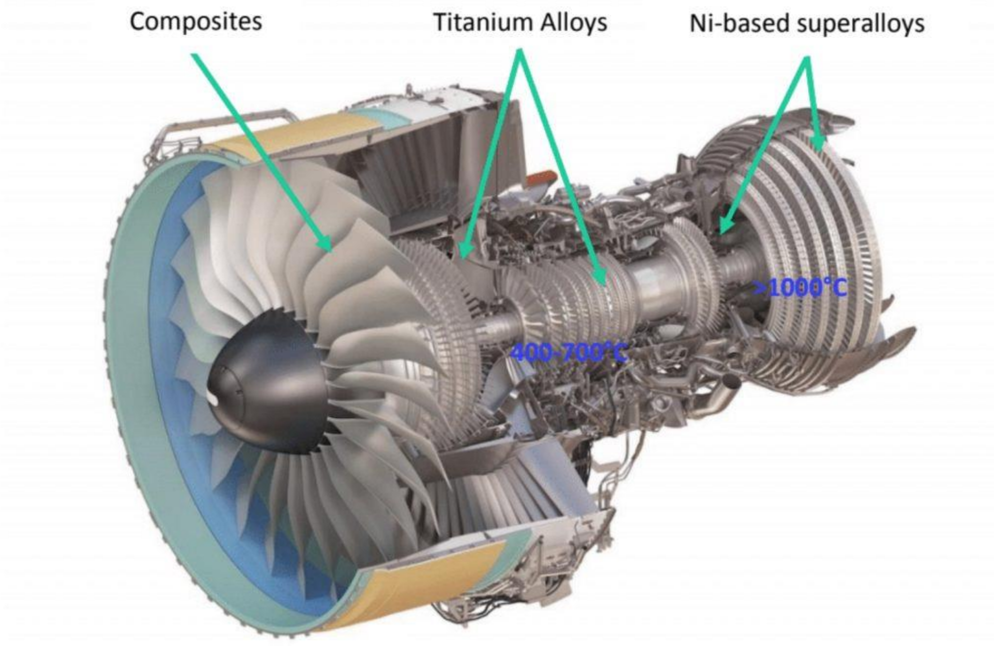
SULZER

Innovations in High-Temperature Alloy Development for Additive Manufacturing: Current Trends and Prospects

Dr Yogi Pardhi CEng FIMMM

ETN Project- Objective & Scope



Objective:

- Find a high-temperature blade material, achieved via stabilization of a high temperature phase (typically high-volume fraction of the γ' phase to at least 1100 °C in Ni and Co alloys), solidus and liquidus temperatures above 1300 °C with a narrow equilibrium freezing range, high resistance to oxidation provided by formation of alumina in oxidizing environments and favourable printability/weldability.

In scope

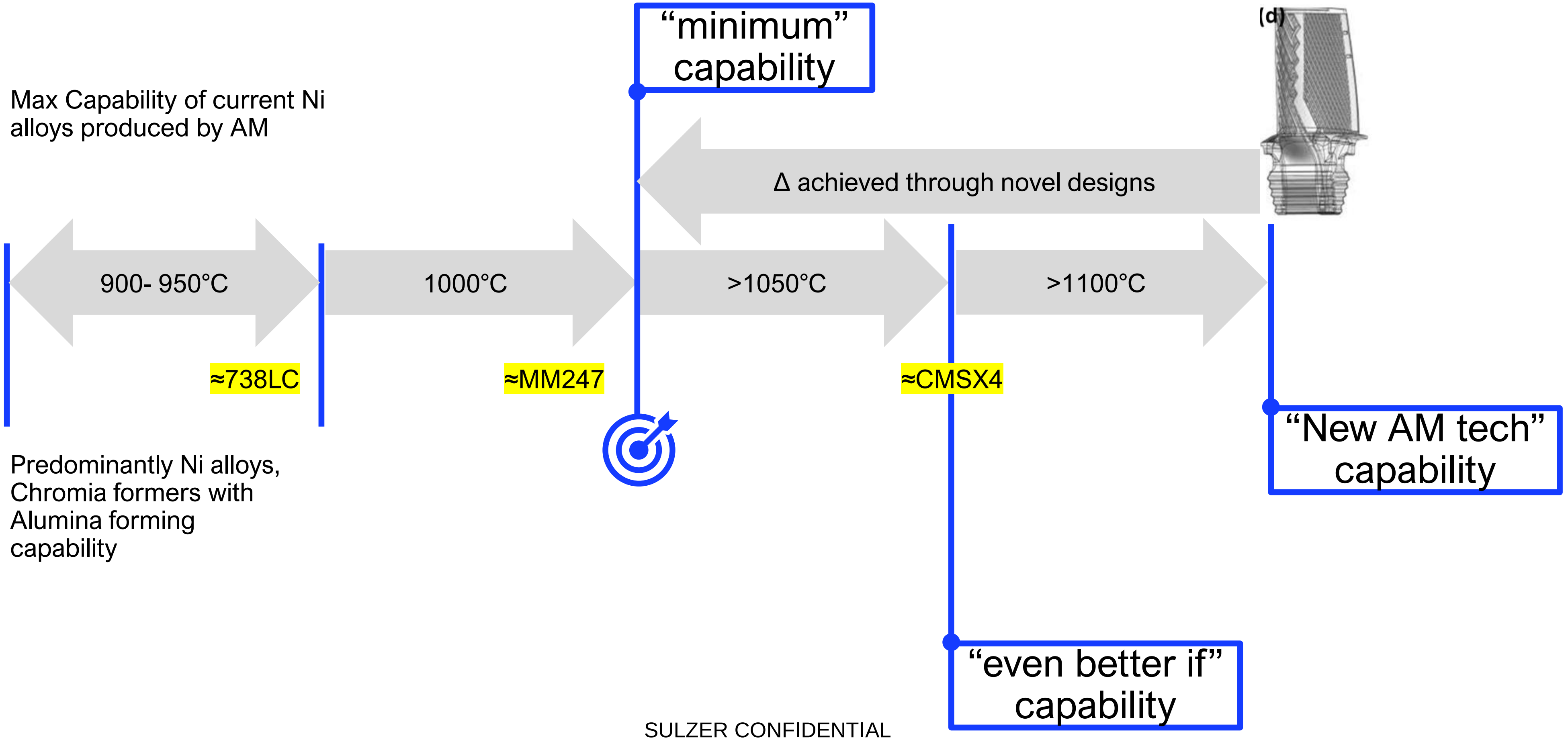
- Review of published information and connect with alloy development companies to search for developed alloys to low TRL (1-3) levels.
- Select 2-3 alloys for investigation and evaluate printability (process parameters) by LPBF, heat treatment, assess key material properties (TBD but Fatigue, Creep, Oxidation).
- Manufacturing demonstration using a gas turbine blade geometry.

Out of Scope

- Development of new alloy from scratch
- Alloys with minor modification of cast/wrought equivalent
- Materials enabled using high temperature bed or future technology

Outcome

- Identify high temperature blade alloy (early TRL) and develop/validate it to TRL3/4 level.
- Minimum 50°C above currently processable high temperature alloys by AM.
- High-temperature alloy with 1000°C metal temperature capability for HP turbine blades.



Alloy development trends

Modification to existing alloys such as IN939, IN738LC and CM247LC has been tried extensively.

Processes are now available for IN939 and IN738LC, still presenting cracking issues when making complex geometries.

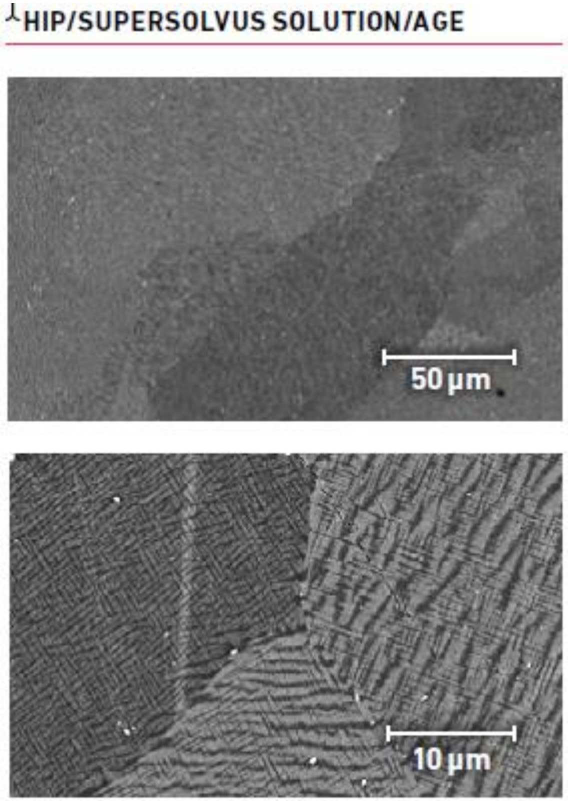
Increasing trend in investigating new alloy chemistries suited to LPBF.

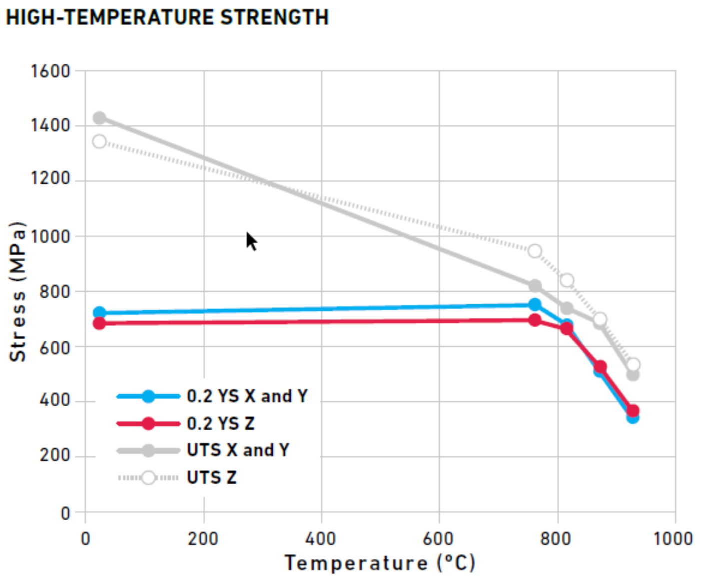
Co based Superalloys

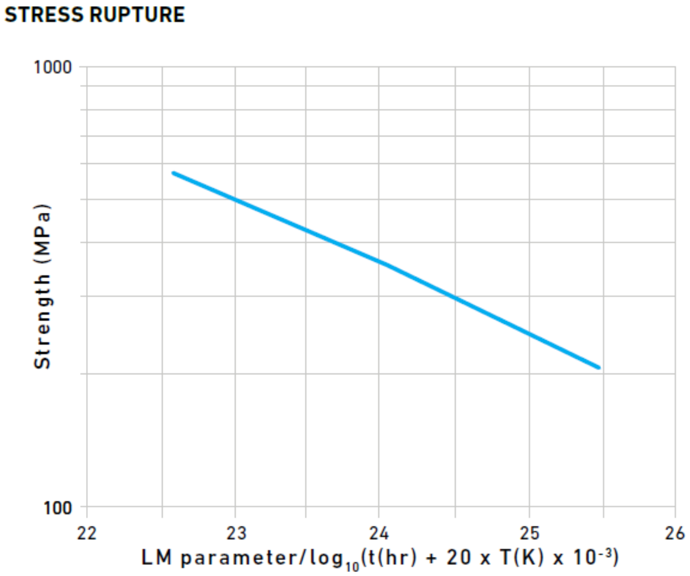
Re-look at Co based superalloys for additive manufacturing by some institutes.

[A defect-resistant Co–Ni superalloy for 3D printing | Nature Communications]

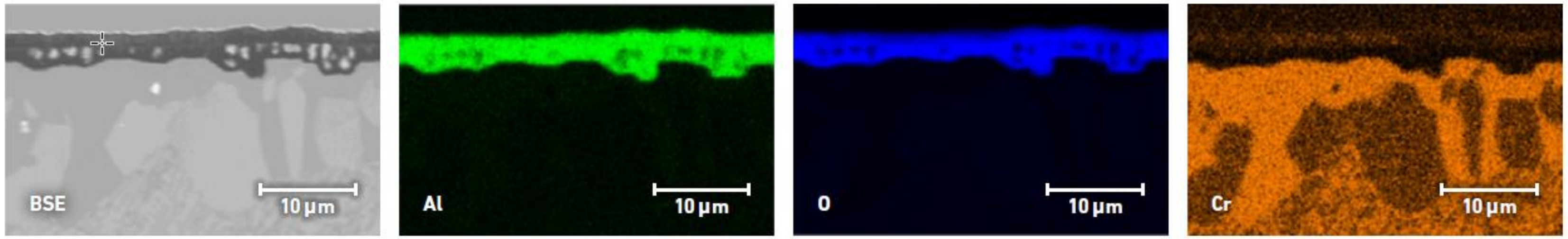
- The γ'-solvus, solidus, and liquidus as 1204, 1329, and 1381 °C, respectively.
- HT window of 125 °C
- An equilibrium freezing range of 52 °C.
- A high-volume fraction of γ' of ~0.7 after aging at 1000 °C,
- A mass density 8.65 g cm^3







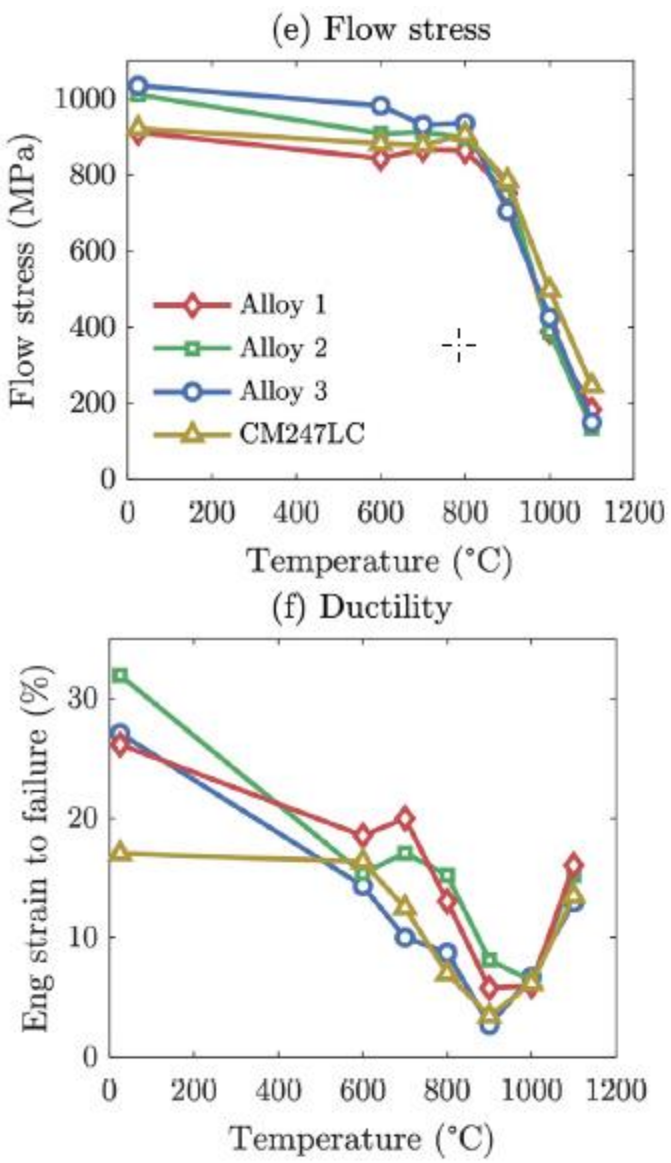
Protective alumina layer formed after 100 hr exposure at 982°C (1800°F)



Research on new Nickel-based superalloys

New alloy compositions from Alloyed, Oerlikon, Liburdi, Carpenter Additive, Höganäs, etc.

- Increasing use of computational methods to develop new alloys.
- Promising compositions have been developed, limited data, no significant breakthrough.
- Combination of alloy chemistry, process parameters and heat treatment is used to achieve target.
- Elongation either at RT or ET can be low.
- Limited information on how these alloys will behave when making complex geometries, like cooled blades.



Comparative analysis of room temperature tensile properties between heat-treated LW 4275 with other high gamma prime Ni-based superalloys.

Material	Fabrication method	HT condition	YS (Mpa)	UTS (MPa)	Elongation (%)	Reference
LW 4275 (Z direction)	LPBF	HT (SA + Aging)	939	1368	23	this work
ABD-850AM	Selective laser melting (SLM)	(SA + 2Aging)	964	N/A	22	[51]
ABD- 900AM	Selective laser melting (SLM)	(SA + 2Aging)	1024	N/A	17	[51]
CM 247LC	Selective laser melting (SLM)	(SA + 2Aging)	911	N/A	19	[51]
IN 939	Selective laser melting (DMLS)	(SA + 2Aging)	932	N/A	6	[51]
IN 738	Vacuum investment casting	HT (SA + Aging)	951	1103	3	[52]
Low carbon IN 738 LC	Vacuum investment casting	HT (SA + Aging)	896	1034	7	[52]
High carbon IN 738C	Vacuum investment casting	HT (SA + Aging)	951	1096	5.5	[52]
Rene 80	Vacuum investment casting	Over ageing	862	1034	5	[53]
MAR M 247	Investment casting	HT (Annealing)	814	980	6	[54]
IN 100	Micro-laser aided additive manufacturing	HT (SA + 2Aging)	976	1045	5	[5]

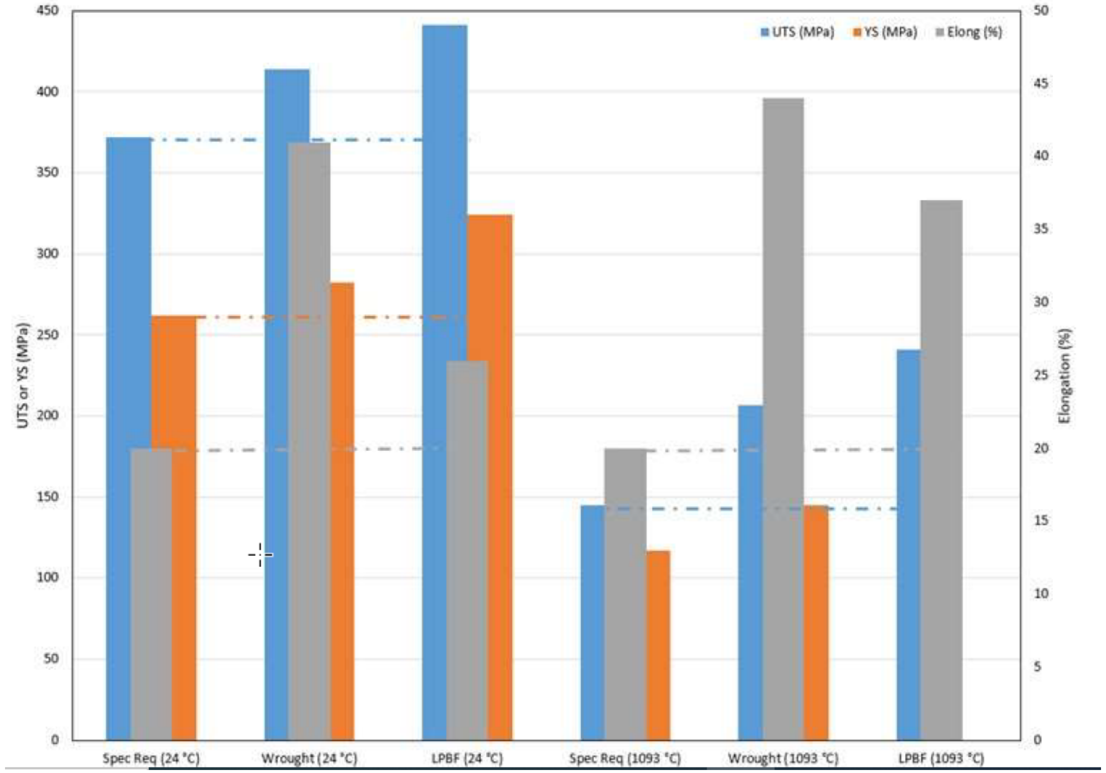
Refractory Alloys for propulsion- C103

Interesting but not suited for blade application with current properties.

- [Additive Manufacture of Refractory Alloy C103 for Propulsion Applications - NASA Technical Reports Server (NTRS)]

Table 3 AM C103 room temperature tensile properties in the Z direction

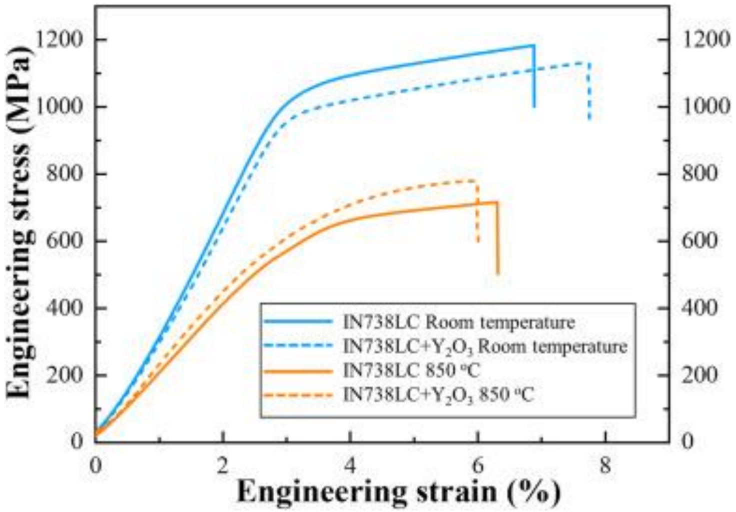
Condition	YS_{avg} (MPa)	UTS_{avg} (MPa)	ε_{avg} (%)
As-Built (Z)	560.43±1.47	410.94±0.12	16.67±0.2
SR (Z)	410.5±0.28	334.9±1.02	20.79±0.4
SR+HIP (Z)	452.46±60.35	326.03±106	18.88±4.83



Nanoparticle (Y_2O_3) reenforced

Can be applied to many materials- many organisations have been working in this area.

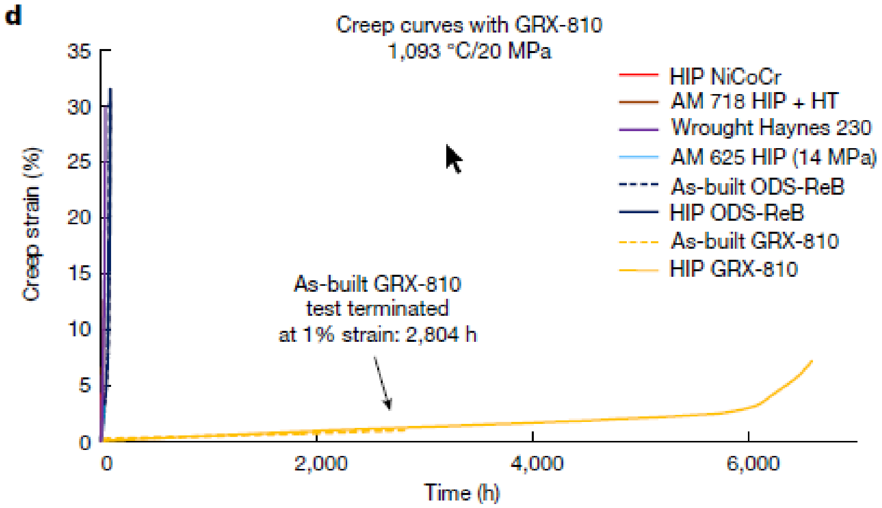
- Y_2O_3 nanoparticles decorated IN738LC superalloy manufactured by LPBF.
- Improved strength at 850 °C.
- Process window is significantly enlarged with the addition of 0.05 wt% Y_2O_3
- Further data needed on material properties and part manufacturability.



Source- Elementum 3D

NASA's GRX 810

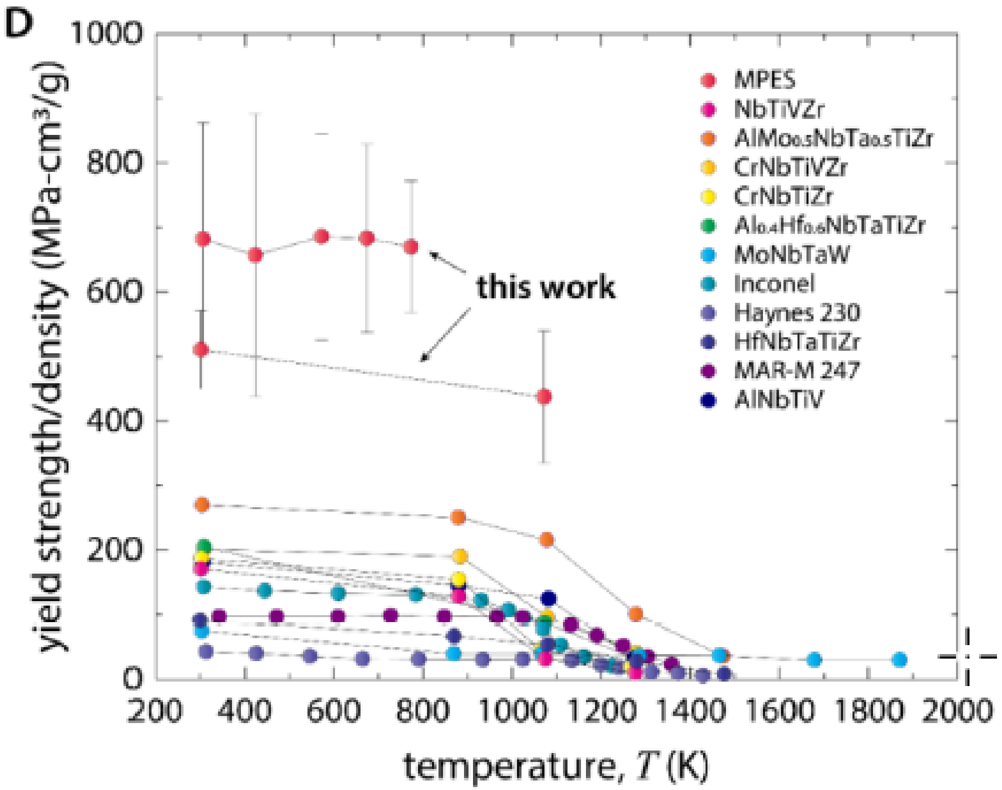
- Y_2O_3 in Ni-Co-Cr matrix
- Claimed to have at 2,000 °F (1,093 °C),
  - GRX-810 twice the strength in resistance to fracturing
  - Great flexibility without cracking when bent and stretched.
  - more than 1,000 times the durability under stress.
  - depends what you compare to
- Creep performance inferior to cast IN738LC.



Multi-principal element superalloy

Five refractory elements and aluminium

- Density 5.7 g/cm3.
- High Hardness.
- Limited information.
- [Extreme hardness at high temperature with a lightweight additively manufactured multi-principal element superalloy - ScienceDirect]



High Entropy Superalloys

- Designing precipitation-strengthened HEAs with desirable properties is a significant challenge due to the chemical complexity.
- Another key issue is the difficulty in obtaining suitable AM processing parameters for these precipitation-strengthened HEAs.

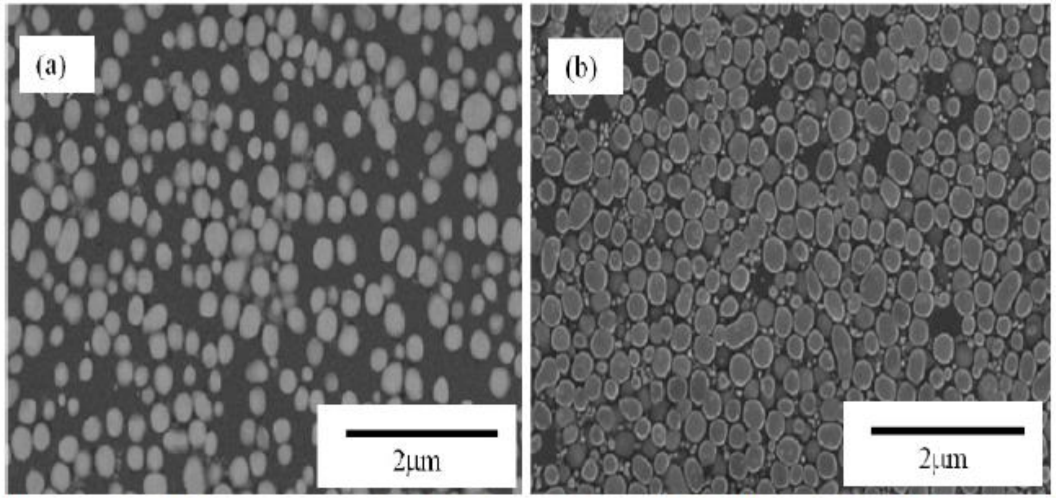


Figure 5: SEM micrographs of specimens aged at 1,050°C (a) Alloy B, and (b) Alloy C.

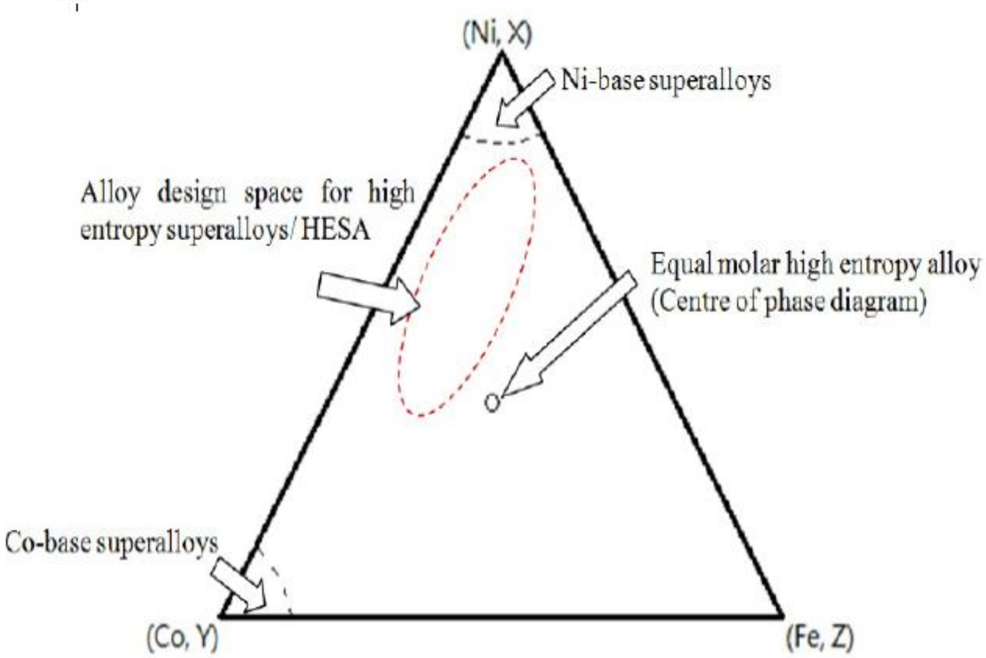


Figure 2: Illustration of the alloy design space for high entropy superalloys.

Summary

Significant progress in recent years on developing new superalloys for additive manufacturing

Increased use of computational methods to reduce alloy development time.

Based on limited published data some alloys show promise.

Still significant gap to single crystal alloys, which can potentially be filled with DfAM.

Gap in published data means it is not possible to select a candidate for use.

ETN project aims to fill the gap for select alloys.