Next Generation Casting Materials for Fossil Power Plants

October 10-14, 2016. Sheraton Algarve, Algarve, Portugal

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

Abstract:

The necessity to reduce carbon dioxide emissions of new fossil plant, while increasing net efficiency has lead to the development of not only new steels for potential plant operation of 650°C, but also cast nickel alloys for potential plant operation of up to 700°C and maybe 750°C.

This paper discusses the production of prototype MarBN steel castings for potential plant operation up to 650°C, and gamma prime strengthened nickel alloys for advanced super critical plant (A-USC) operation up to 750°C.

MarBN steel is a modified 9% Cr steel with chemical concentration of Cobalt and tungsten higher than that of CB2 (GX-13CrMoCoVNbNB9) typically, 2% to 3 Co, 3%W, with controlled B and N additions. The paper will discuss the work undertaken on prototype MarBN steel castings produced in UK funded research projects, and summarise the results achieved.

Additionally, within European projects a castable nickel based super alloy has successfully been developed. This innovative alloy is suitable for 700°C+ operation and offers a solution to many of the issues associated with casting precipitation hardened nickel alloys.

Key words:

Casting, nickel alloys, precipitation hardened, turbine component, G130, MarBN steel.

1) Introduction:

CO_2 emissions from fossil powered plants significantly contribute to global CO_2 emissions and therefore a necessity to increase the efficiency of new builds is often a political directive. As a result, forward thinking governments fund projects to develop new materials for high temperature operation in power plant.

Within the United Kingdom various projects over the last 5 to 6 years have studied the feasibility of producing variant MarBN steels as heavy section castings for turbine components. Demonstration castings and ingots have successfully been manufactured in both the UK funded “IMPACT (3)” and “INMAP (4)” projects. The “IMPACT” project (3) developed a variant MarBN steel, which then was produced as a full scale casting to demonstrate manufacturability within the “INMAP” project (4).

2) MarBN Steel – A novel material for 650°C USC application

MarBN Steel is a martensitic steel nominally 9%Cr, 3%W, 3%Co with precisely controlled contents of B and N. This steel is currently being developed for high temperature fossil plant boiler and turbine applications. UK collaborative R&D project, IMPACT(3), produced a chemically variant grade of MarBN steel and with controlled processing parameters, resulted in creep rupture strength some 30%-40% higher than P92, which is regarded as the current state of the art 9% Cr steel. This could potentially enable an increase in new plant operating temperature of ≥25°C thus improving efficiency and saving ~2% in fuel costs and reducing CO_2 emissions (1).

Within the IMPACT project (3), various chemistry heats of MarBN steel, along with an 8,000kg heat of AOD refined MarBN steel to the new variant chemistry. One of the product forms produced from this heat was a valve bonnet casting with a poured weight of 3,500kg. This design was chosen to simulate the typical main geometrical features and thickness of a large turbine casting. The lower section consisted of a tapered “leg” of typical wall thickness ~80 mm, while its upper section comprised a thicker flanged “head” of maximum thickness 340mm. This casting was subsequently heat treated (normalised and tempered) and sacrificially sectioned for mechanical testing and evaluation. The results are detailed in table 1.

Table 1 - Properties of IMPACT project (3) bonnet casting

					Room Temp °C Impacts				
	UTS	**0.2% Yield**	**El**	**RA**	**I1**	**I2**	**I3**	**I Av**	**Hardness**
Section Thickness	*(MPa)*	*(MPa)*	*(%)*	*(%)*	*(Joules)*				*(HB)*
50mm	829	713	15.5	41	22	29	11	21	262
100mm	826	714	17.5	55	19	14	20	18	255
230mm	840	717	18.0	54	24	31	27	27	259
340mm	807	695	16.5	44	20	12	26	19	252

3)Creep Rupture properties of MarBN Steel Variant

Creep rupture performance is one of the benchmarks that all power generation materials are gauged by. Within UK IMPACT project (3) , the MarBN steel variant produced has been rigorously tested and the creep rupture strength is found to be some 30-40% higher than P92, the current state of the art 9% Cr steel. This could potentially enable an increase in new plant operating temperature of 25°C or more. A useful observation for

MarBN steel is that cast product out performs wrought in creep rupture as detailed in Figure 1.

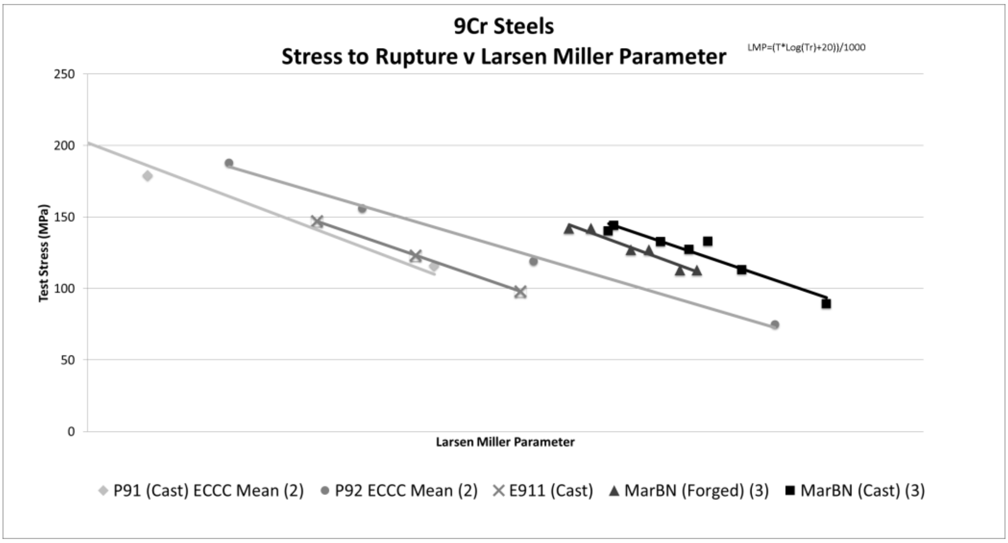


Figure 1 - Comparison of stress to rupture life of MarBN steel vs other conventional 9-10%Cr steels.

Following on from the successful work with the IMPACT project (3), the UK INMAP project (4) demonstrated manufacturability of a full scale industrial size MarBN steel component, validated non destructive testing techniques, and established weld repair procedures. An 8,640kg net weight turbine valve casting was manufactured with a pour weight of 18,000kg. Figure 2 shows a picture of the valve during proof machining.

4) Manufacturability

The foundry has to make many considerations when producing a MarBN steel melt. In terms of steelmaking, secondary refinement is advantageous and an effective deoxidation is essential. One of the main question marks in regards to the commercial manufacturability of MarBN steel is the ability to repeatedly control the chemical composition of B and N especially when melting and pouring castings in air. The incorrect balance of B and N would reduce the creep enhancing features of the MarBN steels design. Therefore it is essential that the foundry producing the material has a proven track record of producing 9% Cr steel, and most preferably of actual MarBN steel.

MarBN is sensitive to heat treatment parameters, there are risks associated with undissolved BN which reduce the expected life of components. Another consideration is the potential to precipitate delta ferrite during austenitisation, and therefore specific steps have to be taken to avoid its occurrence.

Figure 2 – 8,640 Kg MarBN Steel steam valve demonstration casting manufactured within the UK INMAP project (4) (heaviest section 200mm)

5) Weld Repair of MarBN Castings

It is inevitable that a large casting will require some weld repair and therefore weld repair is an important consideration. Welding trials were investigated within the INMAP project (4) where CB2 (X9CrCoWVNbBN9-3-3) consumable was utilised as matching MarBN weld consumables are currently in the development stage and not commercially available.

Figure 3 shows the detail of the weld test plate size and weld preparation detail used for the ASME IX weld qualification.

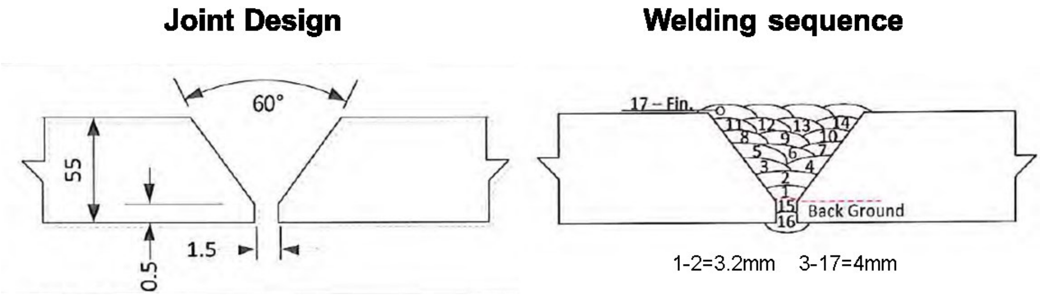


Figure 3 - ASME IX weld preparation details and welding sequence. The plate was subject to PWHT after welding

Table 2 shows the cross weld tensile test results. Four cross weld tensile tests were performed, with acceptable UTS properties. All four tensile tests fractured outside of the weld, and in the HAZ/ parent material.

Table 2 - Transverse weld tensile tests

Test No.	**Yield (N/mm^2)**	**Fracture location**
1	757	8mm clear of weld
2	752	Edge of weld
3	741	10mm clear of weld
4	762	Edge of weld

Table 3 - Impact testing:

Notch location	**Values (J)**	**Average (J)**	**Notch location**	**Values (J)**	**Average (J)**
Weld Cap	32, 40, 37	36	Fusion line root	27, 27, 30	28
Weld Mid	28, 29, 38	32	FL +2mm cap	31, 17, 18	22
Weld Root	35, 37,31	34	FL +2mm mid	32, 17, 21	23
Fusion line cap	22, 17, 20	20	FL +2mm root	44, 35, 23	34
Fusion line mid	12, 15, 24	17			

Bend testing, micro examination and a hardness survey was performed in accordance with the requirements of AMSE IX and were found to be acceptable.

Impact testing was performed as required by ASME IX welding code and at the test locations detailed in Table 3. It can be seen that some impact properties fall below the 27J value typically required by the European PED requirements. More work needs to follow to investigate the potential for increasing room temperature impact properties, especially in the weld fusion and HAZ zone for this parent/filler combination.

A weld procedure was developed to repair a simulated excavation in the 8,450Kg demonstration casting. This simulated excavation was made purposefully large at 200mm x 155mm x 100mm to represent the worse restraint conditions. The repair was given subsequent PWHT and successfully evaluated by NDE and then mechanically characterised.

6) Materials for A-USC operation up to 750°C

Nickel based alloys will be required for A-USC applications with operating temperatures likely reaching up to 750°C. These alloys will need to be precipitation hardened, strengthened by the precipitation of gamma prime γ' and/or gamma double prime γ'' when aged around 800°C. It is unlikely that solid solution strengthened Ni alloys will have the high temperature properties required.

The successful production of heavy section nickel alloy castings, such as a turbine casing, requires a significant leap in foundry technology. 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 high Al & Ti levels, there are challenges regarding microstructural integrity. Large heavy section castings solidify at slower cooling rates than smaller thin section castings. As a result heavy sections can have differing mechanical properties than their thin section counterparts. This is true for most steel castings and forgings and also holds true for nickel alloys. Therefore it is important not to extrapolate thin section results but instead validate thick section components from matching section sacrificial prototypes.

7) Alloy G130 – A castable, precipitation hardened, Ni-alloy for 750°C operation.

G130 is a Ni/Cr/Co Nickel Alloy specifically designed to overcome the casting issues encountered when producing other heavy section precipitation hardened nickel alloys as sand castings. Certain nickel alloys precipitate carbides shortly after solidification or during subsequent cooling. These carbides are relatively large as section sizes increase and tend to crack during heat treatment.

Unfortunately these carbides cause poor grain boundary cohesion and in extreme examples lead to volumetric cracks in the material, while in most cases causes grain boundary cracks detectable by penetrant inspection. This makes heavy section castings very difficult to produce in these alloys without the risk of volumetric cracking. G130 melt chemistry is specifically designed to avoid the precipitation of MX carbides during solidification and therefore avoids many of the issues.

The alloy is designed to have, after suitable aging, a gamma prime portion of approximately 15% to 20%. This level of precipitation achieves creep strength adequate for high temperature design life, while maintaining the ductility required for manufacturability.

Table 4 - Typical Room, and High Temperature Mechanical Properties of G130

Section size 100mm to 200mm (t=$^{1}/_{2}$)				
		20°C	**700°C**	**800°C**
Property	**Unit**	**Typical values at given temperature**		
Tensile Strength	**N/mm^2**	600-710	550-570	440
Yield (0.2% proof)	**N/mm^2**	450-500	380-430	325-360
Elongation	**%**	25 -35	18-30	14
Reduction in Area	**%**	40-46	19-22	35
Av Impact Strength	**J**	100-130	-	-

Table 4 shows the typical room temperature and high temperature tensile properties of Alloy G130 for section sizes ranging from 100mm to 200mm. Figure 4 shows comparative room temperature tensile and elongation results for Alloy G130, Alloy 263, and Alloy 282.

The bar chart clearly shows that cast results for Alloy 263 and 282 in the 200mm section have elongation results less than 10%, while the elongation values for G130 in both 100mm and 200mm sections are greater than 25%. This is because alloy G130 does not exhibit the poor grain boundary cohesion issues that, during our tests, alloy 263 and 282 were prone to.

Figure 5 demonstrates the stress rupture properties of alloy G130. It is generally agreed that the creep design criteria for the A-USC plant is 100,000hrs life, with a stress of 80 to 100MPa and temperature of 700’C.

Figure 6 shows that alloy G130 easily meets this criteria. The material looks highly likely to meet 100,000hrs life with a stress of 80MPa and a test temperature of 750’C.

Figure 6 and Figure 7 show scanning electron microscope images of G130 showing a clean microstructure consisting of grains of gamma with $M_{23}C_6$ carbides uniformly dispersed along the grain boundaries. There is also odd random isolated titanium nitride dispersed within the gamma grains. The images show no evidence of MX carbides which can cause problems with cracking in heavy sections.

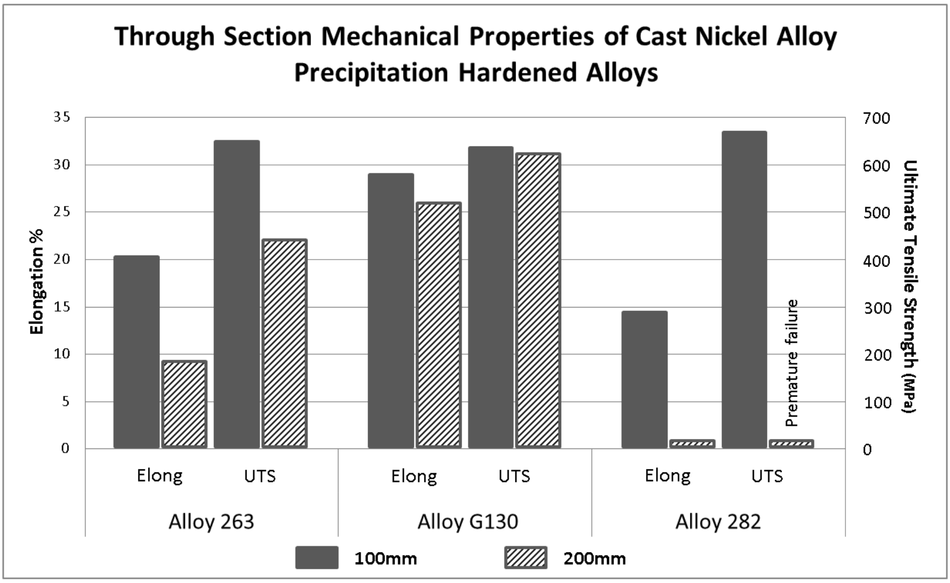


Figure 4 - Comparison of Room temperature mechanical properties of G130 vs castings produced in Alloy 263 and 282.

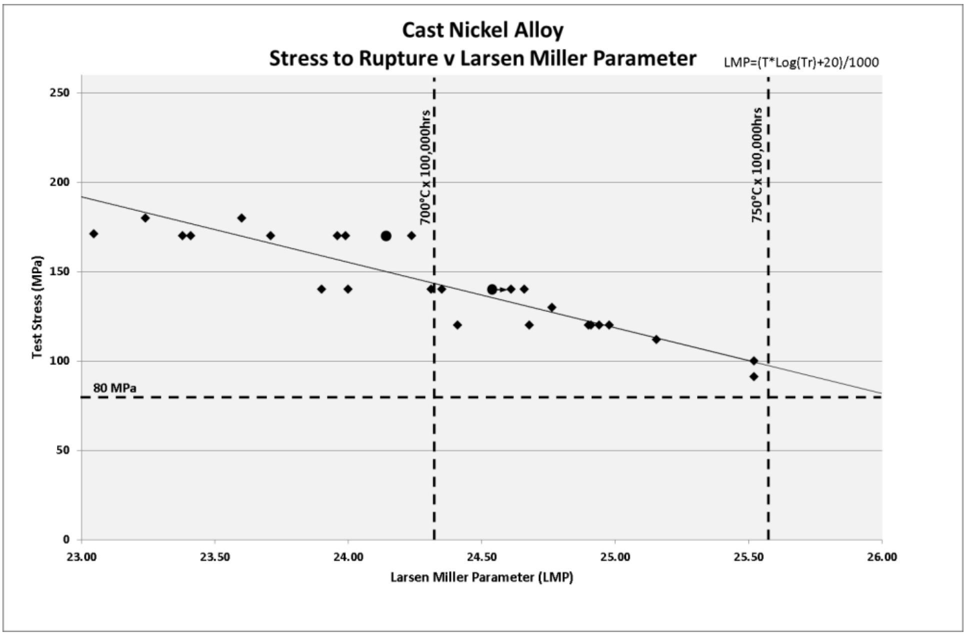


Figure 5 - Stress rupture results of G130. Plotted against LMP with representations of 100,000hr rupture life at 700°C and 750°C. (● data points are cross weld trials – see section 8)

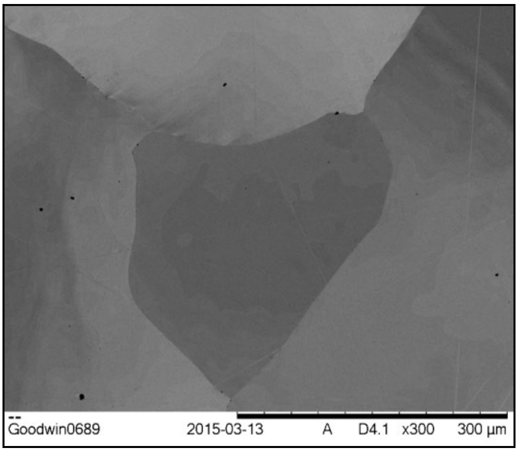


Figure 6- Scanning electron microscope image of Alloy G130 showing a clean microstructure with no evidence of MX carbide precipitation

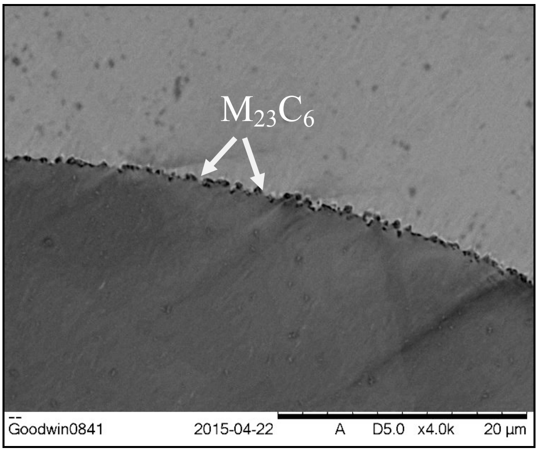


Figure 7 - Scanning electron microscope image of Alloy G130 showing M23C6 carbides on a grain boundary

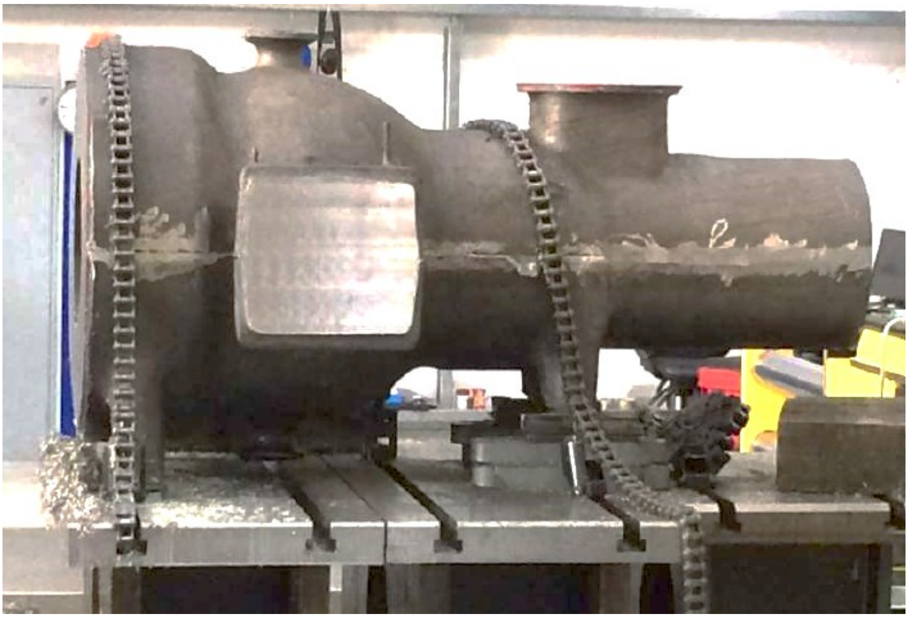


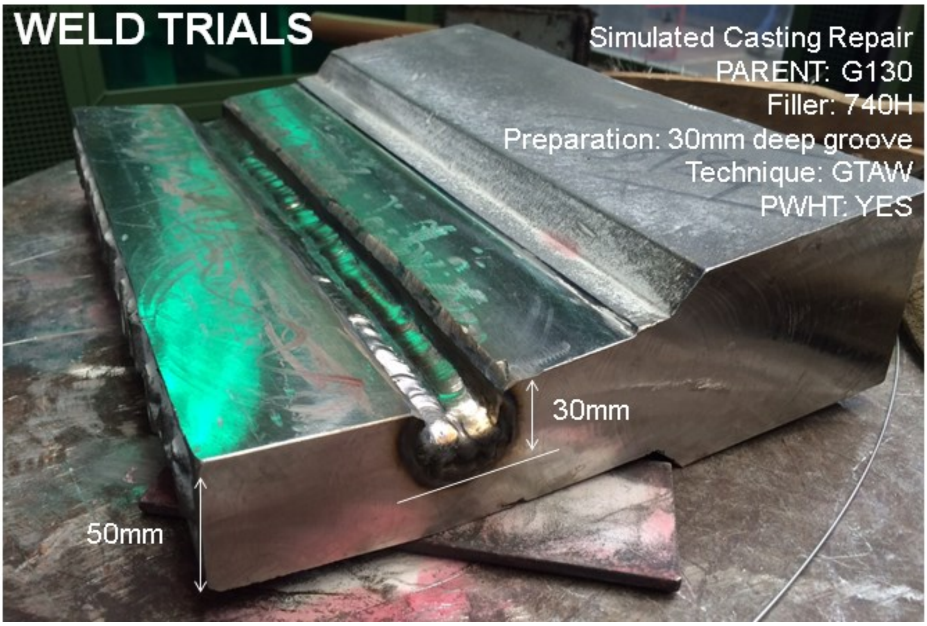
Figure 8 - G130 Stop Valve Cast Body (Net weight 2,000kg; thickest section 180mm) manufactured within the EU funded NextGen Power (6)/ MACPLUS (5) collaboration.

8) G130 Welding Trials

Welding trials were performed on 50mm thick weld test plates in G130 using Special Metals alloy 740H filler wire. The weld depth was 30mm deep, the weld preparation a ‘U’ groove and the welding technique used was gas tungsten arc welding (GTAW). **Error! Reference source not found.** shows details of the weld plate geometry and the plate half filled. Table 5 detailed the room temperature tensile and impact properties achieved from the test plate.

Table 5 - Room temperature mechanicals of welded test plate

	Ultimate Tensile Strength (MPa)	**Elongation (%)**		
Cross weld	743	15		
	749	16		
	Impact 1 (J)	**Impact 2 (J)**	**Impact 3 (J)**	**Av Impact (J)**
All weld	53	50	51	51
Fusion Line	173	174	134	160
HAZ	136	176	100	137



Two Cross weld stress rupture samples are currently on test, are performing well and are detailed as the circle data points in Figure 5. Results of a cross weld hardness survey are shown in figure 10a+b, while figure 11 details the cross weld hardness profile in the cap, mid wall and root locations.

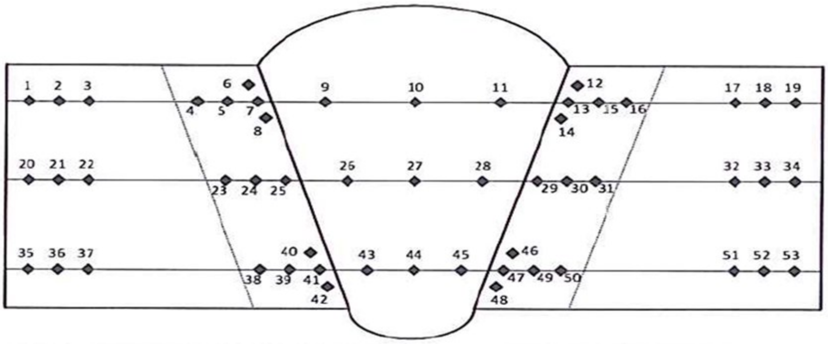


Figure 9a - Hardness survey locations of G130 test plate welded with 740H filler.

Location	Result	Location	Result	Location	Result	Location	Result	Location	Result
1	224	12	230	23	236	34	248	45	327
2	225	13	244	24	220	35	214	46	245
3	223	14	248	25	235	36	214	47	276
4	246	15	232	26	322	37	232	48	250
5	240	16	235	27	315	38	244	49	237
6	230	17	244	28	317	39	234	50	226
7	233	18	251	29	258	40	218	51	237
8	248	19	246	30	240	41	235	52	241
9	330	20	210	31	237	42	248	53	240
10	326	21	216	32	241	43	324	Units: HV10	
11	320	22	220	33	241	44	315		

Figure 10b - Hardness survey results of G130 test plate welded with 740H filler.

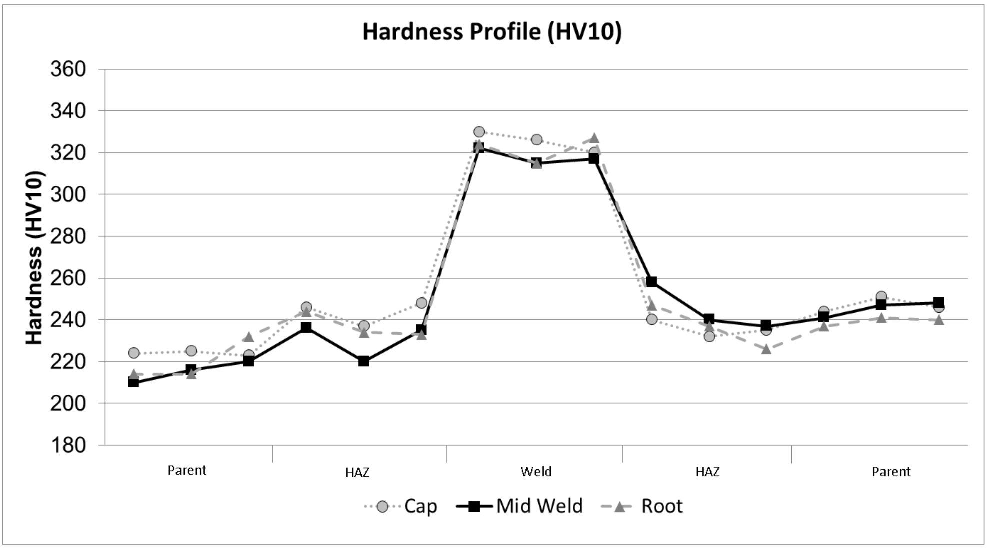


Figure 11 - The cross weld hardness profile of the G130 weld test plate at the cap, mid wall and root positions

Conclusions:

For 650’C operation, MarBN steel has a potential 25°C advantage in terms of operating temperature over its leading competitors. In the UK two full scale castings have been successfully produced, sectioned and characterised. The castings have been successfully inspected, and a weld procedure developed using a CB2 matching filler.

For turbine operation at 700’C to 750’C, a precipitation hardened nickel alloy specifically designed for castings has been developed called G130. This material out performs other precipitation alloys when cast and exhibits good ductility, an important factor for manufacturability and fabrication. Test data in figure 6 suggests G130 is suitable for 100,000hr operation at 80MPa and 700°C, and potentially up to 750°C. Heavy section test material and a prototype stop valve casting has been produced as demonstration components and characterised.

Castings continue to a play an important role in the manufacture of steam valves, casings and ancillary parts for the steam turbine for both USC and almost certainly with new technology A-USC application plant. The casting process is still the preferred route for the manufacture of these components, as it is remains the most cost effective method of producing complex geometry near net shape components with favorable material characteristics that withstand environments within a steam turbine.

Acknowledgments

We would like to acknowledge the collaborative partners within the UK funded “IMPACT” (3) and “INMAP” (4) projects and the EU funded “NextGen Power”(6) and “MACPLUS” (5) projects” for their invaluable work.

PROJECT	PARTNERS
IMPACT(3)	Alstom Power Ltd, Goodwin, E-ON, NPL, Loughborough University, Doosan Babcock,
INMAP(4)	General Electric, Goodwin, Applied Inspection
NextGen Power (6) (Turbine WP)	VTT, Kema, E-ON, Doosan, Monitor Coatings, Cranfield University, Aubert & Duval, Saarchmiede, Darmstadt University, Goodwin, Skoda Power, VUZ.
MACPLUS (5) (WP5)	Centro Sviluppo Materiali (CSM), Goodwin, Alstom Power Ltd, Loughborough University, National Physical Laboratory (NPL), RWE Power AG, Kungliga Tekniska Hoegskolan (KTH)

We would also like to thank Loughborough University for their contribution to the characterisation and evaluation of the nickel base cast alloys discussed in this paper.

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”.*

All trade marks are the property of their respective owners Inconel® 740H is the property of Special metals Corporation, Haynes® A282® is the property of Haynes International, Goodwin® G130 is the property of Goodwin Steel Castings Ltd, and Toshiba TOS-3X is the property of Toshiba Corporation.

References

(1) Allen, D. (2015) ‘STEEL IN HIGH TEMPERATURE POWER PLANT’, Düsseldorf:

(2) ECCC 2005 Datasheet

(3) IMPACT Project (Innovative Materials Design and Monitoring of Power Plant to Accommodate Carbon Capture) Project number 100819. An Innovate UK funded project which ran from April 2010 to December 2013.

(4) INMAP Project (Industrialisation of Novel MarBN Steel for Advanced Power Plants) Project number 101785. An Innovate UK funded project which ran from June 2014 to May 2016.

(5) MACPLUS Project (Component Performance Driven Solutions for Long Term Efficiency Increase in Ultra Supercritical Power Plants). Project number 249809. Funded by EC | FP7 | SP1 | ENERGY 01/01/2011 to 30/06/2016.

(6) NEXTGENPOWER Project(Meeting the Materials and Manufacturing Challenge for Ultra High Efficiency PF Power Plants with CCS)Project number 249745. An European FP7 funded project. May 2010 to June 2015.