DEVELOPMENT OF CASTABLE PRECIPITATION HARDENED NI-BASE ALLOYS FOR 750°C TECHNOLOGY WITHIN NEXTGENPOWER PROJECT

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Abstract

The increasing world wide demand for electricity and the political motivation to reduce carbon dioxide emissions is dictating the need to increase the net efficiency of the next generation of coal fired power plant. This has lead to the initiation of many research and development programmes throughout Europe.

In order to achieve a net efficiency of 45%, live steam temperatures of 750°C are required in A-USC plants operating CCS technology. (1) Currently, commercially availible steels have a upper temperature limit of around 620°C and it is unlikely they can be developed to operate above 660°C. On the otherhand, Ni-base alloys have the potentional high temperature properties to meet the unforgiving parameters of A-USC technology. Therefore, material development has focused on nickel alloys. European programs such as AD700, COMTES, European 50+ and more recently, NextGen Power and Macplus, have investigated the use of nickel alloys in the steam turbine.

So far only solid solution strenghted alloys such as alloy 625 have been proven in full size demonstration castings, however these have a upper limit of around 700°C. Therefore it is precipitation hardended ni-base alloys, strengthened by the precipitation of gamma prime γ' and/or gamma double prime γ'' when aged around 800°C, that are likely to have the required high temperature strength that have been the focus of development within the workpackage of SP2 of the NextGenPower project.

Keywords: Casting, NextGenPower, A-USC, Ni-Alloy, Precipitation Hardened.

1. Introduction

The metallurgy of precipitation hardened alloys are more complex than that of solid solution strengthened alloys, and requires a much more demanding process control. The ability of the methods engineer to accurately predict liquid shrinkage in nickel alloys is also essential for the production of a high integrity component. This is an important issue as the solidification characteristics of nickel alloys are different than for conventional steels and the value of accurate material data sets and calibration of predictive tools is essential.

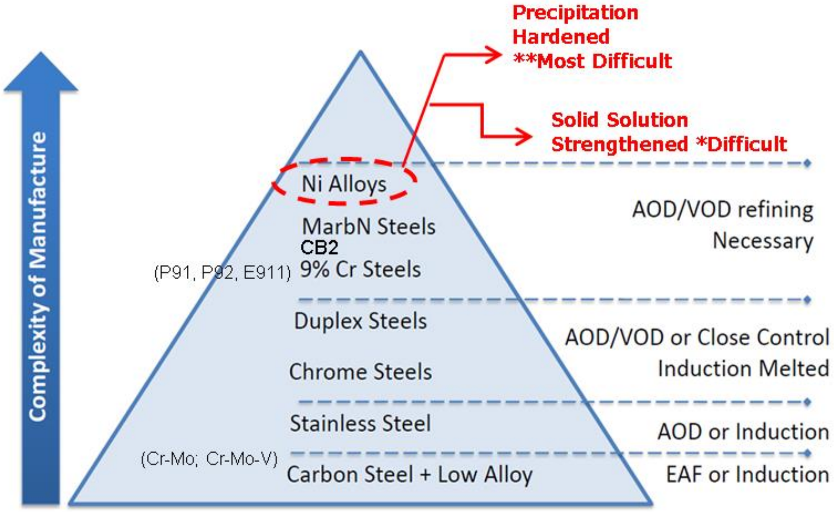

Figure 1 - A representation of casting material processing/manufacturing complexity

The successful production of heavy section nickel alloy castings requires a significant leap in technology, specialised processes and understanding than that required for similarly sized steel castings. Nickel alloys require specialised secondary refinement techniques such as AOD, VOD or VODC to obtain optimum quality and require much different approaches for method design because of the higher concentrations of aluminium and titanium.

In addition to the castability issues of these alloys there are challenges regarding microstructural integrity. Due to the inherent nature of the solidification of castings during their production, heavy sections can have vastly different properties to that of thin. Within NextGenPower Goodwin have made significant progress and this paper summarises the breakthroughs on route to the ultimate aim of producing the worlds first full scale demonstration casting in a precipitation hardened alloy.

2. Candidate alloys

The initial task was to establish candidate precipitation hardened alloys that had the potential to be utilised in cast turbine applications. Knowledge and casting experience from previous R&D projects such as AD700 was drawn upon and the alloys selected were alloy 282, 263, 105, 230 and 740H. During the first SP2 work package technical meeting this selection was narrowed down to three alloys alloy 282, alloy 263 and 740H on the basis of creep strength, sufficient room temperature ductility, oxidation performance and perceived weldability. Special thanks go to Haynes International and Special Metals who allowed Goodwin to produce trial melts of cast alloy 740, 740H and 282 for R&D.

3. Casting of trial melts

Trial melts of the selected alloys have been cast in the form of a step block with section steps of 100mm, 200mm and 300mm respectively, the design of which can be seen in Figure 4. These sections closely represent the wall thicknesses that would be expected in a typical range of steam turbine cast components, and so are very representative of typical cooling rates during solidification. Goodwin’s previous experience showed that small scale trial castings rarely qualify how a nickel alloy behaves when cast in heavy sections.

The chemical composition chosen for these trials were predominately the prescribed wrought chemistry and to our best knowledge had never been produced as heavy section cast components.

Alloy	C	Si	Mn	Ni	Cr	Mo	Nb	Co	Al	Ti	Fe
Alloy 740H	0.046	0.32	0.30	BAL	24.6	0.54	1.31	19.57	1.22	1.36	0.22
Alloy 282	0.034	0.36	0.03	BAL	19.3	8.01	0.03	10.0	1.40	2.10	0.21
Alloy 263	0.057	0.34	0.37	BAL	19.8	5.61	0.01	19.6	0.42	2.05	0.07

Table 1- Trial melt chemical compositions

4. Analysis of trial step blocks

All the step block castings, to varying degrees suffered from microstructural cracking during the heat treatment process, which in cast alloy 282 and 740H blocks resulted in volumetric cracks that were detected upon radiographic examination.

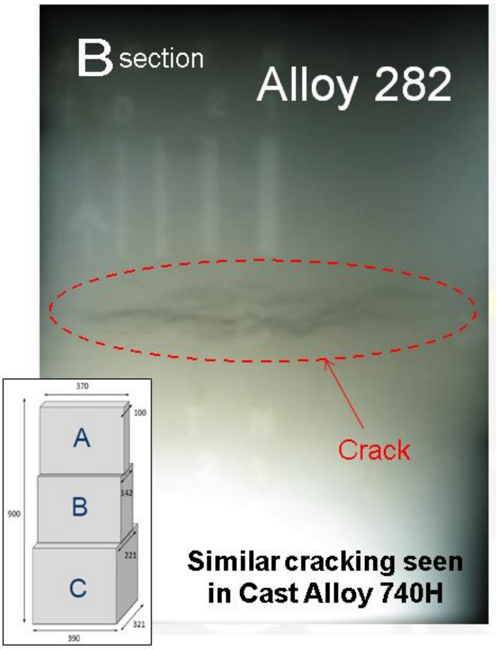

Figure 2 – This type of cracking was seen in cast alloy 282 and 740H. Cast alloy 263 passed RT examination but surface inspection showed deep surface crazing.

Material evaluation and characterisation of each alloy was conducted by Loughborough University who established that the volumetric cracking, although different in each alloy, was always associated with cracked carbides dispersed along the grain boundaries, and often worse in the heaviest sections of the material. Some cracking was also associated with grain boundary vacancies.

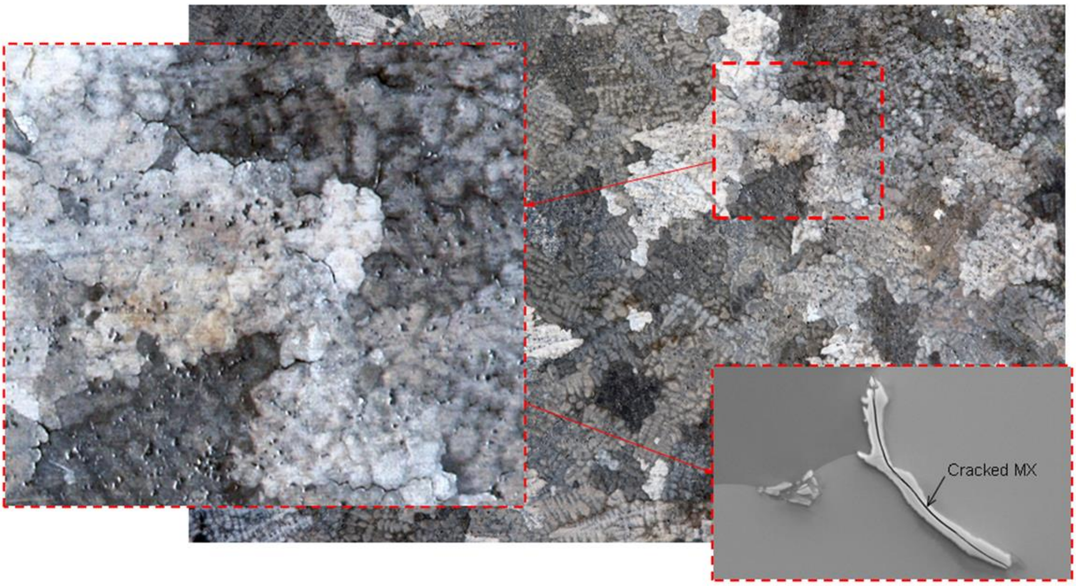

Figure 3 – Example of microstructural cracking associated with cracked MX precipitates after heat treatment

A major deliverable was to manufacture a full scale demonstration casting to evaluate the castability and mechanical performance of the most promising alloy investigated. Due to technical difficulties in producing material with good heavy section microstructural integrity it was decided that further development was required before proceeding to the full scale demonstration casting.

After a period of evaluation and development three additional blocks were manufactured with modified chemistries and optimised heat treatments. The idea being to evaluate these new materials before proceeding to select one of the materials for the full scale component.

Casting of modified alloy trial melts

Extensive R&D was conducted in collaboration with Loughborough University which included:

1) Materials characterisation
2) Thermodynamic simulation
3) Stress analysis
4) SEM, EDX and TEM analysis

Modified chemical composition step blocks were cast in 282-Mod, Alloy 263-Mod and Alloy G130 (Goodwin proprietary alloy). These alloys were selected because they showed predicted castability potential in comparison to the previous castings produced to the wrought chemistry. Again, these step blocks had 100mm, 200mm and 300mm sections to represent those of a typical turbine component.

Figure 4 - Modified cast alloys after knock out of the mould

Each block was heat treated using an optimised cycle. These cycles were determined by laboratory testing after extensive modelling and characterisation performed by Loughborough University.

5. NDT of modified alloys step blocks

All the modified alloys showed improved volumetric integrity after heat treatment. However, cast alloy 282M still had evidence of volumetric cracking while cast alloy 263M and G130 passed RT assessment to ASTM E446/186/280 level 1.

Figure 5 – RT graph of G130 step block

6. Microstructural characterisation of modified alloys

The modified alloys exhibited vastly improved microstructures after heat treatment. Alloy G130 showed very few MX precipitates and those observed were not cracked therefore microstructural integrity was very good. However cast alloy 282M did still contain cracked Mo-rich carbide precipitates although fewer were observed compared to the original castings produced to the wrought composition. Cast alloy 263M, also showed improvements with regards to the modifications made. However heavy section ductility (Table 3) was similar to that of cast alloy 282M which showed a marked reduction compared to G130. This may indicate potential microstructural deficiencies which are still being evaluated.

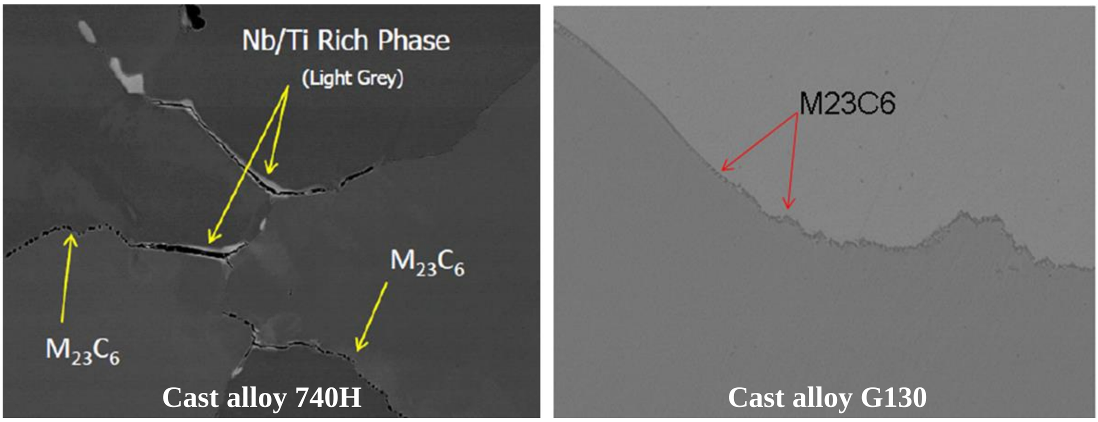

Figure 6 -Example of the improved microstructure in the cast G130 composition compared to the cast 740H composition after optimised heat treatment.

7. Mechanical properties

The mechanical properties of the cast alloys can be seen in Table 2. The original castings produced to the wrought compositions exhibited low ductility and early failures were experienced. This was a result of the microstructural cracking observed.

Alloy	Yield (N/mm^2)	UTS (N/mm^2)	Elongation (%)	R of A (%)	Impacts @ RT (J)
$_1$ Alloy 740H	545	560	5	11.5	22/43/37 Avg 34
$_1$ Alloy 263	444	496	9	-	-
$_1$ Alloy 282	No result – samples fractured prematurely				
$_2$ Alloy G130	410	691	30	42	128/136/110 Avg 125
$_2$ Alloy 282 MOD	588	751	15	18	52/50/50 Avg 51
$_2$ Alloy 263 MOD	506	718	29	28	150/184/205 Avg 180

Table 2 - Mechanical properties obtained from a 50mm section. All material in the solution treated and aged condition.
$_1$ Premature failures due to microstructural cracking, $_2$ No premature failures

The mechanical properties of alloy G130 is a little weaker at room temperature than the cast alloy 282M and 263M yet a marked increase in tensile strength and ductility over these alloys was observed, which was particularly apparent in heavy sections.

Test material from the modified cast alloys were tested by partners within the NextGenPower project which included room temperature mechanical testing and high temperature stress rupture testing.

8. Cast Alloy G130 development:

After a further evaluation period Goodwin successfully cast G130 modified variant compositions (G130A & G130B) which combined further chemistry changes with optimised heat treatments. The preliminary mechanical testing data can be seen in Table 3 where the mechanical properties of both 100mm and 200mm sections show a marked increase in UTS and ductility over cast alloy 282M and cast alloy 263M.

G130 series of alloys produced show good through section mechanical properties whilst other cast precipitation hardened alloys experience a dramatic reduction in mechanical strength in 200mm sections.

Alloy	Cast section thickness	Yield (N/mm^2)	UTS (N/mm^2)	Elongation (%)	R of A (%)	Impacts @ RT (J)
Alloy G-130B	200mm	456	708	39.4	36.7	124/128/134
Alloy 282 MOD		498	554	5	6	88/98/44
Alloy 263 MOD		451	487	9	7	228/228/230
Alloy G-130B	100mm	494	713	38	36.6	168/145/142
Alloy 282 MOD		545	671	14	23	74/85/44
Alloy 263 MOD		419	647	31	50	252/232/246

Table 3 - Mechanical properties obtained from 100mm and 200mm sections from 1500kg cast step blocks

Alloy G130B exhibits high ductility through section, an important factor when considering the difficulty of welding precipitation hardened cast alloys.

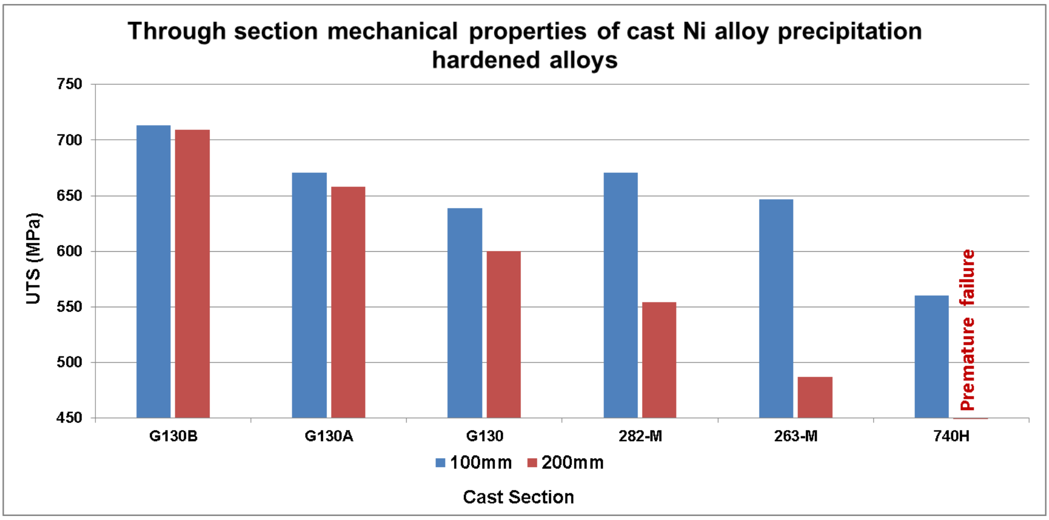

Figure 7 - Through section mechanical properties of modified cast Ni-alloy precipitation hardened alloys in relation to section thickness. Note: No UTS value obtained for cast Alloy 740H due to premature failure caused by microstructural cracking

9. Cast Alloy G130 Stress Rupture:

Short term stress ruptures of G130 alloys plotted against LMP are shown in Figure 8. The graph shows that the materials meet the target of 80MPa for 100,000hrs at 700°C and likely to approach this criteria for 750°C.

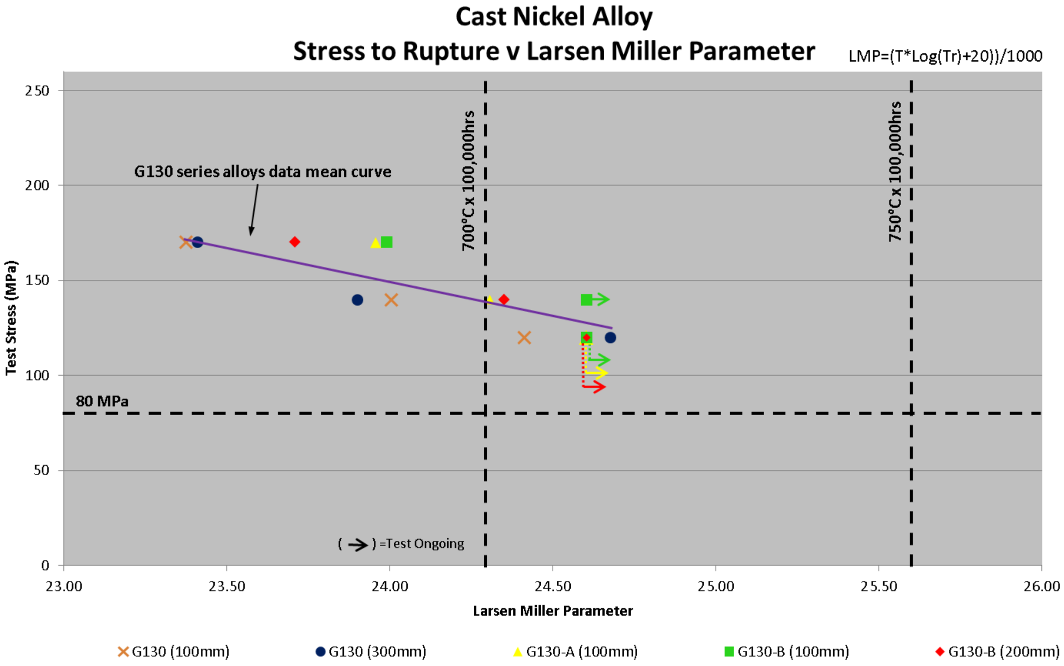

Figure 8 - Stress Rupture plotted against LMP for alloys G130, G130A and G130B

Conclusions:

Over the last 15 years, Goodwin has been involved in the advancement in technology of cast nickel alloys for advanced ultra super critical applications (A-USC). Within NextGenPower and MacPlus projects, Goodwin have successfully overcome many challenges relating to the complexity of casting precipitation hardened Ni alloys and have developed a castable Ni-base superalloy that is looking very promising for suitability for manufacture of cast turbine components operating at 750°C.

Acknowledgments:

We would like to acknowledge the work that Loughborough University has contributed in the characterisation and evaluation of the nickel base cast alloys discussed in this paper, and especially the help of Professor Rachel Thomson and her team.

Notes:

The use of the word “Goodwin” with in this paper relates specifically to the company “Goodwin Steel Castings Ltd, Ivy House Road, Hanley, Stoke-on-Trent, UK”.

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