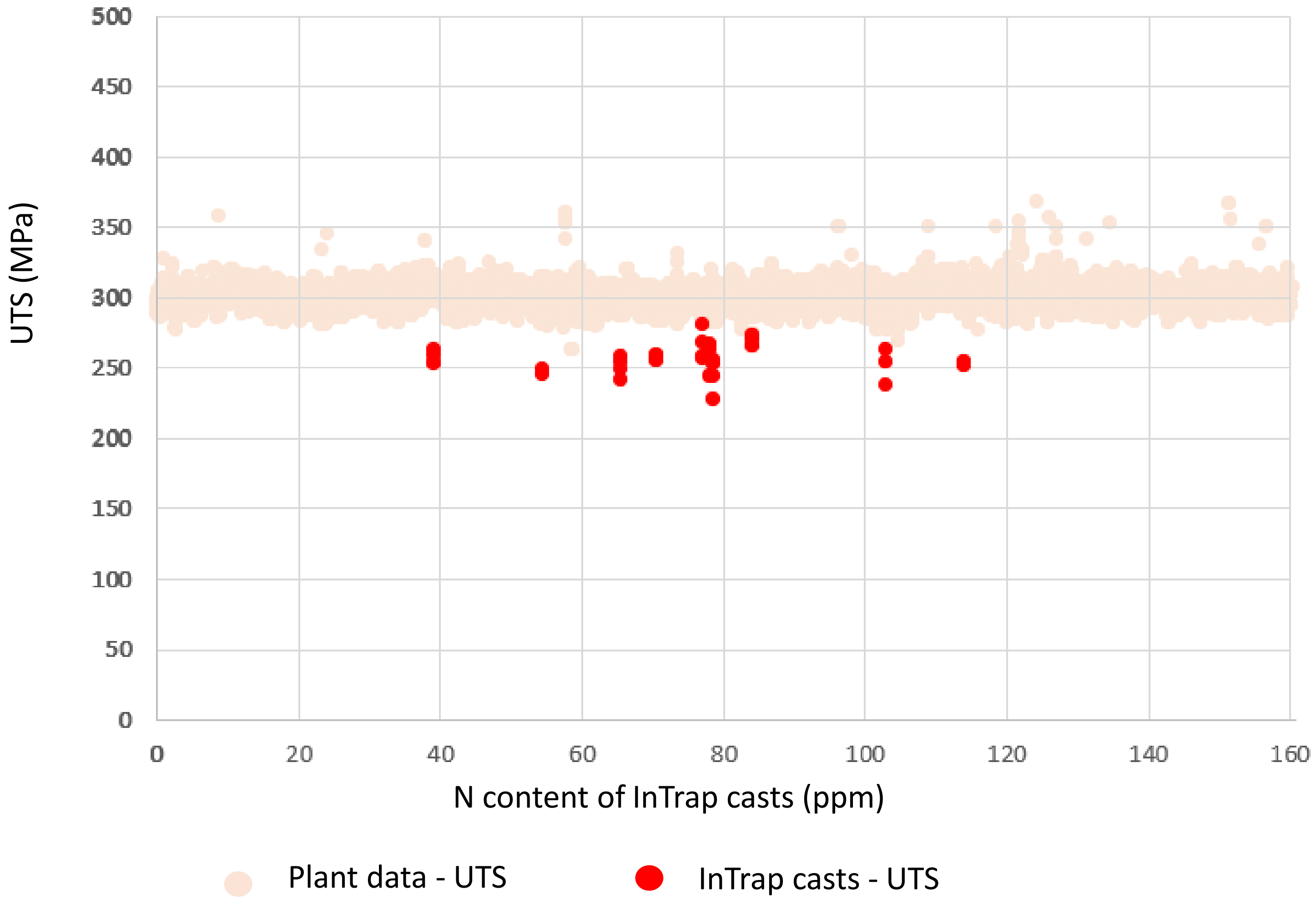
Comparison with plant data




- Expected Break elongation for DX57 ASTM25: 51%
- Expected Uniform elongation for DX57 ASTM25 : 26%
- Results for break elongation from the InTrap casts seem to sit within natural variation of plant data
- Uniform elongation values from the InTrap casts seem generally higher than plant data, although the average uniform elongation of the plant data (23.6±1%) is lower than the expected value for ASTM25 of 26%

# Tensile results - UTS

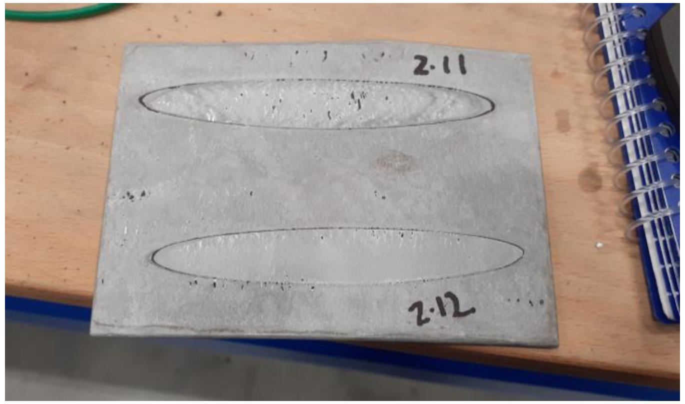
Comparison with plant data




- The UTS of the InTrap casts is lower than typical DX57 and largely outside the range of plant data
- Mean UTS of plant data is 302±10 MPa
- Expected UTS for DX57: 299 MPa

# Mechanical properties of InTrap carrier material

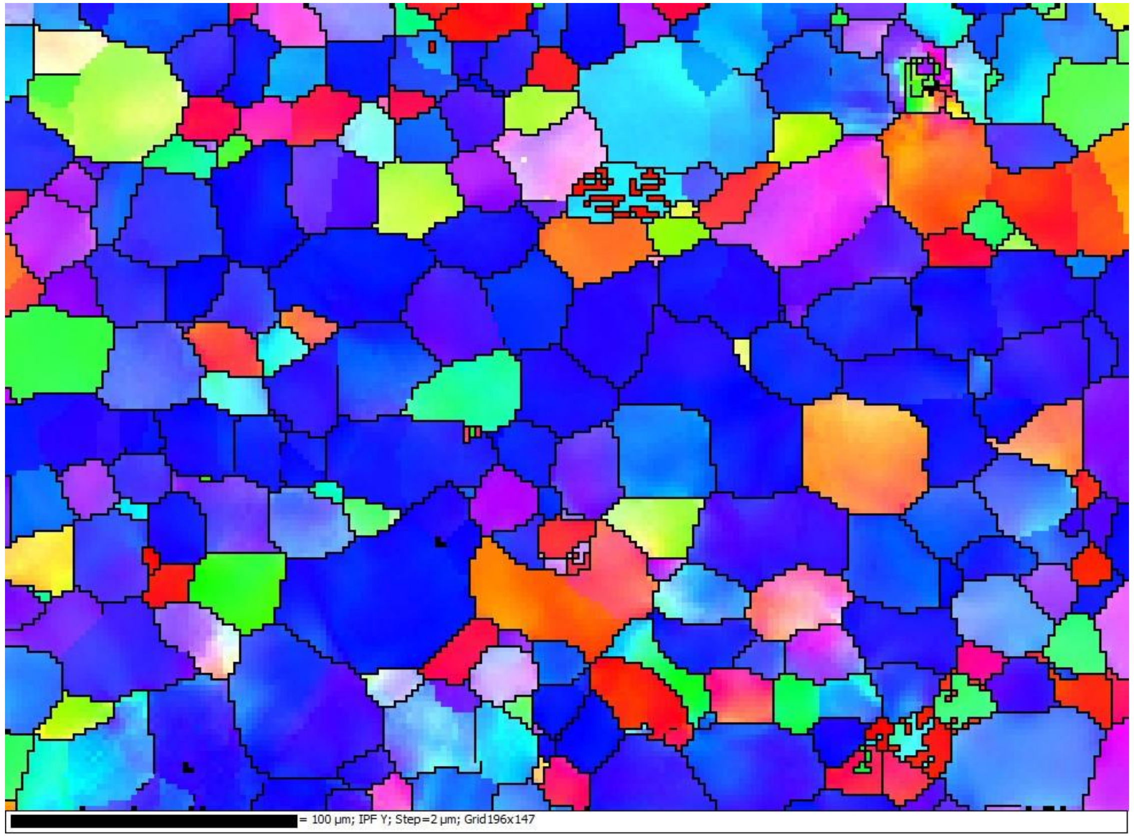
| | UTS (Mpa) | Break elongation (%) | Uniform elongation (%) | R value 20% |
|---|---|---|---|---|
| Expected | 299 | 51 | 26 | 2.01 |
| 2.5L NI | 303 | 48.2 | 26.6 | 2.23 |
| 2.9R NI | 297 | 51.2 | 26.7 | 2.43 |
| IF 2.10L NI | 300 | 49.5 | 26.8 | 1.95 |



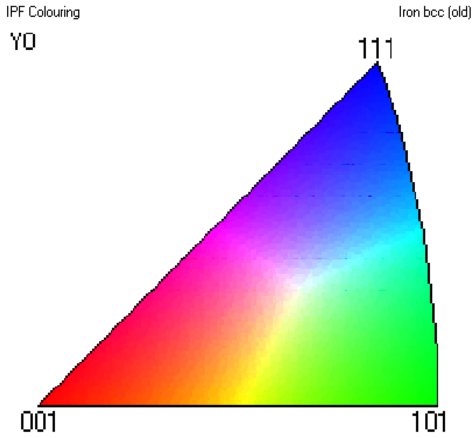

- The InTrap casts were inserted into IF transfer bar which underwent the same processing as the InTrap casts (hot rolling at SaMI, cold rolling, annealing using Gleeble)

- Tensile testing of the carrier material gave mechanical properties similar to the expected values, suggesting the processing route used is representative of industrial scale

# EBSD – texture analysis




IF 2.3M



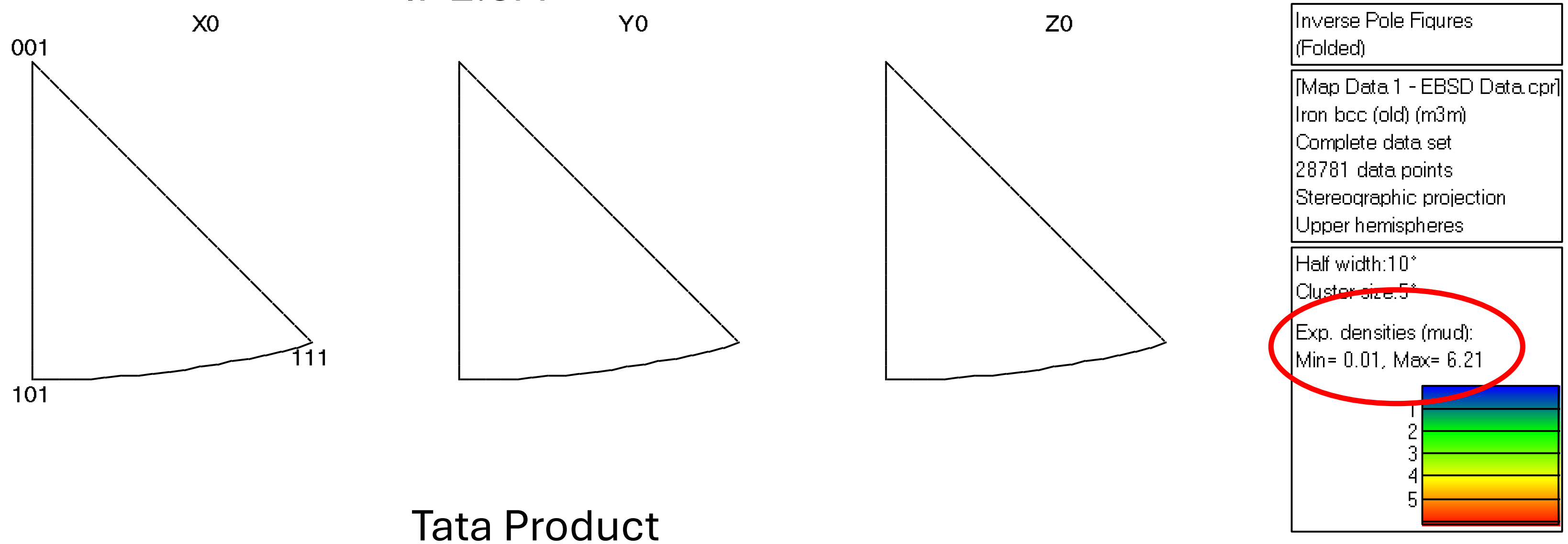

**IF 2.3M Grain size**

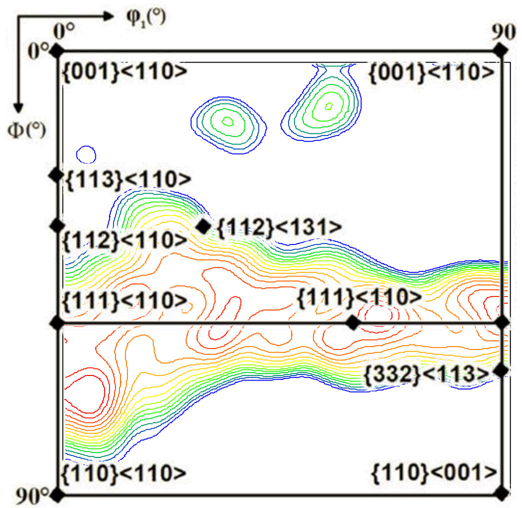
EX 15.695 Average

# 2.3M – texture comparison with Tata product

ODF maps

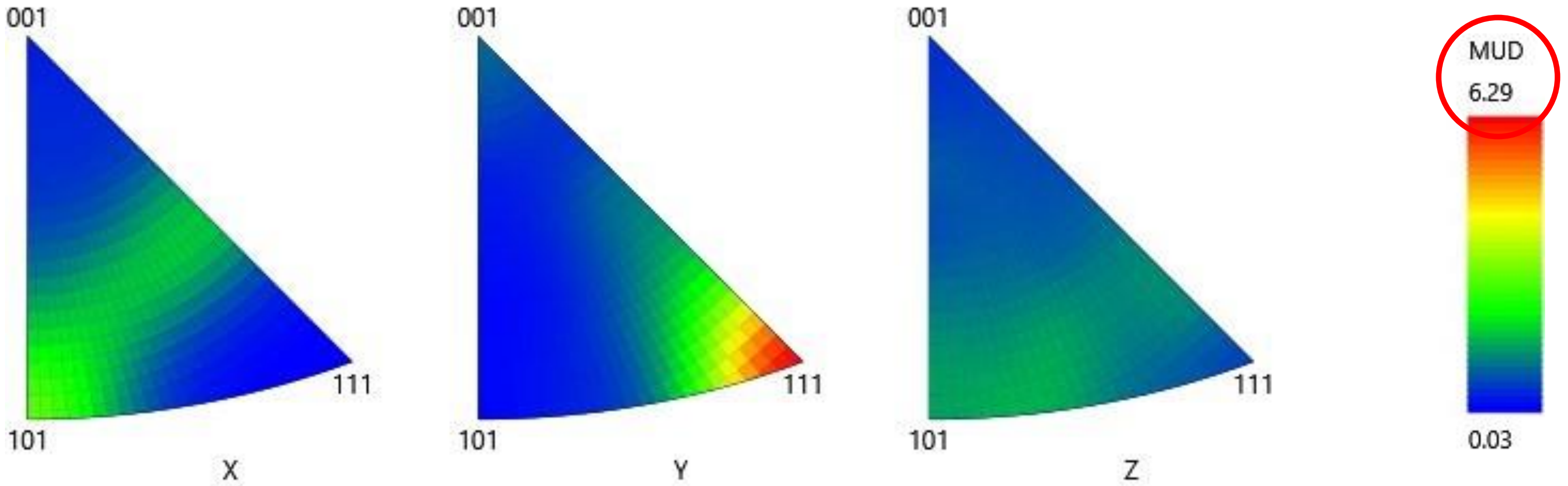
IF 2.3M

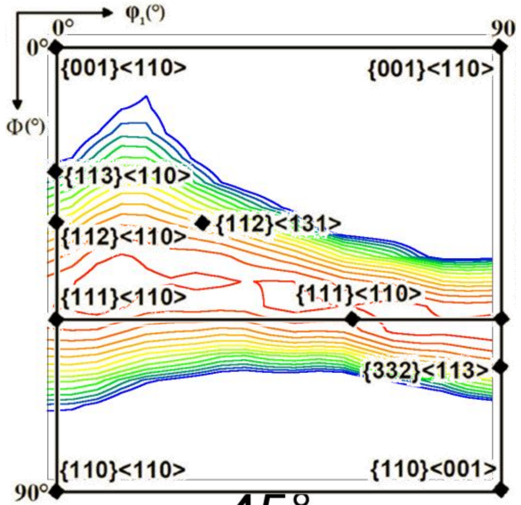



IF 2.3M

Tata Product

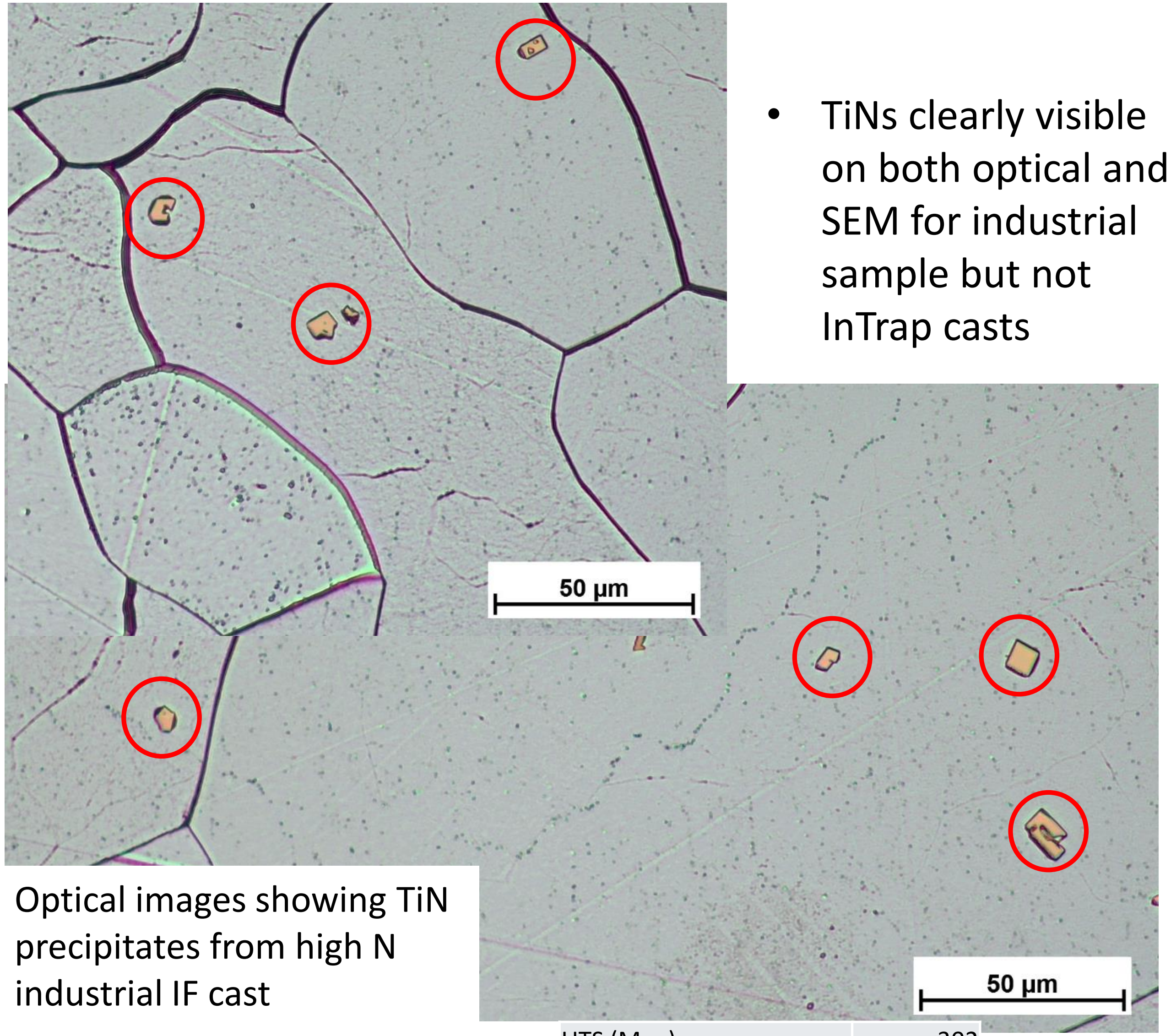



45°

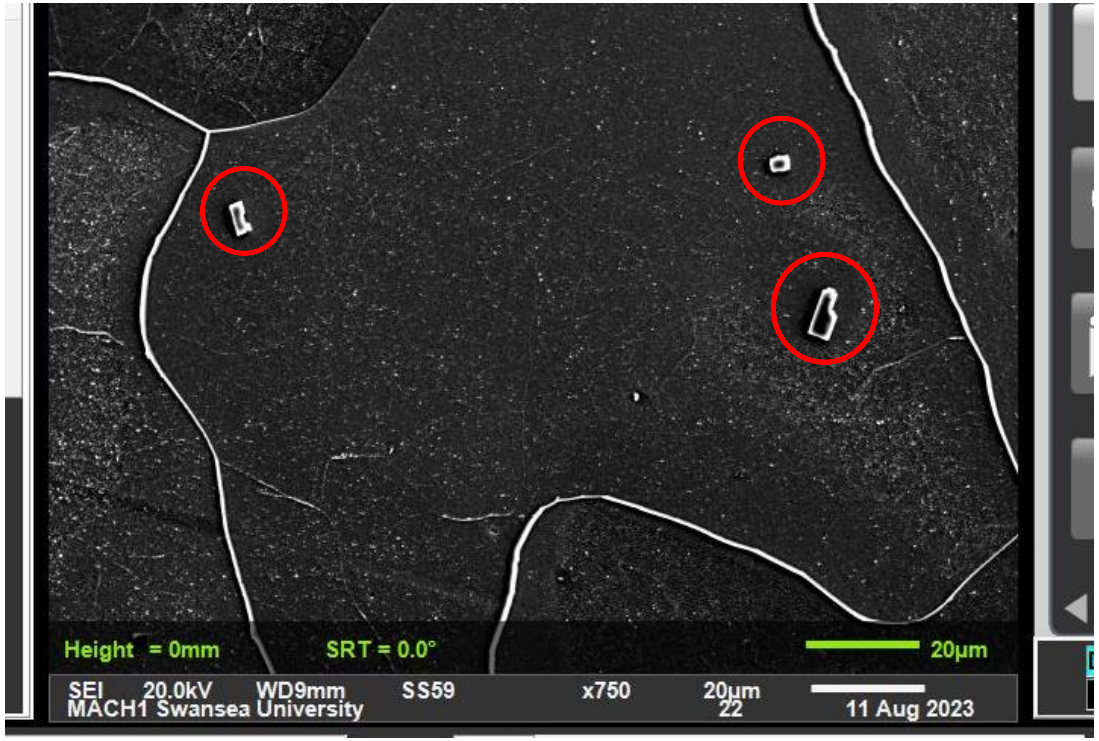
Tata Product

# Microstructural analysis - TiN precipitates




- TiNs clearly visible on both optical and SEM for industrial sample but not InTrap casts

Optical images showing TiN precipitates from high N industrial IF cast



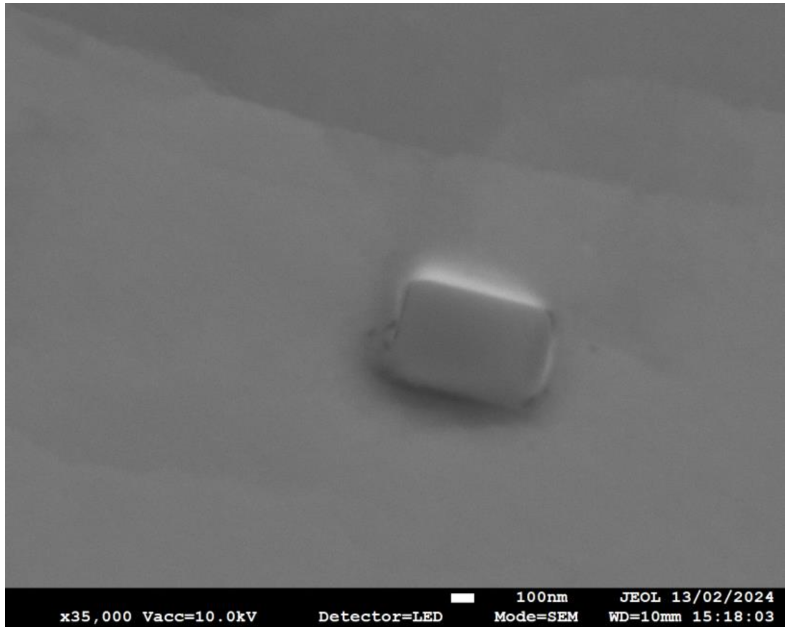

SEM images showing TiN precipitates from high N industrial IF cast, confirmed with EDS

High N industrial cast was fully stabilised with N content of 80ppm. Mechanical properties:

| | |
|---|---|
| UTS (Mpa) | 302 |
| Uniform Elongation (%) | 23.6 |
| Total elongation (A50) (%) | 48.8 |
| r value | 2.01 |

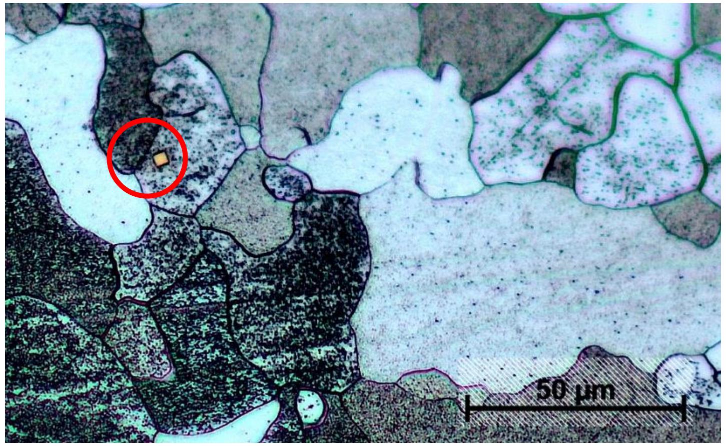
# Impact of small TiN precipitates

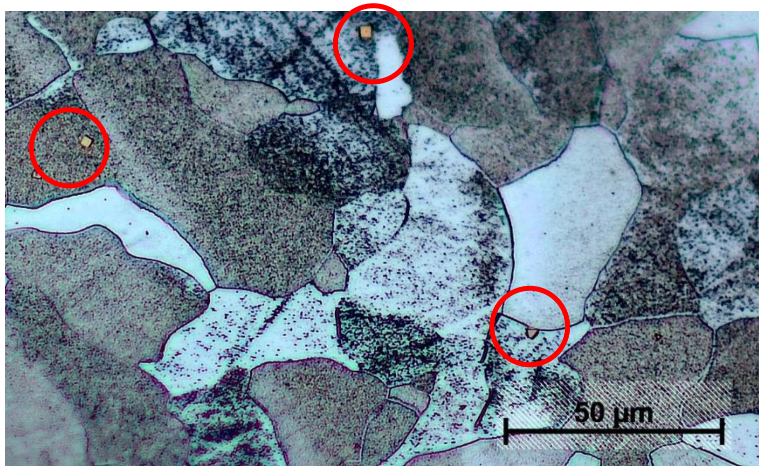
- The high cooling rate of the centrifugal caster means any TiN precipitates formed are likely to be small and finely dispersed and therefore cannot easily be seen on an optical microscope or SEM, unlike the industrial sample with a much slower cooling rate
- As the tensile results did not show a deterioration in mechanical properties with increasing nitrogen content, the InTrap results may suggest that a high cooling rate can minimise the impact of increasing nitrogen content by preventing the growth of large precipitates
- It will be useful to compare the results from casts with slower cooling rates.



# Casting options with slower cooling rates/ longer holding time in liquid


TiNs seen on SEM for 80g route and confirmed using EDS. TiNs formed in 80g route can also be seen optically



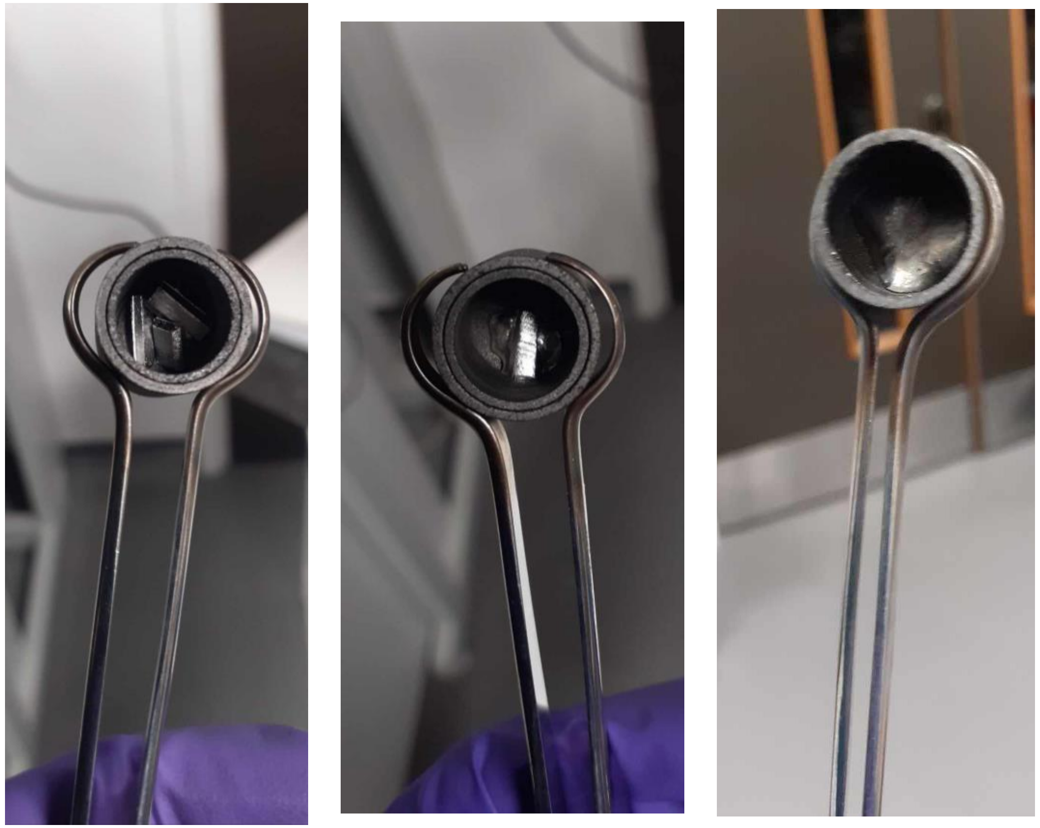




TiNs seen optically on InTRAP carrier material – VIM cast

# Determination of free vs combined nitrogen using Eltra

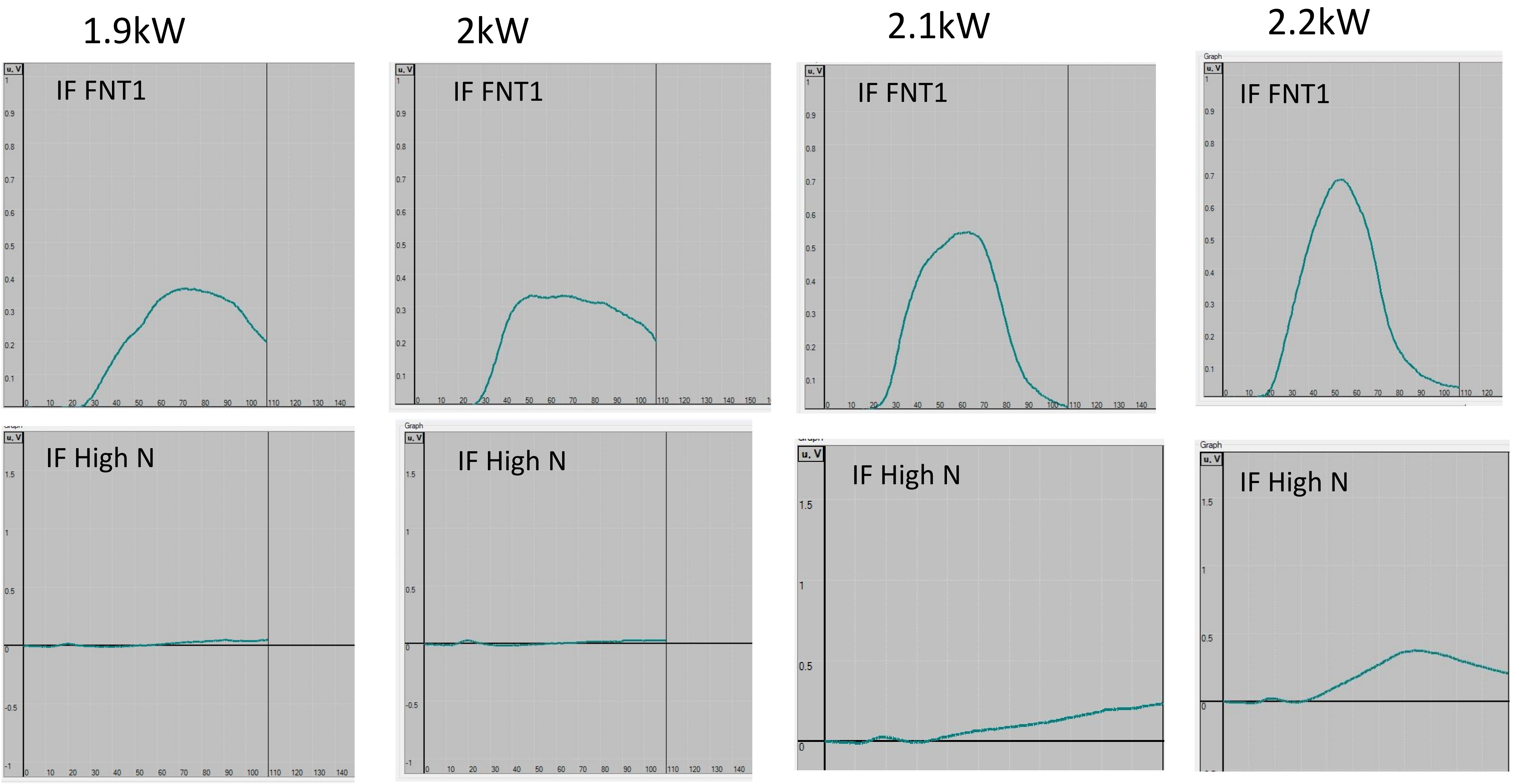
- Aiming to see if free vs combined nitrogen can be distinguished between using the Eltra.

- Samples used:
  - IF FNT1: Lab made (centrifugally cast) no added Ti – unstabilised nitrogen
  - IF FNT3: Lab made (centrifugally cast) fully stabilised
  - IF High N: Industrial high N sample, fully stabilised

Increasing power

# Eltra free nitrogen trials - results



# Summary of results – Eltra free nitrogen trials

IF FNT1

| Date / ti | Sample ID | Oxygen | Nitrogen | Channels | Weight (mg) | Analyse (s) | Application |
|---|---|---|---|---|---|---|---|
| 16.11.2023 | IF FNT--1 - 1.8kW | 106.6 ppm | 46.2 ppm | 1 / 2 | 990.8 | 110 | Default |
| 16.11.2023 | IF FNT--1 - 1.7kW | 39.3 ppm | 0.0 ppm | 1 / 2 | 1032.1 | 110 | Default |
| 16.11.2023 | IF FNT--1 - 1.75kW | 109.8 ppm | 33.5 ppm | 1 / 2 | 1050.8 | 110 | Default |
| 16.11.2023 | IF FNT--1 - 1.85kW | 27.2 ppm | 0.7 ppm | 1 / 2 | 1034.1 | 110 | Default |
| 16.11.2023 | IF FNT--1 - 1.85kW | 94.1 ppm | 37.4 ppm | 1 / 2 | 1006.3 | 110 | Default |
| 16.11.2023 | IF FNT--1 - 1.9kW | 379.4 ppm | 206.2 ppm | 1 / 2 | 1028.2 | 110 | Default |
| 16.11.2023 | IF FNT--1 -2 kW | 367.1 ppm | 221.7 ppm | 1 / 2 | 985.7 | 110 | Default |
| 16.11.2023 | IF FNT--1 -2.1 kW | 368.4 ppm | 239.7 ppm | 1 / 2 | 1015.2 | 110 | Default |
| 16.11.2023 | IF FNT--1 -2.2 kW | 349.1 ppm | 268.0 ppm | 1 / 2 | 1022.9 | 110 | Default |

N first released at ~1.7kW, significantly at ~1.9kW

IF FNT3

| Date / ti | Sample ID | Oxygen | Nitrogen | Channels | Weight (mg) | Analyse (s) | Application |
|---|---|---|---|---|---|---|---|
| 23.11.2023 | IF FNT3 - 1.7kW | 0.0 ppm | 0.0 ppm | 1 / 2 | 1001.5 | 90 | Default |
| 23.11.2023 | IF FNT3 - 1.8kW | 1.2 ppm | 0.0 ppm | 1 / 2 | 1045.1 | 96 | Default |
| 23.11.2023 | IF FNT3 - 1.9kW | 28.7 ppm | 28.8 ppm | 1 / 2 | 1013.4 | 110 | Default |
| 23.11.2023 | IF FNT3 - 2kW | 73.7 ppm | 127.2 ppm | 1 / 2 | 1012.0 | 110 | Default |
| 23.11.2023 | IF FNT3 - 2.1kW | 109.2 ppm | 218.3 ppm | 1 / 2 | 1004.8 | 110 | Default |
| 23.11.2023 | IF FNT3 - 2.2kW | 95.6 ppm | 95.1 ppm | 1 / 2 | 1005.0 | 90 | Default |
| 23.11.2023 | IF FNT3 - 2.3kW | 121.8 ppm | 286.1 ppm | 1 / 2 | 982.5 | 110 | Default |
| 23.11.2023 | IF FNT3 - 2.4kW | 159.1 ppm | 161.2 ppm | 1 / 2 | 1016.9 | 91 | Default |
| 23.11.2023 | IF FNT3 - 2.7kW | 122.8 ppm | 224.3 ppm | 1 / 2 | 1013.9 | 90 | Default |

N first released at ~1.9kW, significantly at ~2.1kW

IF Ind High N

| Date / ti | Sample ID | Oxygen | Nitrogen | Channels | Weight (mg) | Analyse (s) | Application |
|---|---|---|---|---|---|---|---|
| 25.10.2023 | IF High N - 1.7kW | 2.7 ppm | 0.0 ppm | 1 / 2 | 1003.0 | 97 | Default |
| 25.10.2023 | IF High N - 1.8kW | 9.9 ppm | 1.6 ppm | 1 / 2 | 974.7 | 110 | Default |
| 25.10.2023 | IF High N - 1.9kW | 7.1 ppm | 0.0 ppm | 1 / 2 | 1065.0 | 110 | Default |
| 06.11.2023 | IF High N - 1.95kW | 11.3 ppm | 17.2 ppm | 1 / 2 | 970.6 | 110 | Default |
| 06.11.2023 | IF High N - 2kW | 19.7 ppm | 7.5 ppm | 1 / 2 | 1033.7 | 110 | Default |
| 06.11.2023 | IF High N - 2.1kW | 11.1 ppm | 91.9 ppm | 1 / 2 | 1065.1 | 110 | Default |
| 06.11.2023 | IF High N - 2.2kW | 0.0 ppm | 202.8 ppm | 1 / 2 | 956.3 | 110 | Default |
| 06.11.2023 | IF High N - 2.3kW | 12.1 ppm | 205.8 ppm | 1 / 2 | 957.9 | 110 | Default |
| 06.11.2023 | IF High N - 2.7kW | 16.1 ppm | 315.4 ppm | 1 / 2 | 975.9 | 96 | Default |

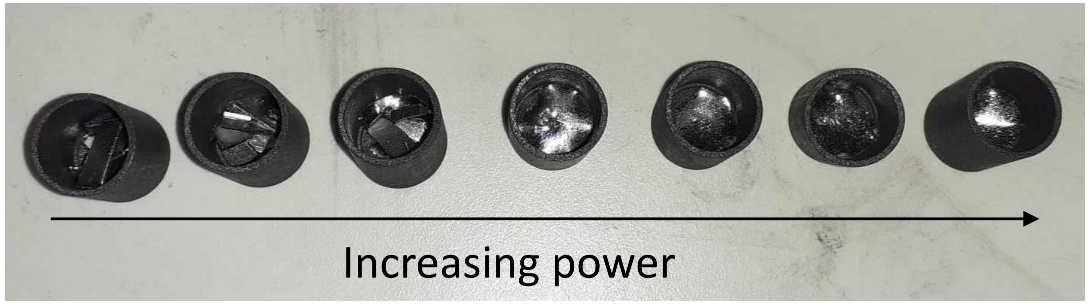
N first released at ~1.95kW, significantly at ~2.2kW

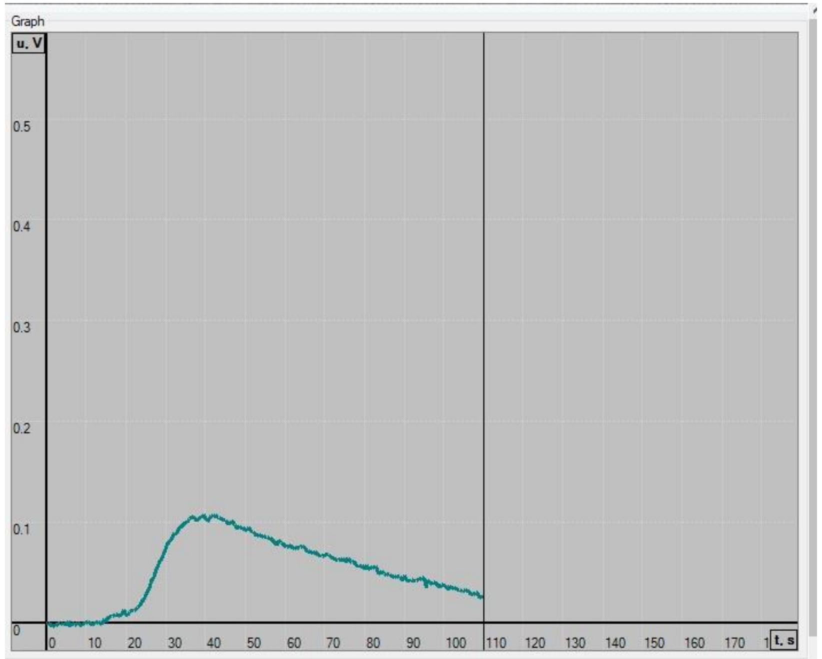
These trials suggest that it may be possible to use the Eltra to indicate if nitrogen is free or combined in precipitates

# Application to InTRAP Study

- This technique was used on the InTrap casts – nitrogen was not released at 1.7kW or 1.8kW but started to be released at 1.9kW – this follows the pattern of the casts with combined nitrogen, suggesting the nitrogen in the InTrap casts was tied up in precipitates.

| Date / ti | Sample ID | Oxygen | Nitrogen | Channels | Weight (mg) | Analyse (s) | Application | C |
|---|---|---|---|---|---|---|---|---|
| 06.02.2024 | IF 2.12L -1.7kW | 15.8 ppm | 0.0 ppm | 1 / 2 | 989.3 | 110 | Default | 1 |
| 06.02.2024 | IF 2.12L -1.8kW | 4.3 ppm | 0.0 ppm | 1 / 2 | 999.1 | 91 | Default | 4 |
| 06.02.2024 | IF 2.12L -1.9kW | 38.3 ppm | 11.5 ppm | 1 / 2 | 993.1 | 100 | Default | 3 |
| 06.02.2024 | IF 2.12L -2kW | 15.4 ppm | 36.1 ppm | 1 / 2 | 996.9 | 110 | Default | 1 |
| 06.02.2024 | IF 2.12L -2.1kW | 54.3 ppm | 32.1 ppm | 1 / 2 | 991.0 | 110 | Default | 5 |
| 06.02.2024 | IF 2.12L -2.2kW | 30.3 ppm | 57.8 ppm | 1 / 2 | 993.7 | 110 | Default | 3 |
| 06.02.2024 | IF 2.12L -2.3kW | 16.7 ppm | 43.6 ppm | 1 / 2 | 986.9 | 99 | Default | 1 |



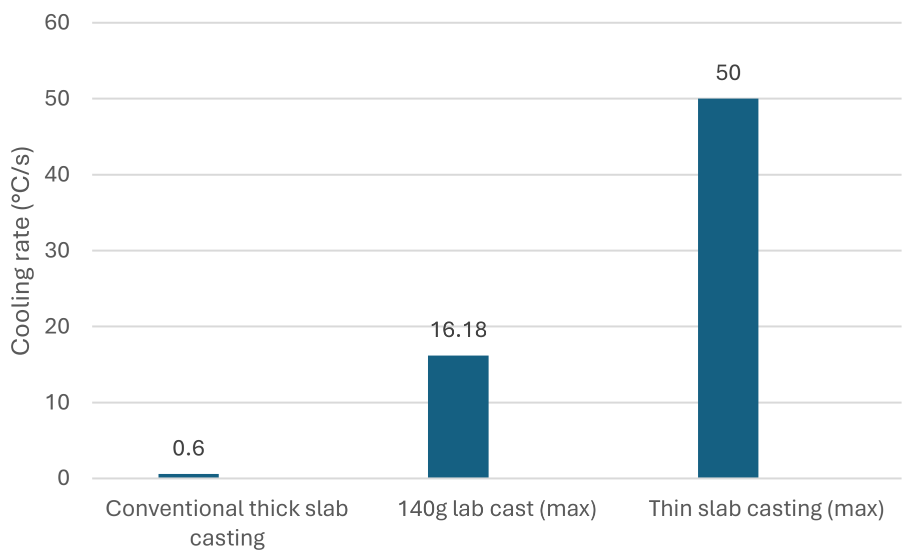

2.2kW

# Conclusions

- InTrap results seem to show no clear deterioration in mechanical properties with increasing nitrogen content – this may be a result of the fast cooling rate, preventing the formation of large TiN precipitates.
- Carrier material for InTrap casts show mechanical properties similar to those expected by plant – suggests processing route can give representative results
- It may be possible to distinguish between free and combined nitrogen using the Eltra

# Future work

- Comparison of results with casts at different cooling rates/ holding time in liquid
    - 80g study
    - VIM casts



# Thank you for listening

Hannah Clarke

967961@swansea.ac.uk

Prifysgol Abertawe Swansea University

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