Advances in Materials Technology for Fossil Power Plants

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S. Birks (1), S. Roberts (2), R. Leese (3)
Goodwin Steel Castings Limited, Ivy House Foundry, Ivy House Road, Hanley,
Stoke-on-Trent, Staffordshire, ST1 3NR, UK
(1) General Manager, (2) Technical Director, Metallurgist (3)

Advances in Ni Alloy Casting Production for +700'C Applications

Abstract:

The drive for reduced carbon dioxide emissions and improved efficiency in coal fire power plant has lead to much work being carried out around the world with regards to material development to enable 700+°C steam temperature operation. At these elevated temperatures and pressures steels just don’t have enough strength, and typically have a temperature limit of around 620°C (possibly up to 650°C in the near future) in the HP environment. 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. Large castings have an important role within the steam turbine, because valves bodies and turbine casings are nearly always produced from a cast component. The geometry of these components is often complex, and therefore, the advantage of using castings for such items is that near net shapes can be produced with minimal machining. This is important, as nickel alloys are expensive, and machining is difficult, so castings offer an attractive cost benefit. Cast shapes can be more efficiently designed with regards to stress management. For example, contouring of fillet regions can help to reduce stress concentrations leads to reduced plant maintenance and casting complex shapes reduces the number of onsite fabrication welds to inspect during outage regimes.

Introduction:

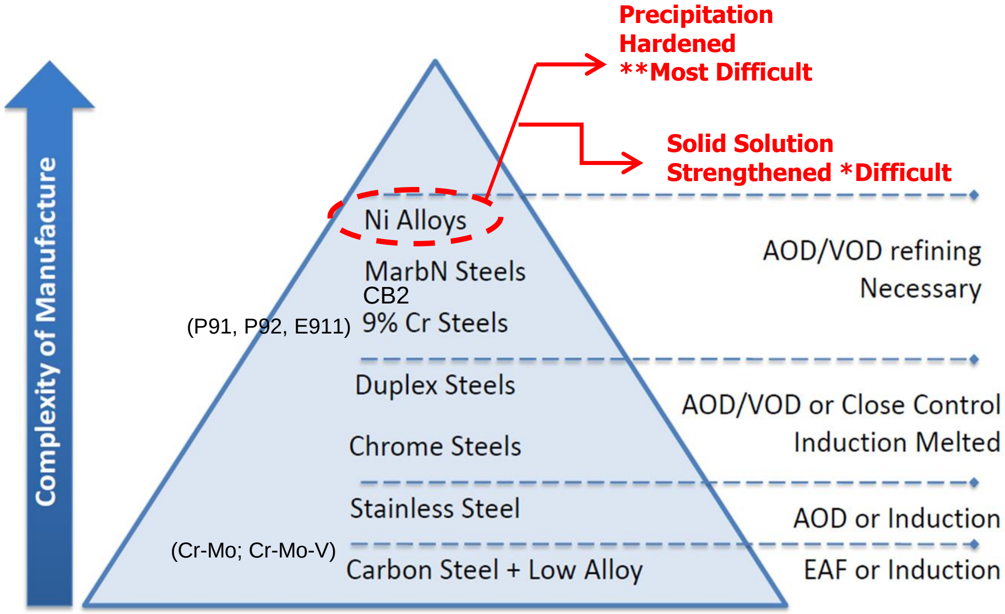
Nickel alloy development for castings has concentrated on two main groups of alloys, solution strengthened and precipitation-strengthened alloys. The solid solution alloys are lower in strength than their precipitation hardened counter parts, but possess good ductility and weldability. However, for plant operation above 700°C and up to 750°C, only precipitation strengthened Ni alloys look likely to have the required high temperature strength.

The successful production of heavy section nickel alloy castings requires a quantum leap in technology, specialised processes and understanding than that required for similarly sized steel castings. Nickel alloys require specialised secondary refinement techniques to obtain optimum quality, require much different approaches for method design and require protection to prevent re-oxidation defects during pouring. The metallurgy can also be more complex, and therefore, require much more stringent process controls, especially with regards to thermal treatments. The ability of the foundry 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 therefore, the value of accurate material data sets and calibration of predictive tools cannot be under estimated. This paper will discuss, in summary, the issues when producing these advanced materials in heavy sections, outline the state of the art advances made in over coming these problems, and detail future work required to further advance the casting technology of these materials.

What is the State of the Art in 2013 for Nickel Alloy A-USC Alloy Castings?

The technology to produce large thick wall nickel alloy castings such as steam valves and casings has been a 15-year progression. Many technical issues have arisen and advances made to counteract such problems. In 1998 Goodwin produced for the European AD700 program first cast candidate materials in the form of test blocks. After a material selection process, subsequent work packages within the program focussed on medium size prototype components in Alloy 625 and 617. Now in 2013, large full scale Alloy 625 components have been produced in both European and Pacific Basin A-USC programs, with section sizes up to 435mm, which has demonstrated manufacturability. Alloy 617 has also been successfully produced in cast sections up to 300mm.

Fig 1: A Representation of Casting Material Processing/Manufacturing Complexity



Alloy 617 is more difficult to produce than Alloy 625 as an air melted casting. However, Goodwin have successfully manufactured in heavy sections both alloys, making them a commercial reality with regards to manufacturability for A-USC applications today.

Table 1: Summary of maximum casting sizes that have been produced in the cast from for A-USC applications by Goodwin

Alloy Type	Largest unit Weight Single Item Produced	Largest Section Size	Largest Fabrication Weld
Alloy 625	11,000kg	435mm	200mm + 220mm Dissimilar weld
Alloy 617 Mod	1800kg	300mm	55mm
Alloy 263	900Kg	300mm	None
Alloy 282	900kg	300mm	None
Alloy 740	800Kg	330mm	45mm
Alloy 740H	900kg	300mm	None

Fig 2: 10,500Kg Alloy 625 HP Casting manufactured by Goodwin 2011-2012
Supplied in the proof machined condition with section Sizes up to 435mm
Goodwin have also produced an 11,000kg HP Casting

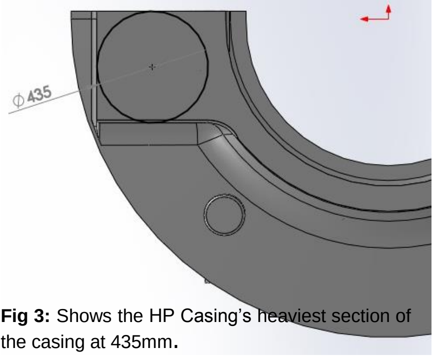


Fig 3: Shows the HP Casting's heaviest section of the casting at 435mm.

Fig 4: Shows the casting during solution treatment just prior to water quench

Fig 5: Nozzle Box Castings: Alloy 617 Mod and Alloy 625
Net Weight: 1,800Kg – both castings supplied in the proof machined condition:
Section size up to 300mm prior to machining

The castings detailed in Fig 2 & 5 were successfully produced using Goodwin's *"Induction Heating Feeder System".* This system is used to control solidification of the cooling casting and to mitigate the risk of solidification stress cracking. The system is important when producing very large section castings, although can be used to produce smaller items such as the nozzle box castings.

How do we melt and pour nickel alloys in air on a production scale?
Nickel alloys, by their very nature, often contain substantial quantities of aluminium and titanium and for small scale components are usually produced by vacuum melting. These elements are added primarily to promote the formation of gamma prime (γ') for strengthening purposes and have a high affinity for oxygen which when cast in air readily oxidise to produce lower than expected recoveries, and oxide film/ inclusion defects.

Air Melting Routes:
The preferred air melting route for these alloys is either electric arc or induction primary melted, followed by secondary AOD refinement. Utilising AOD refinement produces optimised residual element control along with very low gas content. The aluminium and titanium are added as late additions and are protected by an inert atmosphere.

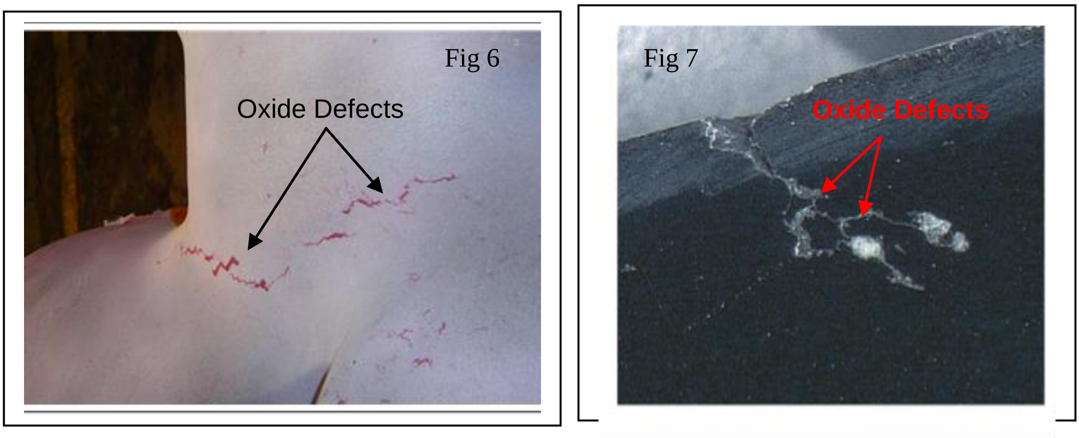
For smaller quantities, induction melting can be used; however, special melting techniques have to be employed to prevent residual gas content pickup, and to protect aluminium and titanium during melt out. Additionally, silica reversion from furnace linings previously exposed to steel melting can cause major problems with silicon pickup in nickel alloys, and pre conditioning often is essential in maintaining low silicon levels required in the final material grade.

Filling the moulds and oxidation prevention:

Running and gating design is essential for the prevention of turbulence in the molten metal stream as the metal discharges from the ladle and enters the mould cavity. The runner and gating system is the key factor that allows the methods engineer to control the molten metal flow into the mould cavity. If not controlled correctly, then the metal can be damaged by oxidation both in the running, gating system and in the mould cavity.

Damaged metal (metal that has been heavily oxidized), and the oxide produced drifts throughout the mould cavity. Due to the density difference between the nickel alloy and the oxide, most oxide will float and gather at the top surfaces (called the cope) of the casting and can be subsequently removed by machining or upgrade repair. However, in thinner wall components where solidification time is relatively quick, the films can be trapped within the solidifying casting, and can constitute a weak point that is difficult to detect by conventional NDE techniques.

Fig 6 & 7: Oxide defects seen in an Alloy 617 casting cast without adequate protection



The higher the amount of aluminium and titanium in the material being poured, then the greater tendency for oxide formation. The prevention of these oxide defects is only remedied by improved pouring technologies, with low turbulence running systems and utilising sealed pouring systems where the mould and pouring stream are protected with inert gas. For the γ' series of alloys, Goodwin use the their “*Total Emersion System” (TES),* where the whole mould and pouring takes place within an enclosed inert gas environment.

Why do nickel alloys have a longer shrinkage cavity than conventional alloys?

The shrinkage characteristics of nickel alloys are far different than for conventional steels. Therefore, the prediction of the solidification characteristics of nickel alloys is more difficult than in steel castings especially when producing heavy section castings, with wall sections over 150mm. Poor prediction will lead to the casting feeders being in adequate and the shrinkage cavity extending into the casting.

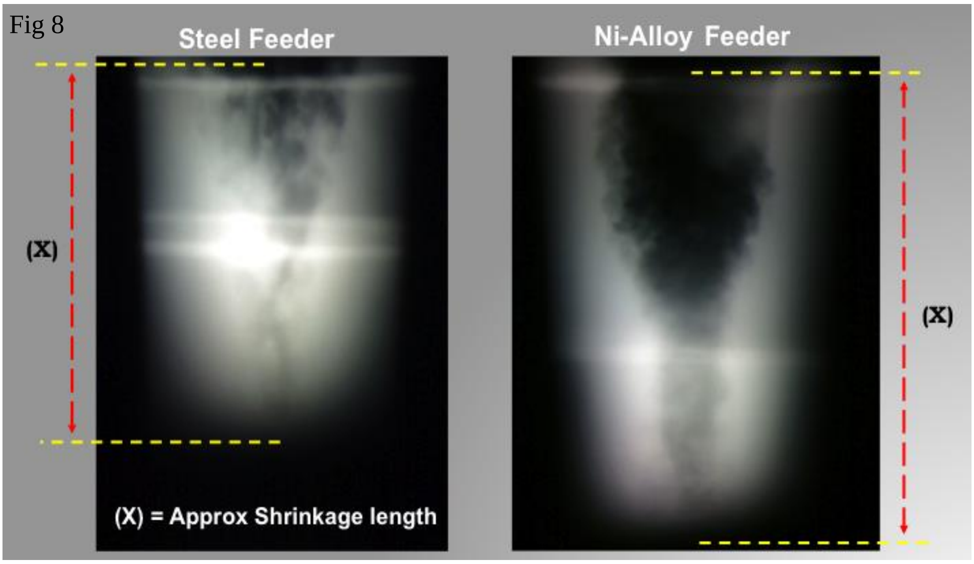


Fig 8: Shows the X-ray of two feeders, one in Alloy 625 and the other in Carbon Steel.

The length of shrinkage (X) is approximately 25% greater in Alloy 625 than seen conventional carbon and low alloy steels.

The reason for the additional length of the feeder pipe is associated with a combination of factors:

a) Thermal conductivity of the material.
b) Freezing range of the last metal to solidify (non-equilibrium composition).
d) Liquid shrinkage characteristics.

Table 2: Theoretical Freezing Range of Typical Cast Alloys:

Alloy	**Estimated Liquid Shrinkage**	**Equilibrium Freezing range**	**Super Heat above Liquidus**
Carbon Steel	5.5%	65’C	70’C
Stainless Steel	5.8%	55’C	100’C
Alloy 625	7.9%	60-70’C	150’C
P91 9% Cr Steel	5.2%	85’C	90’C

Fig 9: Shows the simulated cooling curves of three alloys taken from a point within a heavy section casting. The red line is the cooling curve for Alloy 625, and it can be seen that the thermal arrest time (TA) is 51.5% greater than that of carbon steel. This means that heavy sections take much longer to solidify than conventional materials and then late feed demand is required from the feeders, meaning the feeder “pipe” or cavity extended far beyond what would be expected with conventional alloys.

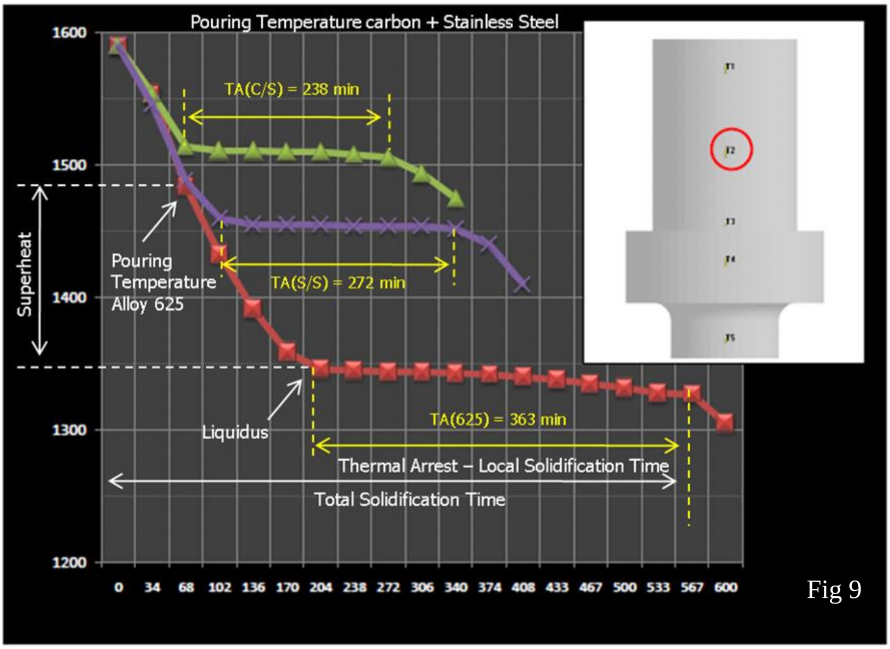


Fig 9

Fig 9: Comparison of solidification time of Alloy 625, Carbon Steel and Stainless Steel at the centre of a heavy section casting (*simulation using Magmasoft™)*.

The ability to accurately predict the liquid shrinkage in nickel alloys is an essential part of successful manufacture. Predictive tools such as solidification simulation software packages have to be accurately calibrated for nickel alloys, and "out of the box" in our view, may not be as accurate as what would be anticipated when dealing with heavy section components.

Casting Solidification Stress Cracking:

This phenomenon is far more prevalent in nickel alloy castings than conventional steels partly due to the poor thermal conductivity of nickel alloys. The cracks are a function of the solidification stresses built up within the casting and feeder arrangement during solidification and further cooling in the mould. The cracks can often appear under risers in heavy section component, and can cause in extreme cases, the castings having to be scrapped.

Fig 10

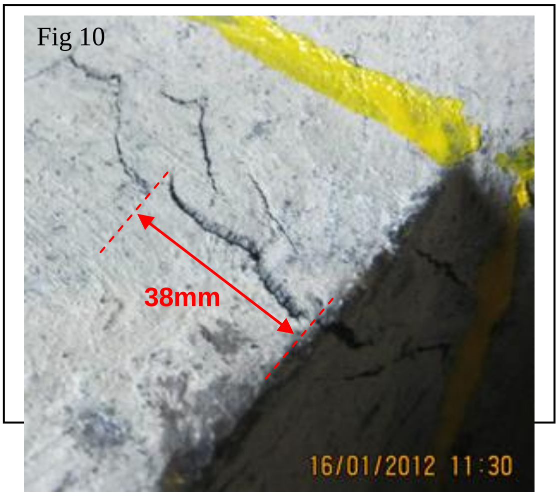


Fig: 10 Shows an example of solidification stress cracks seen in a modified Alloy 617 casting after knockout.

These cracks are highly problematic, as there are difficult to remove without further crack propagation damage, and have to be fully removed before solution heat treatment.

Even with simple geometry the heavier the section size of the casting leads to increased susceptibility for cracking.

The Solution for Solidification Cracking:

Goodwin has developed an *"Induction Heating Feeder System"* specifically for nickel alloys. The feeders of the casting are surrounded by an induction coil so that the outer skin of the feeder can be heated. This allows the feeder to be heated in the molten state after pouring, so that solidification can be controlled, and additionally allows the casting to be cooled in a controlled manner both during and after solidification. This has a number of key benefits listed below:

a) The solidification stresses during cooling can be reduced to prevent stress cracking.

b) The feeder size can be reduced, as the feeders are much more efficient than a conventional feeder. This itself also helps to further mitigate stress cracking, as the feeder section is reduced.

c) Cast yields can be increased to as much as 75%, compared to conventional yields in the order of 40% to 50%.

d) The length of the shrinkage cavity within the feeder can be reduced and the risk of the shrinkage cavity extending into the casting eliminated.

Fig: 11: Schematic of an Induction Feeder Unit

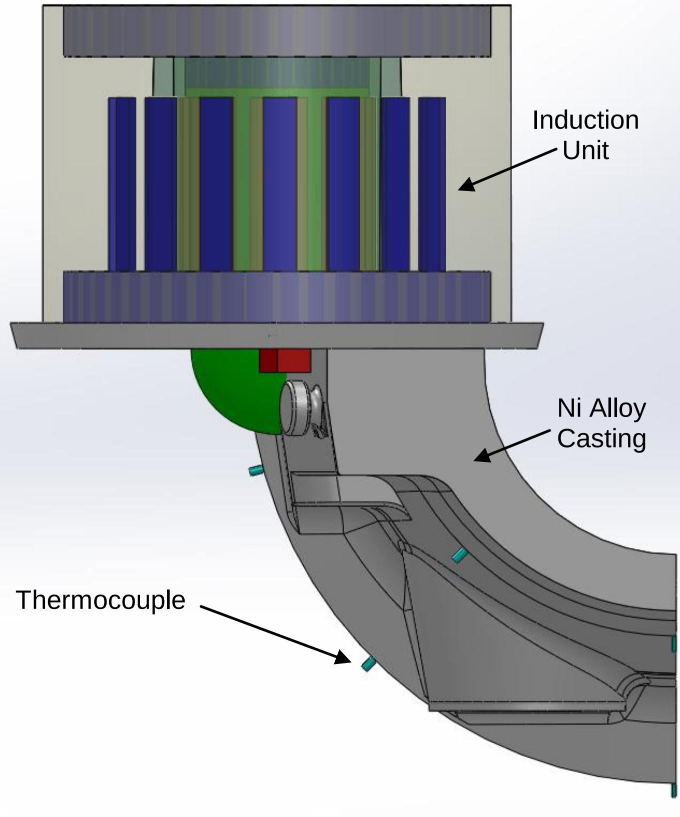


Fig 11: Shows a schematic of one of the induction units placed around one feeder of a cast turbine casting.

Thermocouples are placed within the mould to monitor the solidification sequence of the casting, and ensure the heating cycle is performing accurately.

Applying additional heat or cooling by the induction system can rectify any excursion from the designed zonal temperature profile within the casting and feeder.

Some of the worlds heaviest section Ni alloy castings have been produced using this system.

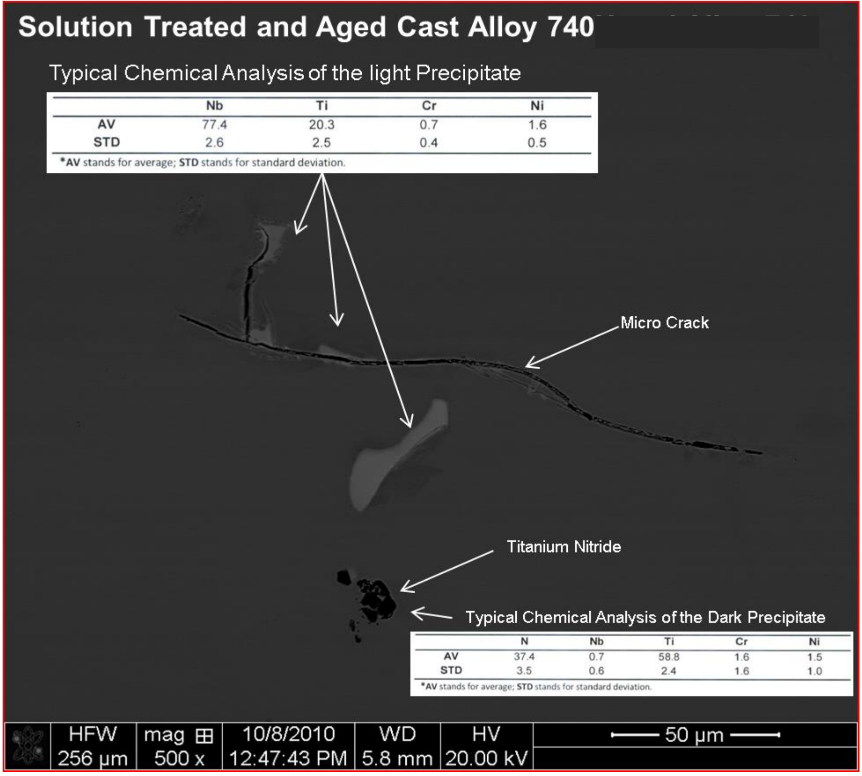
The Next Challenge - Precipitation Hardened Alloys: (750'C Operation?)

The next generation of A-USC nickel alloys are the precipitation hardened series of alloys, and are strengthened by the precipitation of gamma prime γ' and/or gamma double prime γ'' when aged around 800'C. These alloys are inherently stronger than predominantly solution strengthened nickel alloys, and the technology to manufacture, as a large casting is not fully in place. Therefore, alloys such as Alloy 263, Inconel® 740, and Haynes® 282® are not yet a commercial reality as castings.

These alloys contain higher concentrations of aluminium and titanium, which make them inherently more difficult to cast in air, and require additional special process techniques to minimise oxidation during both melting and pouring. The alloys are also stronger than traditional solid solution strengthened nickel alloys, with lower ductility, and so the expectation is that weld repair and fabrication in heavy section will be far more challenging.

Alloy 263, Inconel® 740H and Haynes® 282® have been investigated as part of the European NextGen Power and Macplus projects in the form of castings. However, all the step blocks castings produced, to varying degrees, suffered from microstructural cracking during the heat treatment process, which resulted in volumetric cracks that were detected upon radiographic examination.

Fig. 12: Cracking seen in Heavy Section Cast Alloy 740



Typical Chemical Analysis of the light Precipitate

	Nb	Ti	Cr	Ni
AV	77.4	20.3	0.7	1.6
STD	2.6	2.5	0.4	0.5

*AV stands for average; STD stands for standard deviation.

Typical Chemical Analysis of the Dark Precipitate

	N	Nb	Ti	Cr	Ni
AV	37.4	0.7	58.8	1.6	1.5
STD	3.5	0.6	2.4	1.6	1.0

*AV stands for average; STD stands for standard deviation.

After evaluation of the microstructural defects in collaboration with Loughborough University, it was determined that the wrought chemistry and original heat treatment regime was not optimal for Alloy 263, Inconel®740H and Haynes®282® in the cast form. 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, where some dissolution had taken place during the heat treatment process.

It was decided that modified chemistries and heat treatments were required in an attempt to eliminate the cracking seen within the original cast blocks and to produce castable materials. An additional series of blocks have been produced earlier this year within the NextGen/MacPlus collaboration.

Table 3: Chemistries of original Step Blocks Produced: (Major Elements Only)

Alloy	C	Si	Mn	Ni	Cr	Mo	Nb	Co	Al	Ti	Fe
Inconel ®740	0.047	0.21	0.24	BAL	25.8	0.38	1.39	20.62	0.94	2.16	0.66
Inconel ®740H	0.046	0.32	0.30	BAL	24.6	0.54	1.31	19.57	1.22	1.36	0.22
Cast 740 MOD	Variant Cast Chemistry										
Haynes® 282®	0.034	0.36	0.03	BAL	19.3	8.01	0.03	10.0	1.40	2.10	0.21
Alloy 282 MOD	Modified Chemistry										
Alloy 263	0.057	0.34	0.37	BAL	19.8	5.61	0.01	19.6	0.42	2.05	0.07
Alloy 263 MOD	Modified Chemistry										

Fig:13 -Modified Chemistry Step Blocks before feeder removal

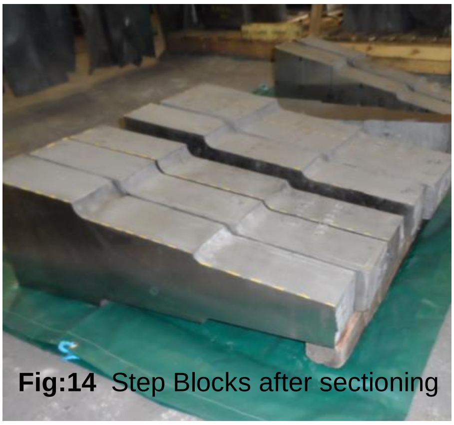


Fig:14 Step Blocks after sectioning

Table 4: Room Temperature Mechanical Properties (t= 50mm section)

Original cast compositions versus new modified compositions

Condition- solution treated and aged at 800°C for 8hrs

Alloy	UTS (N/mm^2)	Yield (N/mm^2)	Elongation (%)	R of A (%)	Impacts @ RT (J)
◆Inconel ™740	600	575	4	10	36/28/46 Avg 37
◆Inconel ™740H	560	545	5	11.5	22/43/37 Avg 34
◆Alloy 263	496	444	9	-	-
◆Haynes® 282®	No result – samples fractured early – no results could be obtained				
⊙Cast 740 MOD	691	410	30	42	128/136/110 Avg 125
⊙Alloy 282 MOD	751	588	15	18	52/50/50 Avg 51
⊙Alloy 263 MOD	718	506	29	28	150/184/205 Avg 180

(◆) =Premature failure due to microstructural cracking. (⊙)=No premature specimen failures.

Fig 15: Example: Alloy 740H Impact Specimen (Standard Composition)

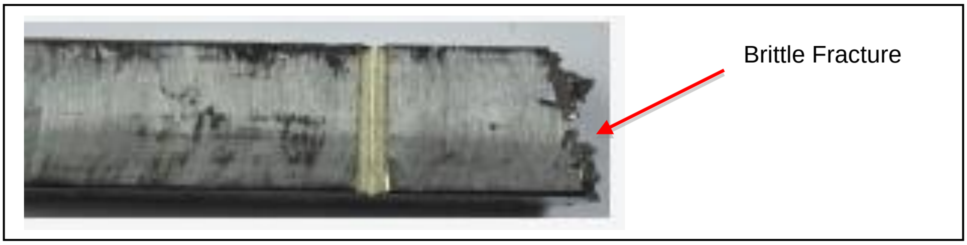


Fig 15: Shows an impact specimen from the standard cast chemistry for Alloy 740H. The specimen has broken outside of the notch and is showing brittle fracture characteristics. This was caused by cracked carbide precipitates at the grain boundaries. (Results 10Joules) –The tensile specimens showed the same problem with fractures taking place outside of the gauge length.

NEW MODIFIED MATERIAL: Goodwin Variant Chemistry

Fig 16: Broken Tensile and Impact Specimens: **Alloy 740 Modified Composition**

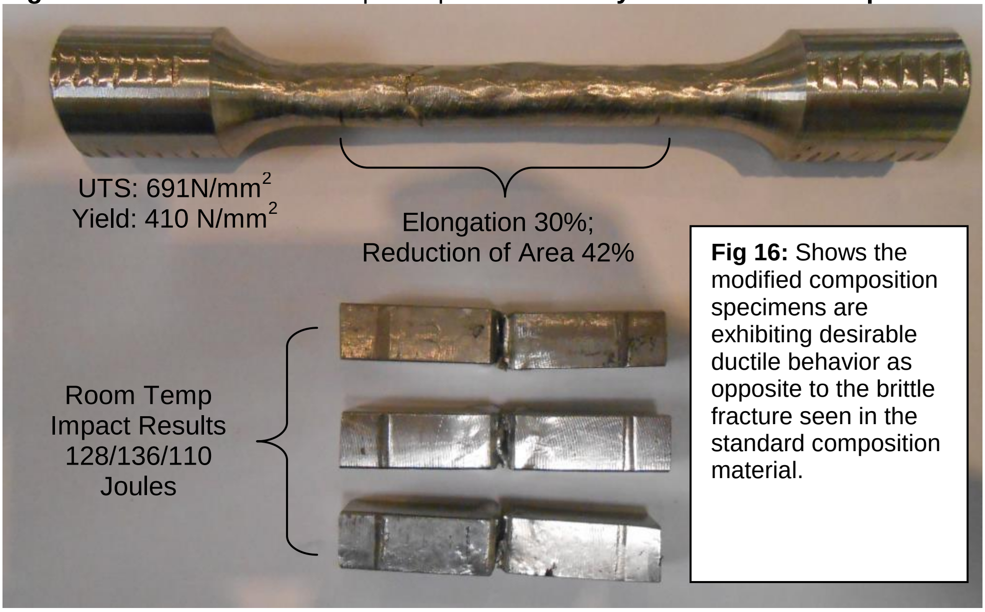


Fig 16: Shows the modified composition specimens are exhibiting desirable ductile behavior as opposite to the brittle fracture seen in the standard composition material.

The mechanical property of the new modified cast chemistry variant 740H is a little weaker at room temperature than the original cast specification. However, the first goal is to make the material castable, and then further optimisation with chemistry and aging can be considered if lower strength is considered an issue.

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)

Ni Alloys for 700°C Application:

Castings in the materials Alloy 625 and Alloy 617 have now been successfully produced in very heavy section for A-USC applications. Therefore, full-scale castings are now a commercial reality with regards to manufacturability.

Ni Alloys for 750°C Application:

These are the next series of alloys for A-USC application, with high strength and therefore higher application temperature. These alloys as castings are not yet a commercial proposition as there are certain technical issues, which have to be addressed. Goodwin have been working on solving these issues over the last 5 years within the European A-USC programs and Pacific Basin projects.

The aim of such programs is to make the alloys first castable, and indeed in optimising the chemistry there maybe a strength trade off that has to take place. The first stage is always to cast the alloys in thick section, and often, only then can issues be identified and plans are put in place to address the issues. Thin section samples do often represent what is to be found when up-scaling to heavier sections.

Goodwin has been investigating the manufacturability of Alloy 263, 740H and 282. These have all been cast in step block sections with steps of 100mm, 200mm and 300mm respectively. 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.

The main issues with these alloys are the inter-granular microstructural cracking during heat treatment. Our investigation has led us to change the chemistry of the three alloys to outside the normal wrought chemical ranges to improve their castablity. Then further modifications of the solution temperatures are also planned in order to further address the cracking issues.

Modified chemistry cast step blocks of all three alloys were cast in March this year and have not been fully evaluate. However, the room temperature testing of 50mm test coupons cast along side the step blocks have been completed, and the results are looking very promising.

Early optical microstructural evaluation in the 50mm section has shown no evidence of cracking in the modified 740H cast variant, and within the next few months will have additional heavy section characterisation results, and later this year high temperature test data.

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, her team, and the students working with her, whose contribution has been invaluable.

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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