Alloy Development for Automotive Turbocharger Turbine Wheels

Doncasters Superalloys

ICI 65th Annual Technical Conference & Expo

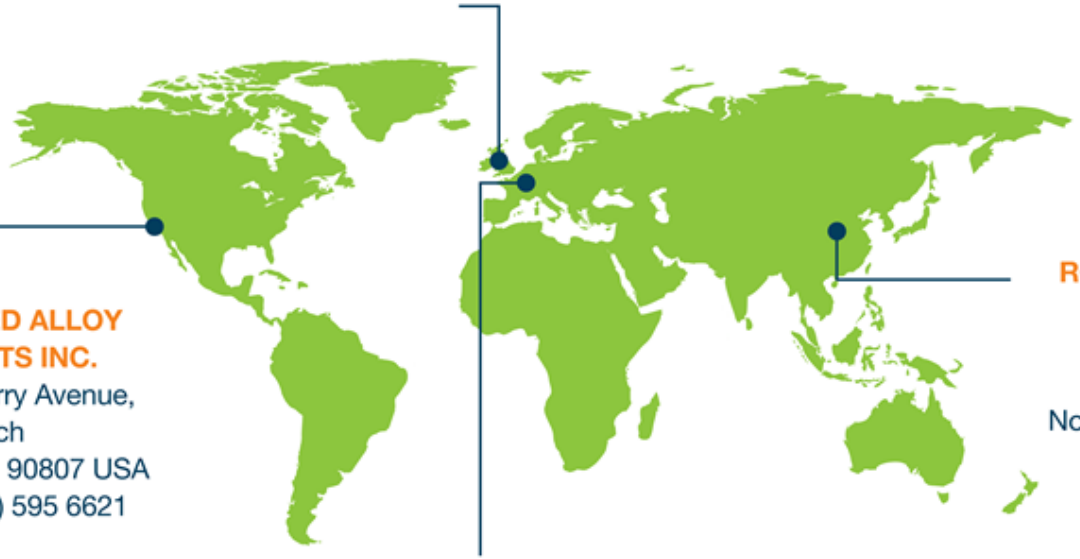
October 2018

DONCASTERS

Introduction

Doncasters Superalloys consists of four dedicated vacuum alloy foundries globally

ROSS & CATHERALL
Forge Lane, Killamarsh, Sheffield S21 1BA
T: +44 (0) 114 248 6404



CERTIFIED ALLOY PRODUCTS INC.
3245 Cherry Avenue,
Long Beach
California, 90807 USA
T: +1 (562) 595 6621

CELEBRATING 75 YEARS 1943 - 2018

BOCHUM SUPERALLOYS
Bessemerstrasse 80, Bochum
44793, Germany
T: +49 (0) 234 6221

BOCHUM SUPERALLOYS

ROSS & CATHERALL SUPERALLOYS (CHINA) CO. LTD
Jiangsu Z Park
No.47 Chuangzhi Road
Kunlun Street
Liyang City
Jiangsu Province
China
T: +86 13774333220

ROSS & CATHERALL
SUPERALLOYS (CHINA) CO.,LTD.

Copyright Doncasters Group 2018 Strictly Private & Confidential

Introduction

It is important to understand turbocharger turbine wheel design requirements and how this affects material property requirements

- Turbine wheels can be subject to tensile stresses >600MPa and temperatures > 1472°F (800°C)
- The pursuit of increased fuel economy and reduced CO_2 emissions has led to increasing exhaust gas temperatures
- In some engines turbocharger inlet temperatures can exceed 1976°F (1080°C) under harsh acceleration
- Competing technologies threaten to take market share from the turbocharger market
- Alloy selection is key to ensure turbochargers remain competitive

Copyright Doncasters Group 2018 Strictly Private & Confidential

Alloy Selection

- IN713C has been the most commonly used alloy for turbine wheel for a number of years
- The operating temperature of IN713C has a ceiling of around 1976°F (980°C)
- For applications where temperatures exceed 1976°F (980°C) other alloys are normally considered:
  - Mar-M246
  - Mar-M247

Copyright Doncasters Group 2018 Strictly Private & Confidential

High Temperature Candidate Alloys

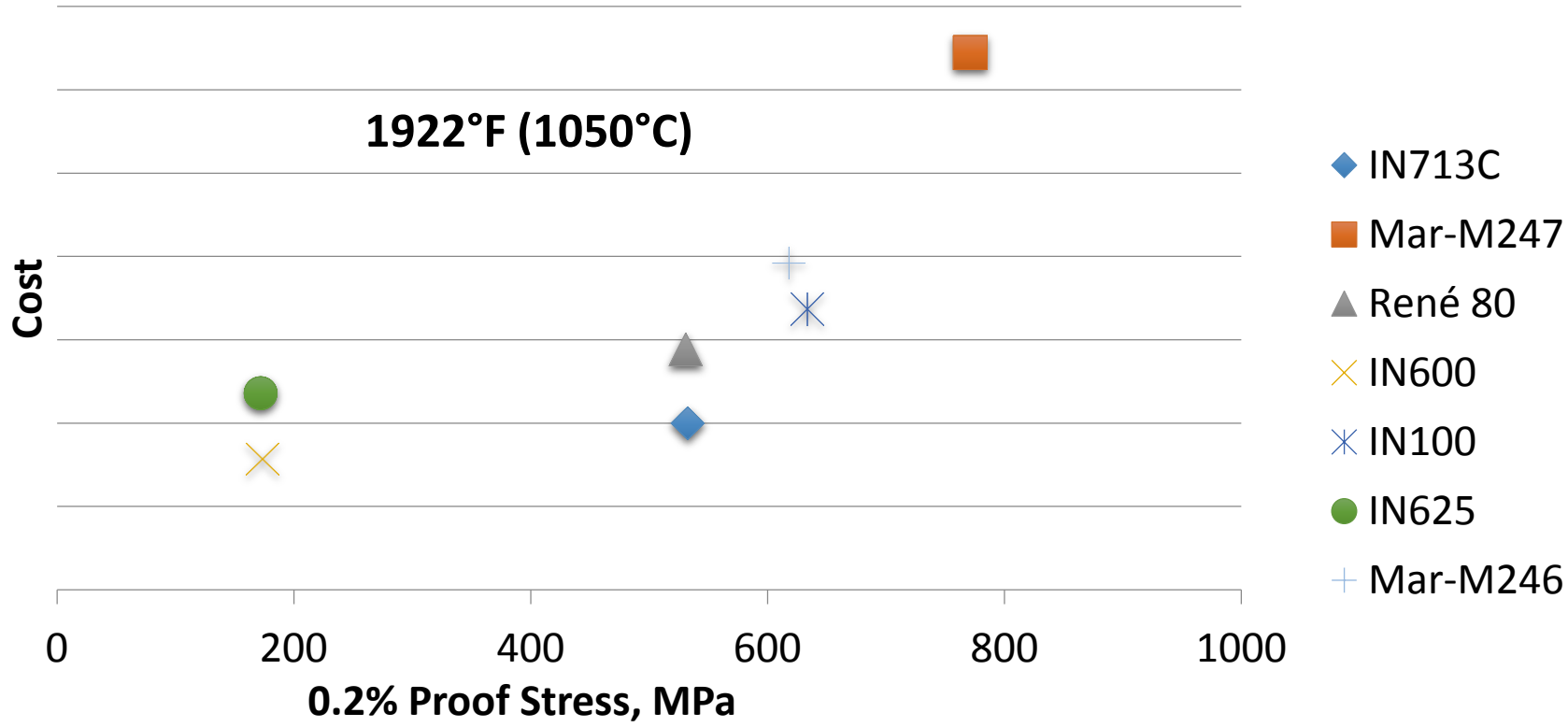
Here we consider alloys for high temperature applications above 1922°F (950°C)

- Mar-M246 and Mar-M247 are normally considered for wheels exposed to high temperatures
- Various other existing alloys have also been considered

Alloy	C	Cr	Ni	Co	Mo	W	Nb	Ta	Ti	Al	B	Zr	Hf	V	Fe	Si	Mn	Cu
IN713C	0.10	13.5	73.0		4.5		2.0		0.8	6.0	0.010	0.06						
Mar-M247	0.16	8.2	60.0	10.0	0.6	10.0		3.0	1.0	5.5	0.015	0.05	1.5					
René 80	0.16	14.0	60.3	9.5	4.0	4.0			5.0	3.0	0.015	0.03						
IN600	0.15	15.5	72												8.0	0.5	1.0	0.5
IN100	0.16	10.0	61.5	15.0	3.0				4.8	5.5	0.015	0.04		0.8				
IN625	0.20	21.6	65.2		8.7		3.9		0.2	0.2								
Mar-M246	0.15	9.0	59.8	10.0	2.5	10.0		1.5	1.5	5.5	0.015	0.05						

Copyright Doncasters Group 2018 Strictly Private & Confidential

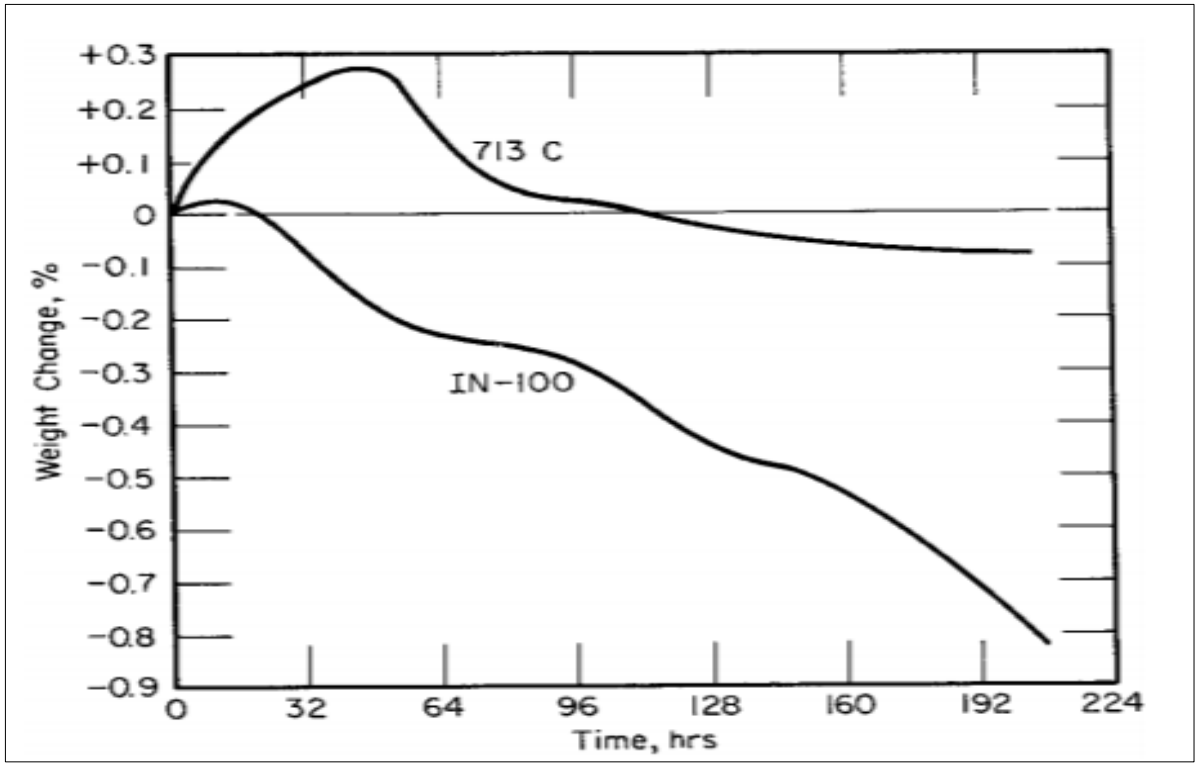
High Temperature Candidate Alloys



- Mar-M247 is often chosen for the very high temperature applications where temperatures briefly exceed 1976°F (1080°C)
- Mar-M246 is suitable for intermediate applications

Copyright Doncasters Group 2018 Strictly Private & Confidential

High Temperature Candidate Alloys

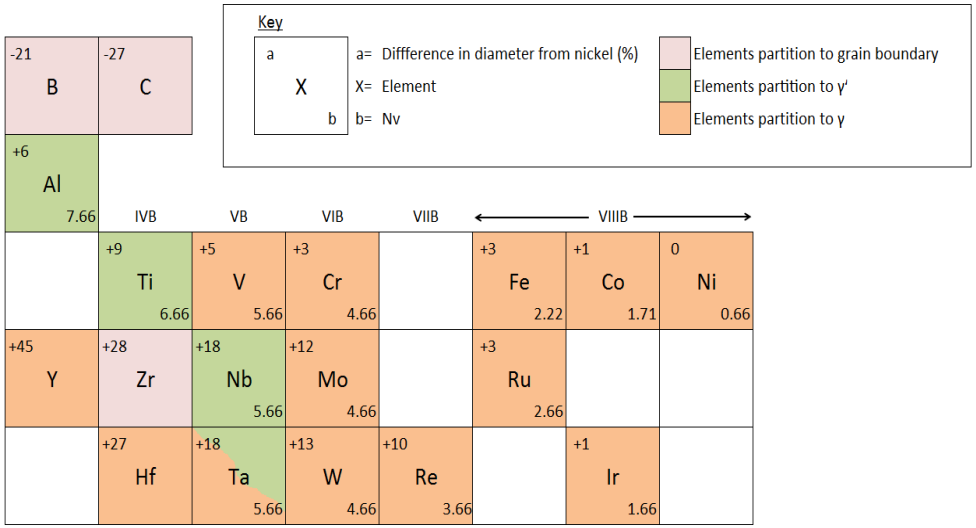


- IN100 appears to be a good candidate alloy when considering cost versus mechanical properties
- Due to it's poor oxidation resistance however it is not a suitable alloy for turbine wheels

Copyright Doncasters Group 2018 Strictly Private & Confidential

High Temperature Candidate Alloys

- Most candidate alloys were developed for other applications such as IGT or aerospace gas turbines
- Gas turbine alloys were designed to exhibit high creep resistance



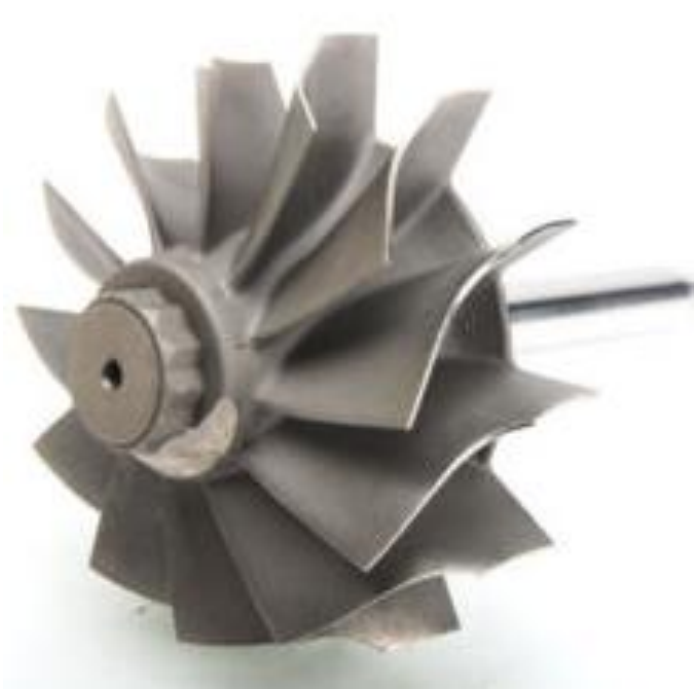
- Gas turbine alloys were designed for a low cyclic load frequency applications when compared to turbocharger turbine wheels
- Gas turbine components can be coated so oxidation resistance could be compromised to maximise solid solution strengthening and the gamma prime fraction
- There is an opportunity to develop a more cost effective alloy designed specifically to meet the needs of a turbocharger turbine wheel

Copyright Doncasters Group 2018 Strictly Private & Confidential

Alloy Design Criteria

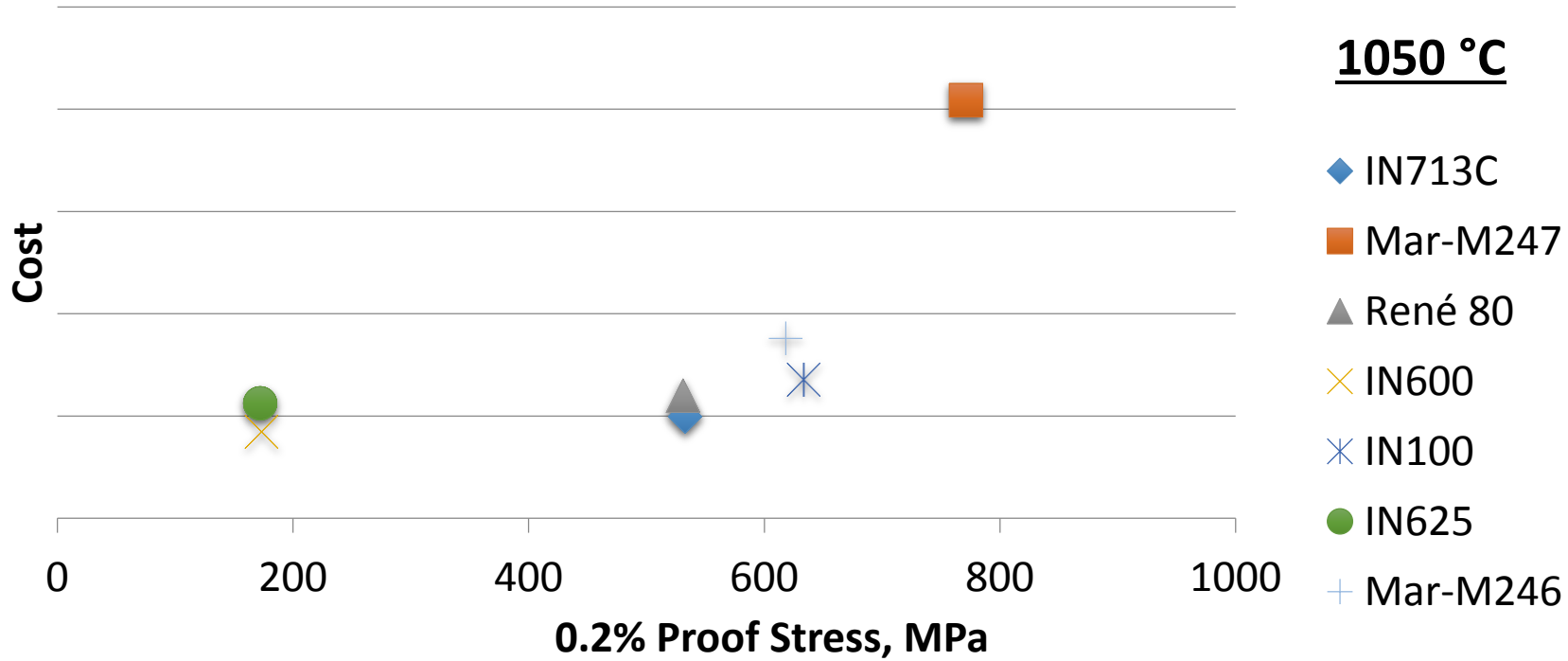
A number of factors affect alloy selection for turbocharger turbine wheels

- Tensile strength
- Hot oxidation and corrosion resistance
- High temperature performance
- Fatigue strength
- Density
- Creep strength
- Cost



Copyright Doncasters Group 2018 Strictly Private & Confidential

Tensile Strength



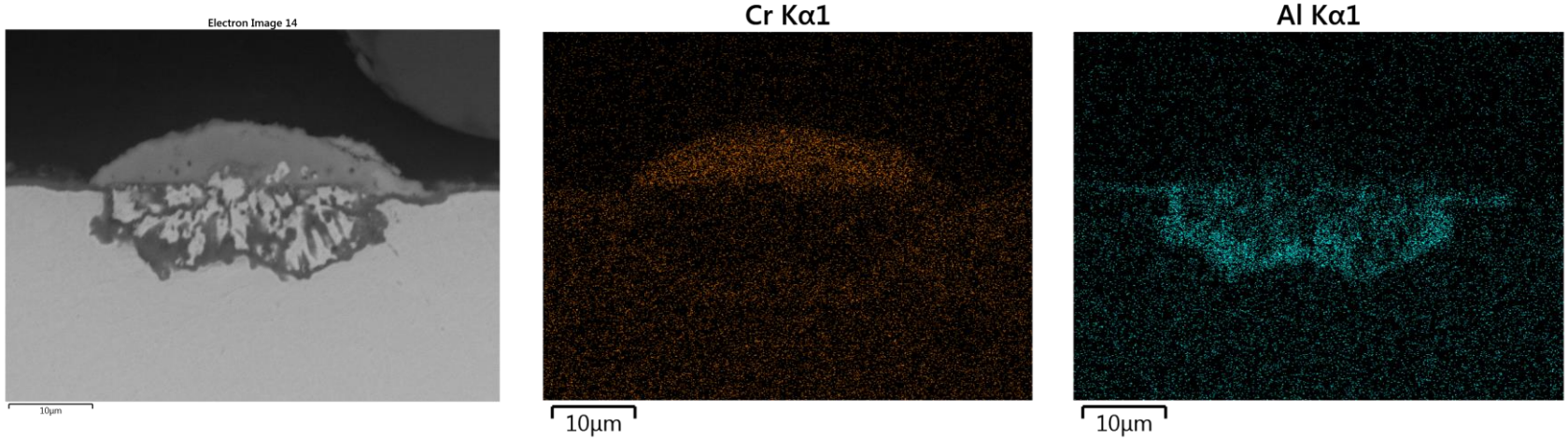
- For turbine wheels at operating temperature the typical minimum tensile properties are approximately:
  - UTS: 860 Mpa
  - Proof Stress: 700 MPa
- Common alloys used in turbocharger turbine wheel manufacture such as IN713C do not meet these mechanical properties above 950°C

Copyright Doncasters Group 2018 Strictly Private & Confidential

Hot Corrosion Resistance

In Ni based superalloys corrosion protection is afforded by the presence of a protective oxide layer

- Below 1742°F (950°C) protection is primarily afforded by Cr_2O_3
- At higher temperatures protection is given by Al_2O_3
- It is important to maximise Al while considering the effect on the N_v

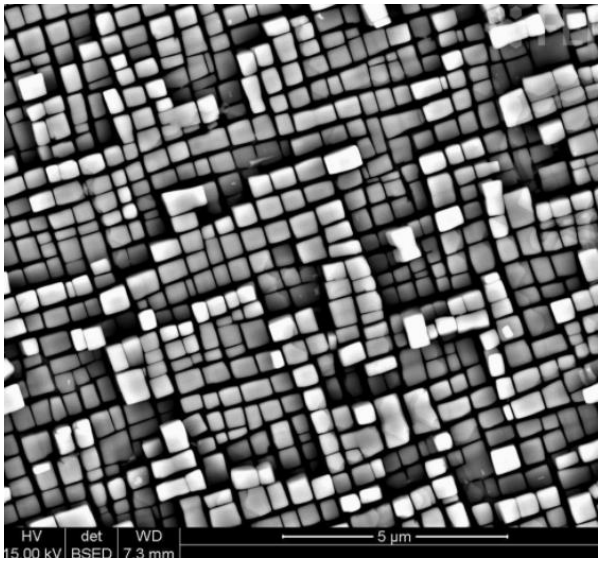


SEM image and EDX maps of oxide layer in a Ni based superalloy formed at 1742°F (950°C)

Copyright Doncasters Group 2018 Strictly Private & Confidential

High Temperature Performance

- Ni superalloys can operate at 70% of their melting temperatures due to the presence of gamma prime, $Ni_3(Al,Ti)$
- Gamma prime has a low lattice misfit with the gamma matrix, which confers stability
- It is important to balance Al and Ti to maximise the gamma prime fraction
- Al and Ti have a high number of electron vacancies
- High concentrations lead to elevated N_v which increases the likelihood of TCP phases



Copyright Doncasters Group 2018 Strictly Private & Confidential

Fatigue Strength

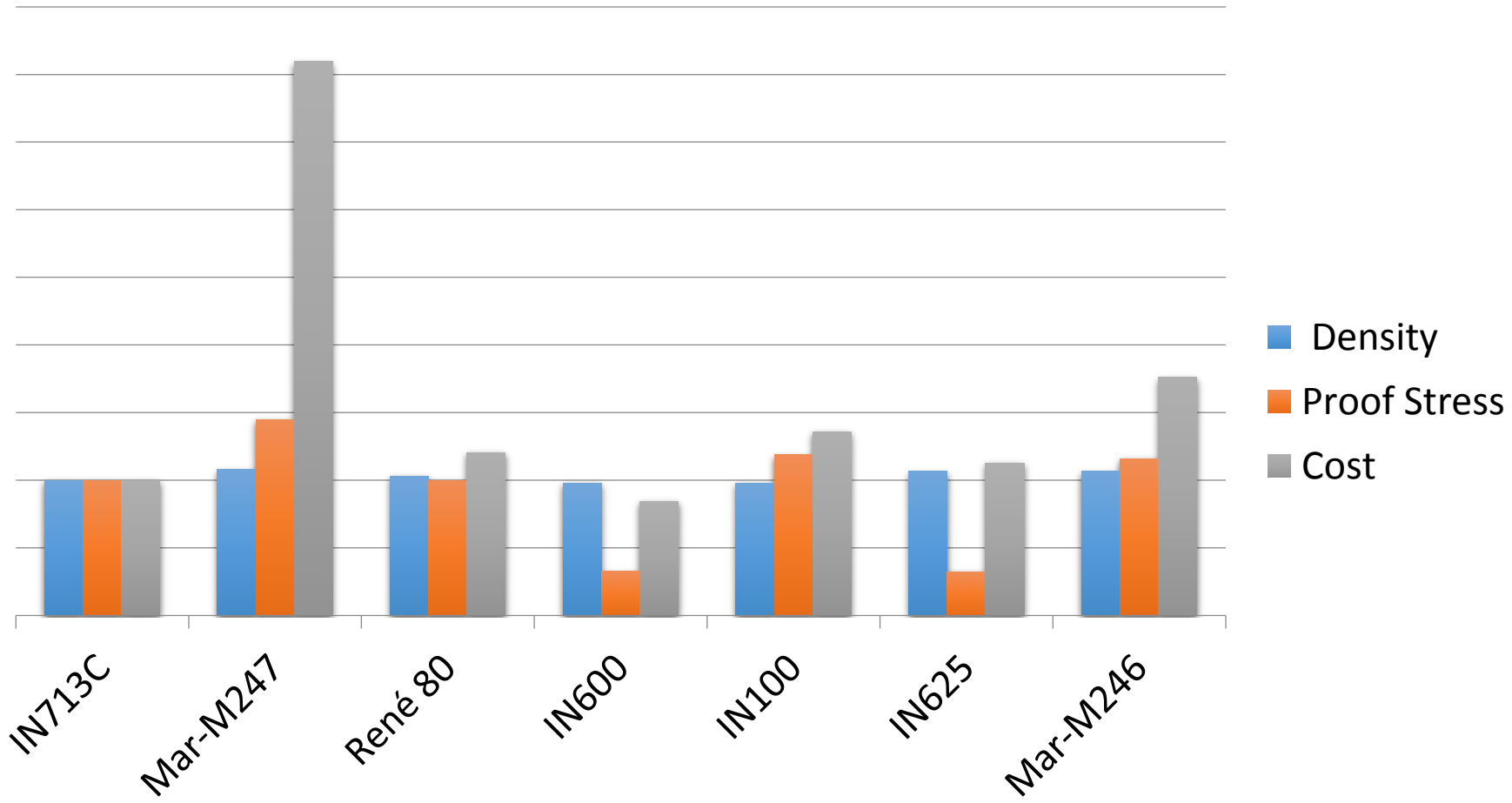
The fatigue strength of an alloy depends very much on the deformation mode applied

- Turbocharger turbine wheels are subject to high cycle fatigue (HCF), low cycle fatigue (LCF) and thermomechanical fatigue (TMF)
- At the blade tips the fatigue mode is HCF
  - Due to asymmetric loading cause by turbocharger design
  - Affected by microstructure, eutectic content and carbide type and morphology
- The hub is affected by LCF
  - Caused by vehicle acceleration and deceleration
  - Affected by casting defects such as porosity
- It is evident from the modelling of turbine wheels that they are affected by TMF

Copyright Doncasters Group 2018 Strictly Private & Confidential

Density

Low alloy density is desirable to reduce turbine wheel weight, reducing spool up time



Copyright Doncasters Group 2018 Strictly Private & Confidential

Creep Strength

- The creep strength requirement of turbocharger turbine wheels is lower than that of gas turbine blades
- Notwithstanding the solid solution strengthening elements, those that are employed to maximise creep strength are often expensive:
  - Tantalum
  - Hafnium
  - Rhenium
  - Ruthenium
- Therefore there is an opportunity to design a more cost effective high temperature turbocharger alloy
- For turbine wheels sufficient creep resistance can be obtained by the presence of grain boundary carbides

Copyright Doncasters Group 2018 Strictly Private & Confidential

Raw Materials Costs

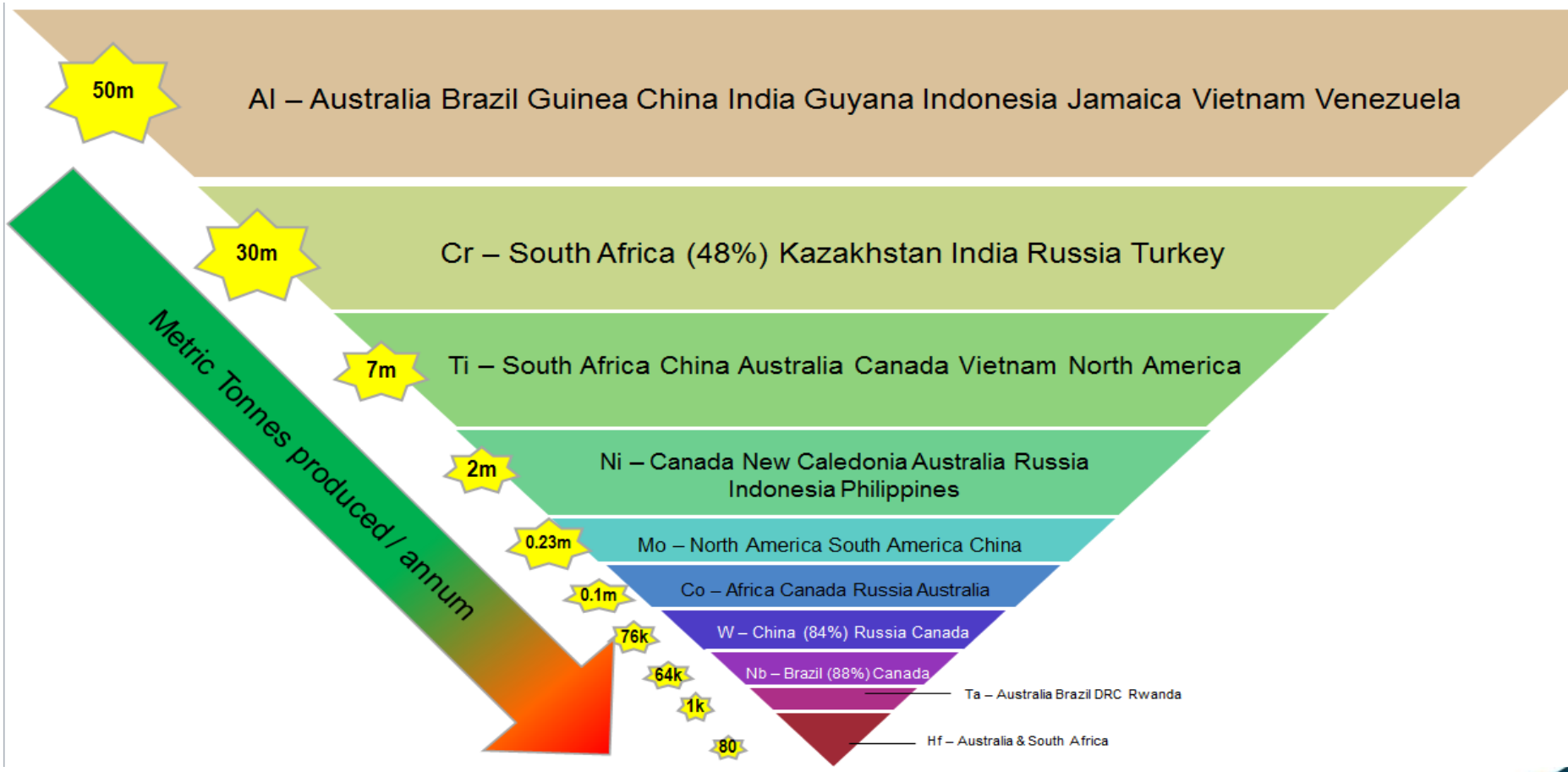
The cost of raw materials makes up a huge proportion of alloy cost and the subsequent cost of a turbine wheel, which is why it is a key factor in alloy selection

- Existing alloys that exhibit sufficient mechanical properties were developed with less emphasis on cost because optimum fuel efficiency is a greater driver in gas turbine applications
- Co is much more expensive than when many existing alloys were designed
- Other expensive additions such as Ta, Hf, Re and Ru increase alloy price considerably
- To reduce costs it is possible to substitute some expensive elements for cheaper alternatives such as replacing Ta with Nb

Copyright Doncasters Group 2018 Strictly Private & Confidential

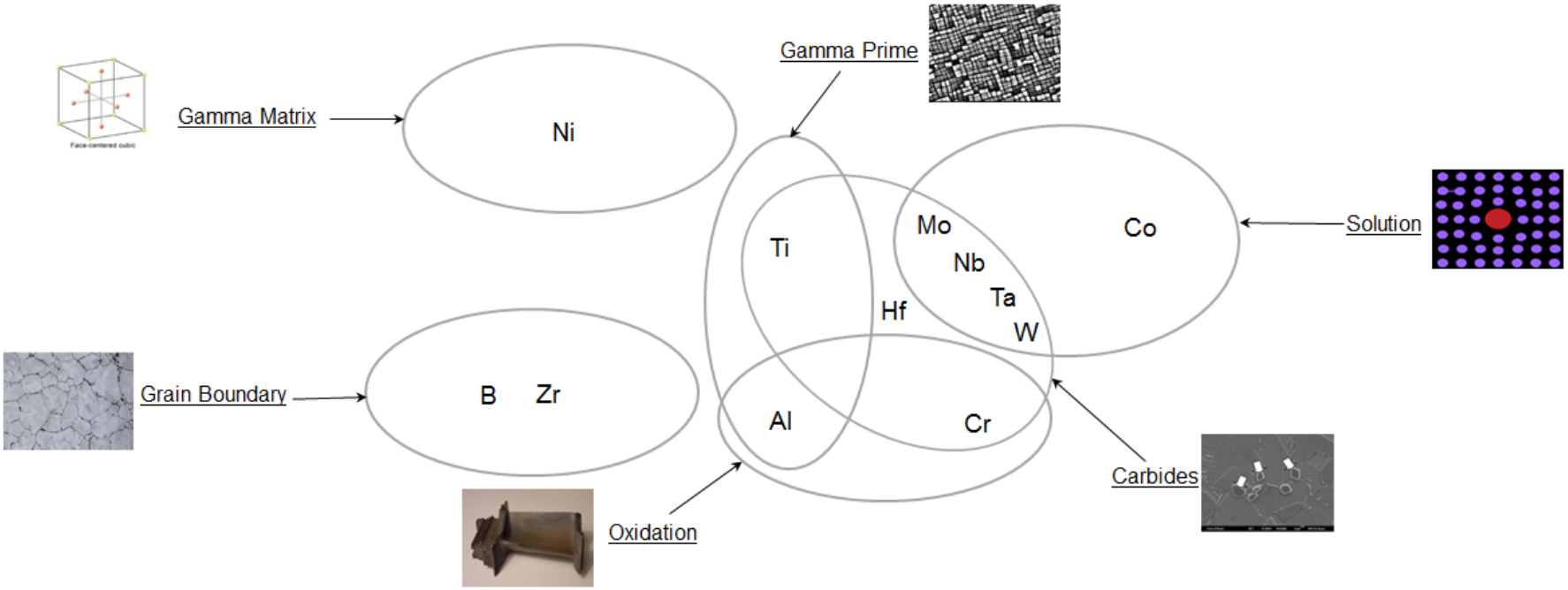
Raw Materials Costs

Many superalloys utilise elements which are very limited in availability, which drives price up



Copyright Doncasters Group 2018 Strictly Private & Confidential

Raw Materials Costs



- In some cases expensive elements can be substituted for less expensive ones, e.g. Ta for Nb
- Co goes into solution in the γ matrix and is interchangeable with Ni

Copyright Doncasters Group 2018 Strictly Private & Confidential

New Alloys

Using the logic we have discussed, two new alloys have been developed - RCV09 and RCV11

Alloy	C	Cr	Ni	Co	Mo	W	Nb	Ta	Ti	Al	B	Zr	Hf	V	N_v
RCV09	0.1	12.5	Bal.		4	0.5	2		0.8	6.6	0.01	0.06		0.25	2.39
RCV11	0.16	8.2	Bal.	10	5	7	2.2	0.8	1	5.5	0.015	0.05	0.5		2.37

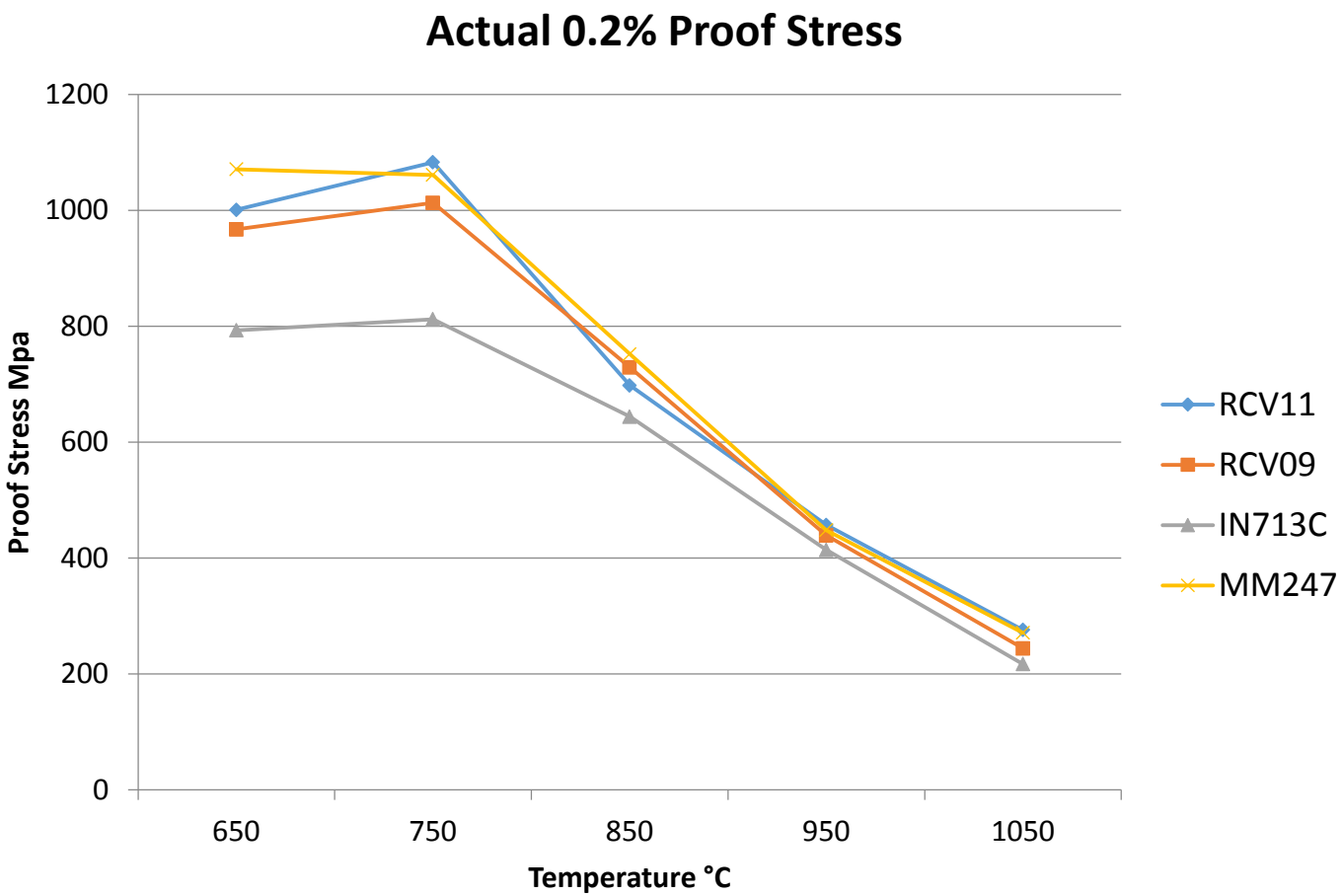
For RCV09 and RCV11 there is a patent pending: GB2554879

- RCV09 is designed to exhibit sufficient mechanical properties for turbine wheel applications at a higher temperature than IN713C
- RCV09 does not to exceed 110% of the cost of IN713C
- RCV11 was designed to exhibit similar high temperature mechanical properties to Mar-M247
- RCV11 is significantly (~30%) lower cost than Mar-M247

Copyright Doncasters Group 2018 Strictly Private & Confidential

Mechanical testing of New Alloys

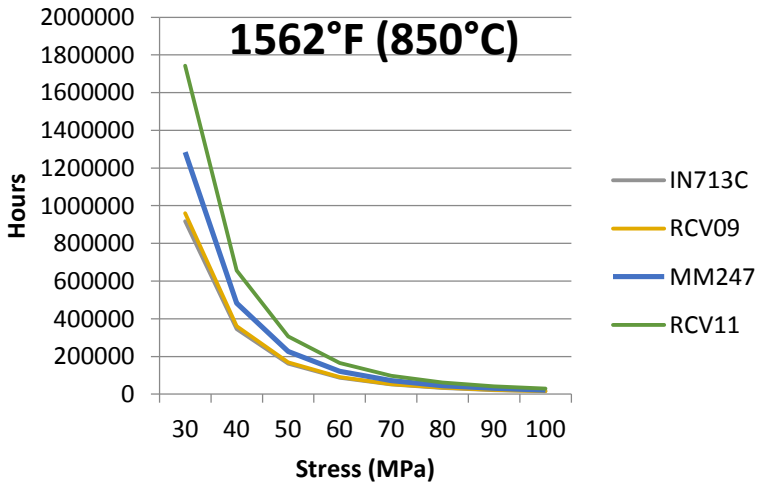
Initial tests have shown that the tensile properties are as intended which is in line with modelling data

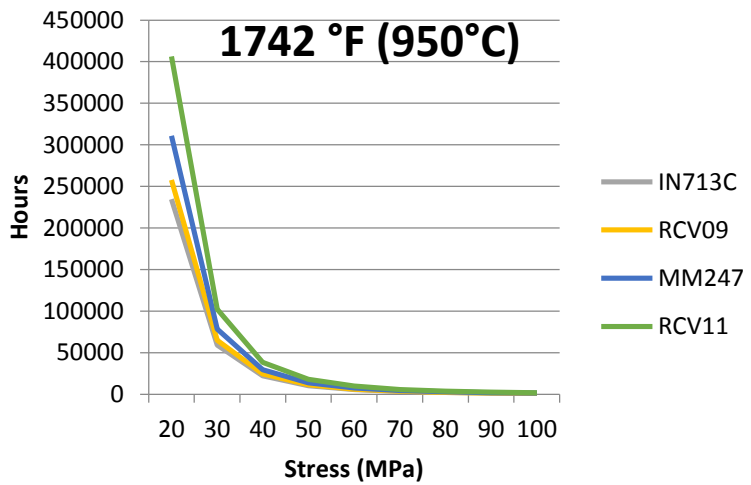


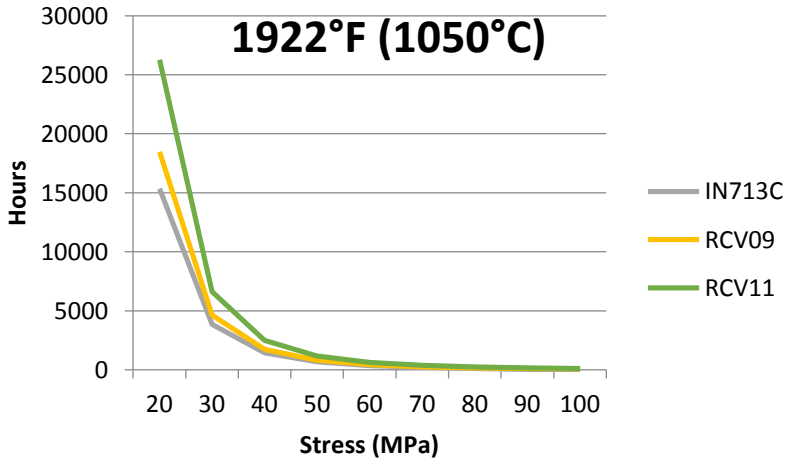
Copyright Doncasters Group 2018 Strictly Private & Confidential

Mechanical testing of New Alloys

Stress rupture modelling data shows that the rupture life of RCV11 is expected to exceed that of Mar-M247 and the rupture life of RCV09 is expected to exceed that of IN713C



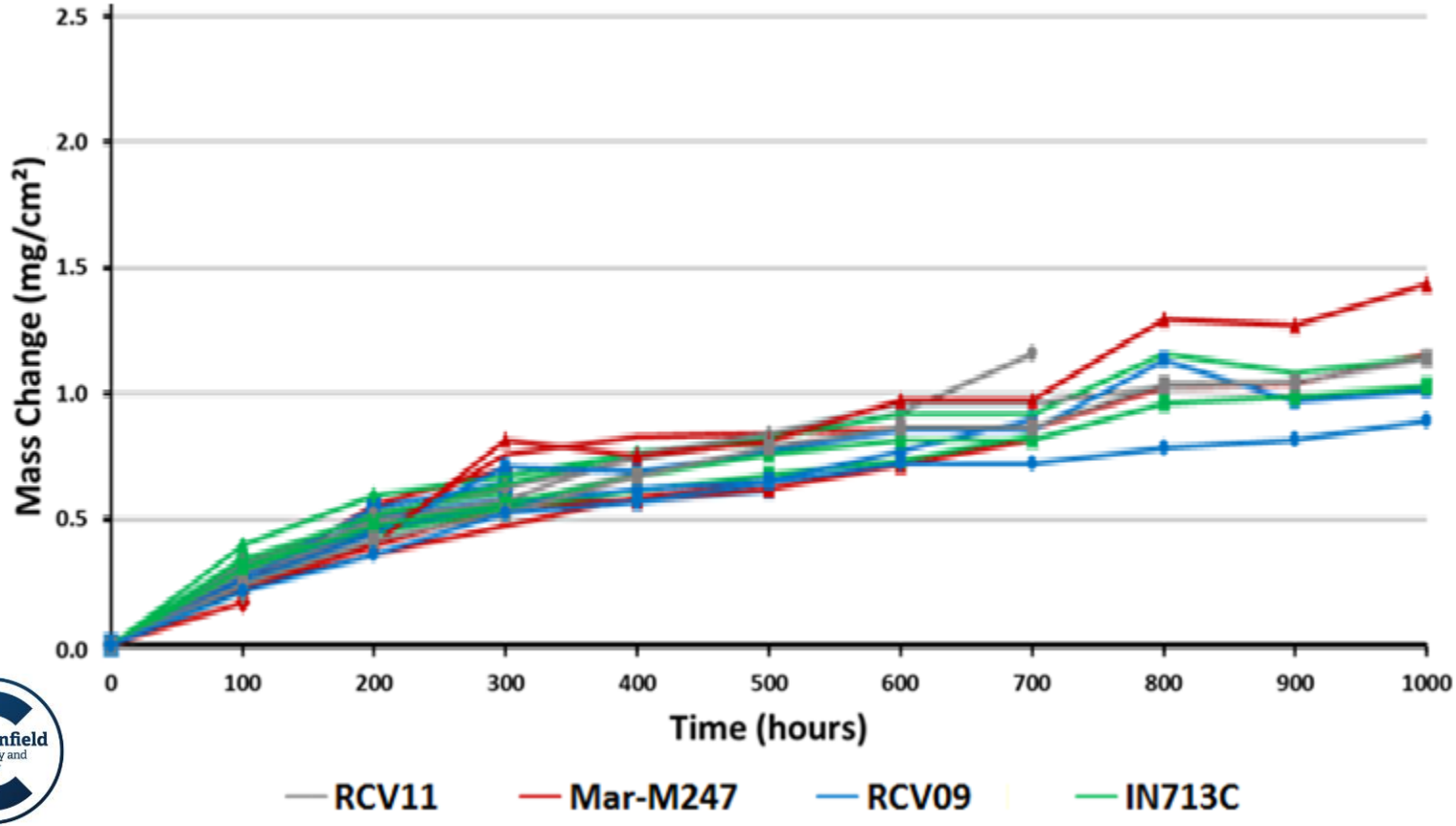




Copyright Doncasters Group 2018 Strictly Private & Confidential

Hot Corrosion Tests

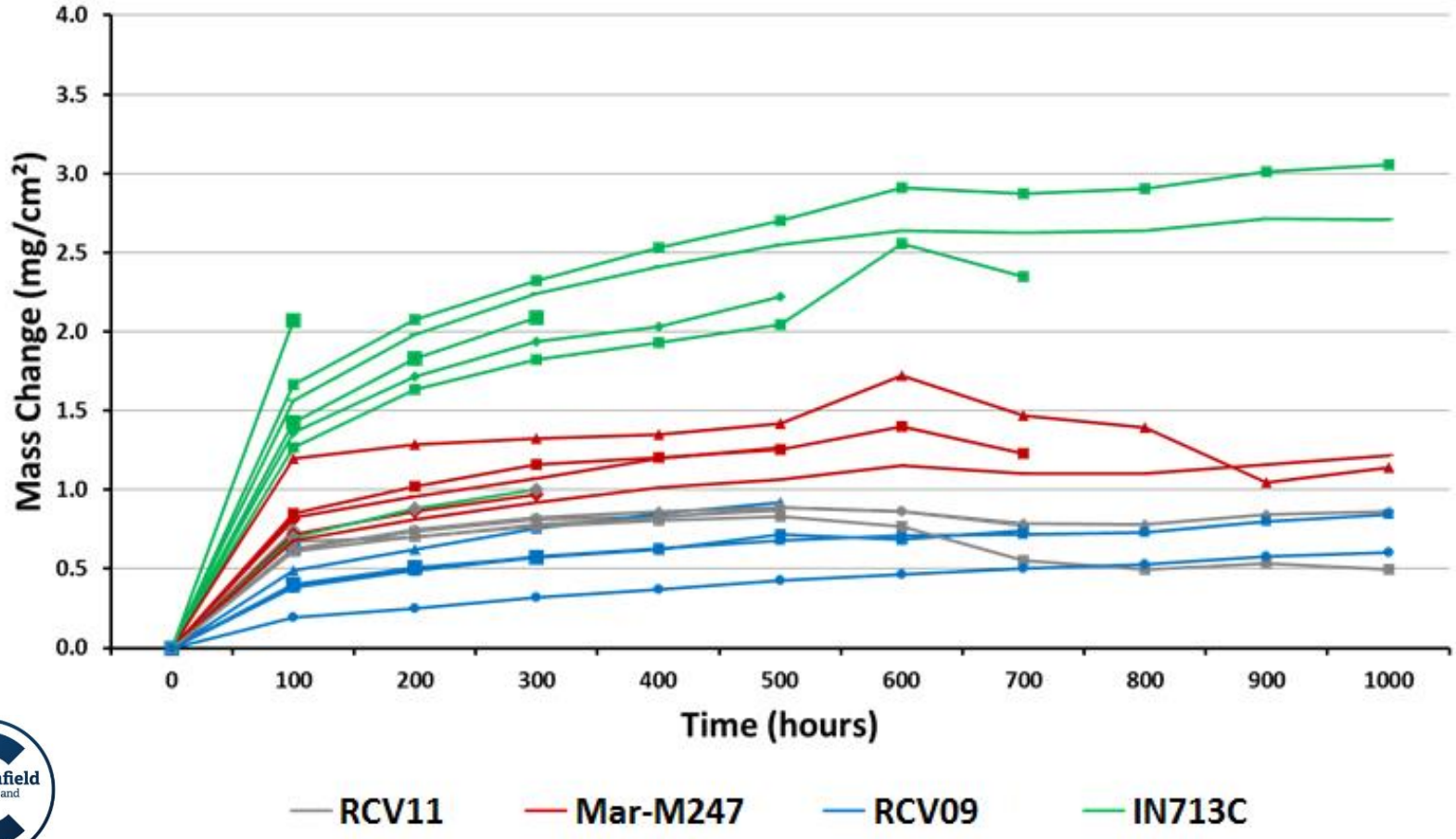
In a gasoline exhaust gas environment at 1562°F (850°C) there is very little difference in mass change



Copyright Doncasters Group 2018 Strictly Private & Confidential

Hot Corrosion Tests

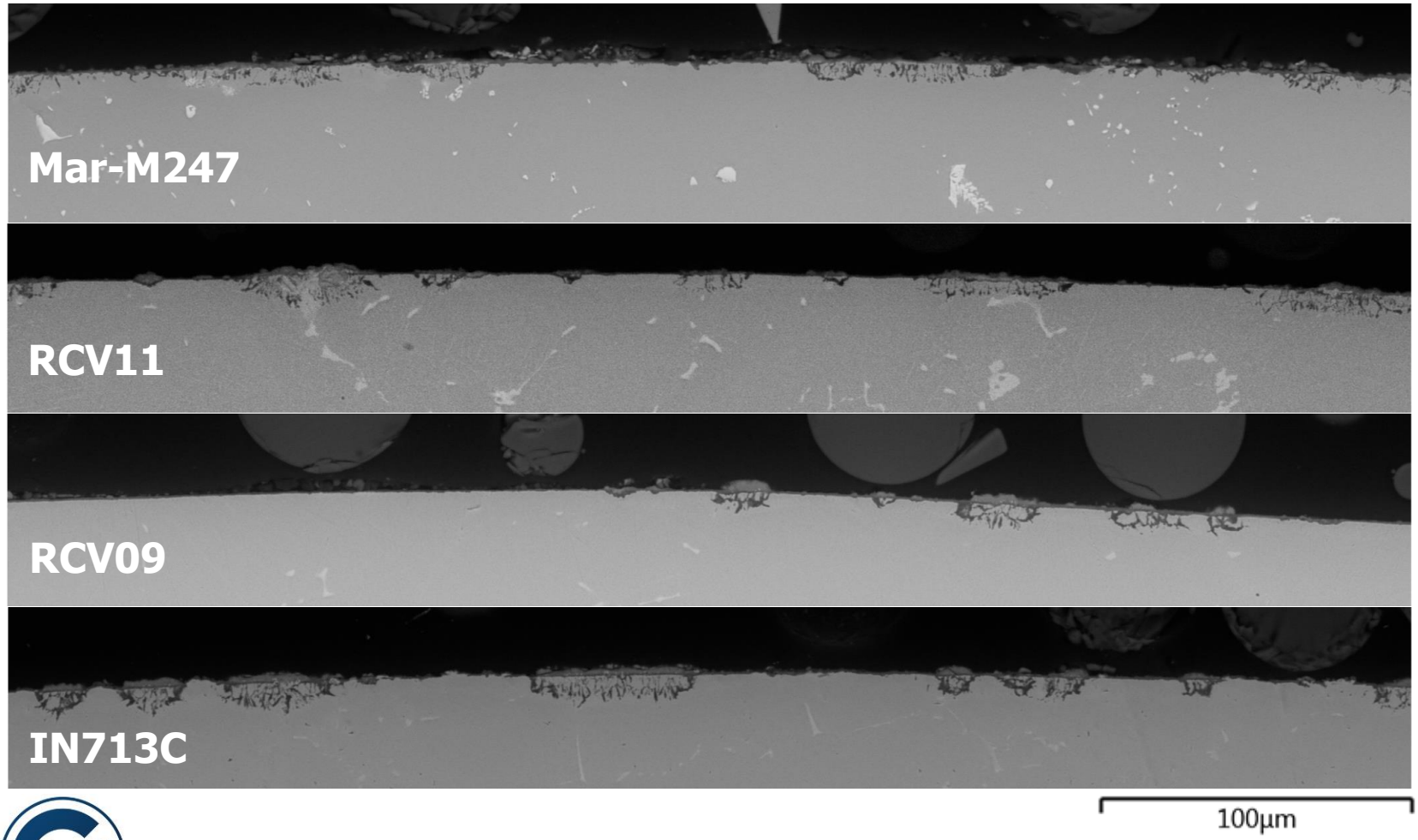
At 1742 °F (950°C) there are clear differences in alloy performance



Copyright Doncasters Group 2018 Strictly Private & Confidential

Hot Corrosion Tests

SEM: 300 h data at 850 °C



Copyright Doncasters Group 2018 Strictly Private & Confidential

Hot Corrosion Test Summary

- Internal precipitates
  - IN713C – Mo/Nb/Ti(?) rich
  - Mar-M247 – Ta rich RCV11 – Ta/Mo rich
  - RCV09 – Mo/Ti rich
- Low rates of metal loss
  - For all alloys at 1562°F (850°C)
  - For all alloys except IN713C at 1742 °F (950°C)
  - 1922°F (1050°C) test to run
- Damage morphology
  - Internal aluminium-rich oxides
  - External chromia-rich oxides
  - Damage appears to spread laterally across surface with time as well as increasing slightly in depth

Copyright Doncasters Group 2018 Strictly Private & Confidential

Summary

- There is a clear requirement for new bespoke alloys for turbocharger turbine wheels
- Two new alloys have been designed from first principles
- So far tests have shown that RCV09 and RCV11 perform well
- Further tests are ongoing
  - High temperature mechanical testing
  - High temperature fatigue tests – LCF, HCF and TMF
  - Hot corrosion test at 1922°F (1050°C)
- Turbocharger OEM's have been engaged to perform further testing such as on a gas stand
- Once the data is fully collated a data sheet for the new alloys will be compiled

Copyright Doncasters Group 2018 Strictly Private & Confidential

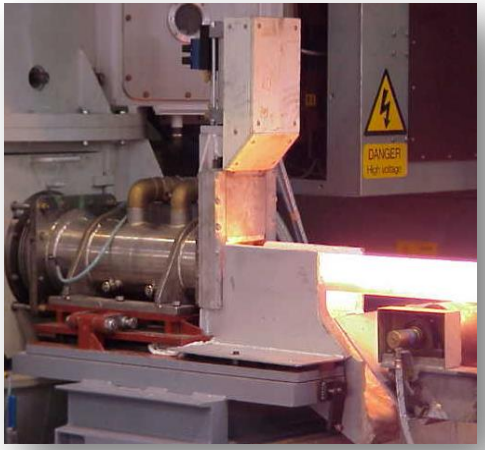
Thank you!

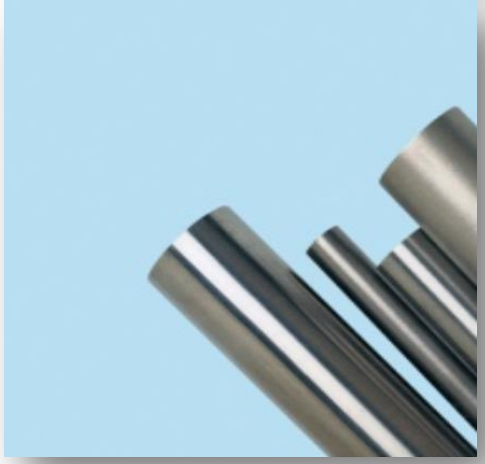
DONCASTERS
SUPERALLOYS

Tom Sellers
Technical Sales Manager

Ross & Catherall
Forge Lane, Killamarsh, Sheffield,
South Yorkshire, S21 1BA, UK
Direct: +44 (0) 114 247 9839
Mobile: +44 (0) 7713 215 403
Email: tsellers@doncasters.com

www.doncasters.com





Copyright Doncasters Group 2018 Strictly Private & Confidential