MATERIALS DEVELOPMENT FOR BOILERS AND STEAM TURBINES OPERATING AT 700 °C

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ABSTRACT

In Europe development of boilers and steam turbines for plant operating at temperatures in excess of 700°C is being carried out within the EU supported AD700 project. This collaborative project involves all of the major European power plant manufacturers supported by utilities and research institutes. The first phase of the project began in 1998 and has been extended to run until the end of 2003. A second phase began in 2002 and runs until the end of 2005, although it is hoped this phase will also be extended to allow the continuation of longer term creep tests. The objective is the development of all technology necessary for the construction and operation of such plant.

This paper describes the development of the high temperature materials technology essential to underpin the development of the AD700 power plant technology. It describes the factors influencing alloy design and selection and the scope and results of investigations on candidate alloys carried out within the project. It then goes on to describe the programme of full-scale prototype component manufacture which is currently in progress. These prototype components are being characterised through extensive long term testing programmes. The development of joining procedures for these materials is also described.

KEYWORDS

Materials, qualification, furnace panels, superheater, boiler, steam lines, turbine, AD700, alloy

1. THE AD700 PROJECT

The overall objective of the AD700 project is to develop and demonstrate a new generation of pulverised coal-fired power plants featuring advanced steam conditions [1]. This will be achieved through the application of nickel-based superalloys to bring the live steam temperature up to about 700°C, resulting in an increase in efficiency from around 47%, representing the current state-of-the-art plant, to around 55%, an increase yielding reductions in fuel consumption and carbon dioxide emission of almost 15%. The plant will have an output within the range of 400-1000MW, making it suitable for the range of utility scale generation. The project involves nearly all the major European power plant manufacturers and their material suppliers, the largest European utilities and major research organisations.

The principal innovation which underlies this development is the replacement of iron-based alloys by nickel-based alloys for the highest temperature components. These alloys are already used in the aerospace and gas turbine industries so that the project is to some extent one of technology transfer. However much larger components are required for boilers and especially for steam turbines than are currently produced for gas turbines and there are significant technical challenges to be met to achieve the manufacture of larger components. In addition, these components will be required to operate under significantly different conditions of environment, stress and temperature. Therefore demonstration of manufacturing capability and appropriate material characteristics is required. Nickel-based alloys are much more expensive than alloy steels and this aspect is motivating further innovations to minimise the requirement for these alloys. This is being achieved through radical new concepts in plant architecture and turbine construction and also through material developments to maximise the strength of austenitic and ferritic steels.

The first phase of the project began in 1998 and has been extended until the end of 2004 to allow the continuation of long term creep tests. A second phase began in 2002 and runs until the end of 2005, although it is hoped this will also be extended for similar reasons. The objective is the development of all technology necessary for the construction and operation of such plant.

2. MATERIAL SELECTION

Development and demonstration of appropriate materials and their properties, especially in the case of the nickel based alloys, is critical to establishing the technical feasibility of the new power plant concept. As well as creep strength sufficient for long term operation at these high temperatures (typically 100,000 hour rupture strength of around 100MPa at the metal temperature is required), materials requirements include corrosion resistance in boiler flue gases and under conditions of steam oxidation, resistance to thermo-mechanical cycling and the ability to be manufactured and welded in thick section.

Most modern-day nickel based alloys have been developed from a relatively simple Ni20%Cr alloy. In order to achieve the required creep properties, further strengthening through solid solution strengthening or dispersion strengthening is necessary. Additions of elements like Mo, W and Co confer solid solution strength. Alloys relying principally on this mechanism, such as alloys 230 and 617, are used in the solution treated condition and have the advantage of being relatively easy to weld with no requirement for complex post weld heat treatment. However their proof strengths are relatively low and where this property is important additions of Ti and Al to form dispersions of the gamma prime precipitate, conferring high proof strength as well as improved creep strength, can be made. Alloys such as these, for example alloy 263 and waspaloy, must be aged after solution treatment to produce the strengthening dispersion and thus post weld heat treatment requirements are more complex. Additions of Ti and Al are limited by the requirement for weldability: where these additions are too high the kinetics of gamma prime precipitation become such that precipitation occurs in the heat affected zone (HAZ) during welding, the reduced ductility resulting from which leads to the potential for HAZ cracking. An alternative approach to dispersion strengthening is by alloying with Nb, leading to the more sluggishly precipitated gamma double prime. With regard to corrosion resistance, where flue gas corrosion resistance is required, increased levels of Cr may be necessary. Finally the economic aspects of material selection cannot be neglected so, in order to mitigate the high cost of nickel-based alloys, significant additions of Fe, such as are made in the case of alloys 718 and 901, may be considered.

3. BOILER MATERIALS

In order to realise a 700 °C USC boiler, extensive materials development and qualification is necessary, including the use of Ni based superalloys in the most severely exposed components. These developments can be categorized into three groups reflecting the key components of such plant, i.e:

- Furnace panels
- Superheaters
- Thick section components and steam lines

3.1 FURNACE PANELS

The behaviour of water and steam in the furnace panels changes rapidly as steam pressure increases from sub to super critical conditions, and in particular, at constant enthalpy increase (constant heat input) the rise of water/steam temperature also grows rapidly. Therefore, the water/steam temperature at the outlet of the furnace panels of super critical boilers grows constantly, as steam parameters moves towards the advanced conditions of 350 bar and 700 °C planned for the AD700 technology.

Typically, the enthalpy at the outlet of the furnace panels would be in the range of 2600-2700 kJ/kg, and Figure 1 indicates how temperature grows from ~375 °C to ~450 °C as steam pressure increases, which means growing problems with the strength of conventional well proven low alloyed steel like 13CrMo 44. On the other hand the cooling characteristics of single phased super critical water/steam are good as no evaporation takes place.

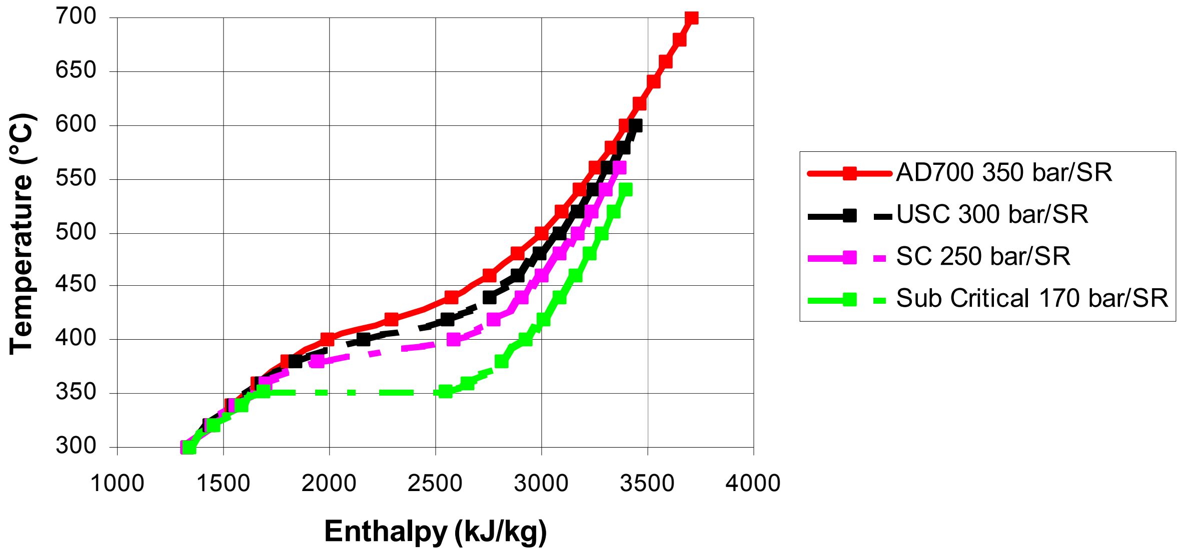

Fig. 1. Water/steam temperature versus enthalpy

However, also increased steam temperatures, which rise from 540-560 °C into the range of 700 °C add to the temperature rise of water/steam in the furnace panels, as feed water and live steam flows are reduced. In these circumstances the steam temperature in the furnace outlet panels will grow to around 525 °C, resulting in a calculated mid wall temperature of 575 °C at start of service. Further, due to the growth of magnetite on the internal tube surface, mid wall temperatures could increase to about 600 °C, if low alloy steels were used. Therefore more oxidation resistant and stronger furnace tube materials are needed than the 1Cr 0.5Mo used at present.

Three newly developed steels have been selected as candidate materials for furnace panels in future boilers with advanced steam parameters. The high alloyed 12%Cr tube steel HCM12 developed by Sumitomo Metal Industries and Mitsubishi Heavy Industries has excellent creep strength, oxidation and corrosion resistance and, due to a duplex microstructure of approximately 30% δ-ferrite and 70%

tempered martensite, it is possible to weld this steel without preheat and post weld heat treatment (PWHT) [2]. The lower alloyed 2½%Cr tube steel HCM2S developed by Sumitomo Metal Industries and Mitsubishi Heavy Industries and the Mannesmann developed 2½%Cr tube steel 7CrMoVTiB1010 both have sufficient high temperature strength and a metallurgy which makes it possible to omit PWHT [3,4]. The chemical composition and mechanical properties for all three steels are given in Figure 2.

Chemical composition, mass %

	C	Cr	Mo	W	Others
1Cr½Mo	0.13	0.9	0.5		
HCM2S	0.06	2.25	0.3	1.6	V,Nb,N,B
7CrMoTiB1010	0.07	2.4	1		V,Ti,N,B
HCM12	0.1	12	1	1	V, Nb

Creep rupture strength

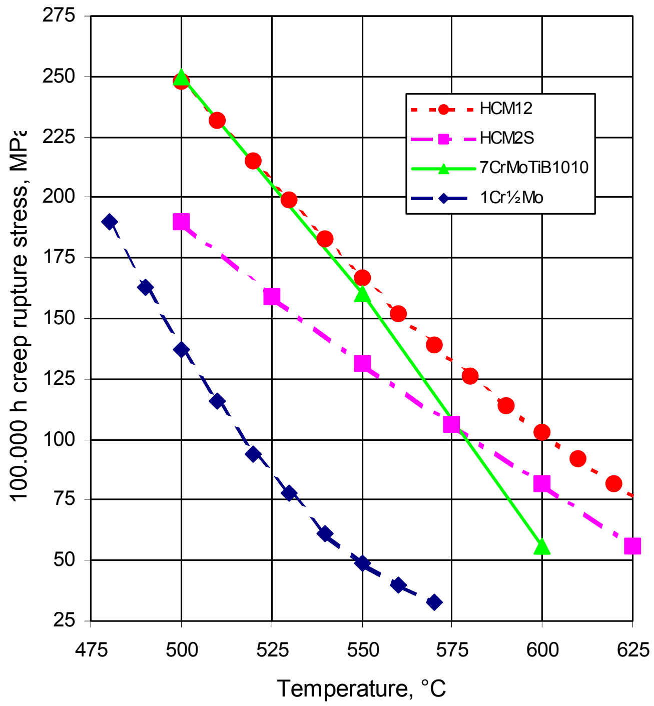

Fig. 2. Materials for furnace panels

Testing of HCM12, HCM2S and 7CrMoVTiB1010 is in progress in Europe to establish practical experience with the handling of these steels. In the furnace panels of an existing subcritical once through boiler, test sections of all three steels have been installed, and service under cycling conditions has been tested for several years. For the HCM2S and 7CrMoVTiB1010 tube materials no problems have been encountered during the production of the test panels or during operation at steam temperatures up to 500 °C. For the tube steel HCM12 which has a rather complicated microstructure, lack of sufficient filler material has caused problems with cracks after welding due to embrittlement, and further development of suitable filler material is required before a reliable welding procedure can be established. Nonetheless, test panels of HCM12 have been successfully service exposed with steam temperatures up to 530 °C under cycling conditions. Moreover, a full size wood chip fired boiler furnace construction operating with steam temperatures up to 540 °C for more than five years demonstrates that HCM12 is a candidate for furnace tubes in future advanced USC boilers.

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In connection with the in-plant test and the construction of the wood chip boiler, a computer furnace panel calculation programme has been set up by Elsam to simulate the service exposure and life consumption of a furnace panel in a USC boiler during operation [5]. Calculations first of all demonstrate that at media temperatures higher than around 450°C the temperature rise during operation is strongly dependent on the rate of self oxidation and on the deposition rate of oxides from the feed water. High quality feed water chemistry assuring minimum oxide in feed water is therefore essential if USC plants with advanced steam parameters are to be realised.

Based on these calculations it can be demonstrated that the use of either HCM2S or 7CrMoVTiB1010 is sufficient for media temperatures up to 475 °C. For higher media temperatures only HCM12 should be considered due to the need for better oxidation resistance.

In COMTES700, fabrication trials leading to in-plant exposure testing have just been finished and in-plant test began in July 2005. The possible use of the nickel alloy INCONEL® alloy 617 is investigated in parallel as an alternative to HCM12. Of course, alloy 617 has much better mechanical properties and does not generate any internal oxide, and therefore it can be exposed to much higher temperatures than HCM12. The fact that alloy 617 tubes cost roughly 10 times more than HCM12 and call for a far more expensive fabrication means, however, that the whole boiler economy must be carefully considered before such a choice of material is taken.

3.2 SUPERHEATER TUBING

For superheater tubing the aim is to develop an improved austenitic tube material with sufficient strength and flue gas corrosion resistance to operate at steam temperatures around 650 °C, and to develop a Ni base superalloy to fill the gap up to 700 °C steam temperature. Intensive development work is ongoing in the AD700 project to demonstrate a suitable austenitic tube material with 100,000 hour rupture strength of about 100 MPa at 700 °C and a Ni based tube material with 100,000 hour rupture strength of 100 MPa at 750 °C - both materials to demonstrate a flue gas corrosion resistance better than 2 mm metal loss during an exposure of 200,000 hours.

Austenitic tube material
30 trial melts were manufactured based on the following alloy design principles:

- Precipitate strengthening through the precipitation of Nb(C, N), NbCrN and Cu-rich precipitates.
- The precipitation of fine M(C, N) to induce the precipitation of fine and stable $M_{23}C_6$.
- Addition of W to improve the high temperature strength and stabilise carbonitrides. The creep rupture strength of W alloyed steels is much higher than that of the Mo alloyed steels at higher temperatures.
- Addition of a large amount of Ni, approximately 25 wt%, together with a relatively high amount of N and low amounts of Mn, Mo and Si to suppress the precipitation of sigma phase.
- A Cr content of approximately 23-25 wt% and low Mo content to improve the corrosion resistance in coal-fired boilers.

All trial melts were forged to bars simulating a tube production. After appropriate heat treatment, fourteen of the samples were tested for mechanical properties as well as steam oxidation and flue gas corrosion resistance up to 5,000 hours. This screening test indicated that four of the fourteen tested trial melts might be able to meet the targets. After another 10,000 hour testing one of the four alloys showing the best properties was selected. The chemical composition and room temperature mechanical properties of this alloy called Alloy 174 are shown in tables 1 and 2.

Table 1. Chemical composition for alloy 174

C	Cr	Ni	W	Co	Cu	Nb
0.08	22.2	24.9	3.5	1.5	3	0.49

Table 2. Mechanical properties at room temperature for alloy 174

Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction of area (%)	Hardness (HV)	Charpy impact value (J/cm^2)
785	345	55	70	195	216

Figure 3 demonstrates the improvements in creep rupture strength compared with some of the best commercial austenitic superheater tube alloys. The extrapolated rupture data of alloy 174 are based on 20,000 hours of testing. Ongoing steam oxidation and flue gas corrosion test demonstrate properties comparable to or slightly better than those obtained for a large variety of 22 - 25% Cr austenitic superheater steels. So far all targets are fulfilled. Full scale tube production has been successfully demonstrated by the production of 50 m superheater tubes with dimensions 41.4 mm OD x 8 mm wall thickness, and fabricability trials including welding and bending have been completed successsfully. Different filler materials were considered for similar and dissimilar welds. So far, Inconel alloy 617 has been chosen due to its excellent mechanical properties, comparable to alloy 174.

Chemical composition, mass%

	Cr	Ni	W	Nb	Cu	Others
Super 304H	18	9		0,4	3	N
NF709	20	25		0,25		Mo, Ti, N
HR3C	25	20		0,4		N
SAVE 25	23	20	1,5	0,4	3	N
Alloy 174	22	25	3,5	0,5	3	N

Creep rupture strength

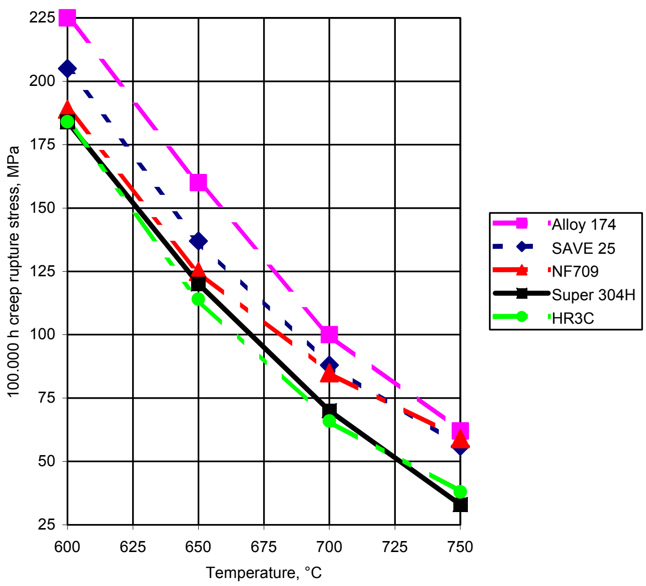

Fig. 3. Materials for superheater tubes

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Long term creep rupture properties for base material as well as cross-weld specimens and micro-structural stability test are ongoing and will complete the characterisation of this super austenite which will be launched in the market under the name Sanicro 25.

Nickel base tubing

A literature survey conducted by Special Metals concluded that an existing alloy, viz. NIMONIC® alloy 263, had adequate strength to meet the creep requirement, but, from previous work, it was felt that its corrosion resistance would be inadequate. Hence it was decided to develop a new alloy based on alloy 263 for the superheater and reheater tubular components, which would be exposed to corrosive flue gas/ash conditions. The alloy optimisation process considered creep strength and corrosion resistance. Over thirty trial compositions were produced in 22 kg heats which were worked to bars. Improvement of the coal ash corrosion resistance of the alloy was developed in a series of coal ash corrosion tests at different temperatures employing samples with a systematic variation in alloy constituents. The tests used an atmosphere of 15 vol % CO_2 + 10 vol % H_2O + 1 vol % SO_2 with balance N_2 , and the test specimens were coated with a synthetic coal ash, K_2SO_4 + (Fe_2O_3/Al_2O_3/SiO_2) in the ratio 1:1:1.

The resultant optimised chemical composition which was selected is given in Table 3. The new alloy INCONEL® alloy 740, based on alloy 263, is a nickel chromium cobalt alloy which is age hardenable by the precipitation of gamma prime but also benefits from solid solution hardening. Table 4 gives the ash corrosion results for this alloy.

Table 3. Composition of INCONEL alloy 740

C	Ni	Cr	Mo	Co	Al	Ti	Nb	Mn	Fe	Si
0.03	Bal	25.0	0.5	20.0	0.9	1.8	2.0	0.3	0.7	0.5

Table 4. Penetration results for INCONEL alloy 740 in coal ash corrosion tests at 700 °C

Time (hours)	Metal loss (μm)	Depth of attack (μm)
116	0	4
500	4	14
1000	5	19
1984	16	33
5008	39	60

A large creep test matrix is presently underway covering two major test temperatures, 725 °C and 775 °C, with some shorter term tests at 700, 750 and 800 ºC. Test durations up to 65,000 hours are being targeted, and the results to date are shown in Figure 4.

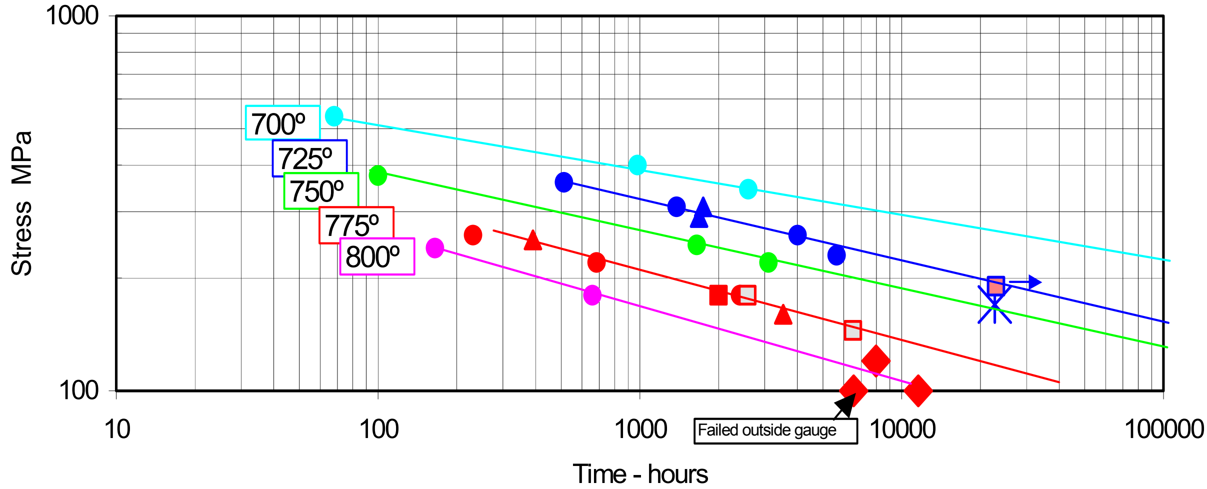

Fig. 4. Inconel alloy 740 creep results

Ageing trials are underway with target times up to 70,000 hours. Up to now, 1,000, 3,000 and 15,000 hours have been completed at 700 °C, 750 ºC and 800 °C. The long term ageing trials are being carried out on material which has been given the initial strengthening/ageing treatment of 4 hours at 800ºC. After 1,000 hours at 700 °C, the Charpy impact values dropped to some 45% of the values after the initial ageing/strengthening treatment, and further exposure to 3,000 hours exhibited a reduction to around 27% (of the initial aged/strengthened values). The absolute values after 3000 hours are around 25 J.

Welding trials have been initiated and have demonstrated that alloy 740 is readily fabricated in the annealed condition. Joining is accomplished with the gas tungsten-arc welding (GTAW) process using both INCONEL Filler Metal 740 and NIMONIC Filler Metal 263. If a high joint strength is required, the deposited weldment may be precipitation hardened. The need for repair of boiler tubes is inevitable and successful welding on aged material has been undertaken although the mechanical test results are not yet available.

A commercial size cast of the alloy has been produced and put through the normal tube production route to produce 100 m superheater tubes with dimensions 38.1 mm OD x 7.7 mm wall thickness. Welding trials and fabrication trials – i.e. tube bending - have been successfully performed and long term creep rupture data for base material as well as cross-weld specimens and microstructural stability test are ongoing and will complete the characterisation of this nickel alloy.

In the frame of Emax, fabrication trials of superheater sections partly made of Sanicro 25 and alloy INCONEL® alloy 740 leading to in-plant exposure testing have been finished successfully. In-plant tests taking these superheater tube materials to temperatures above 700 °C began in September 2004 at the power plant Esbjergværket [6] and in July 2005 at the power plant Scholven respectively.

3.3 THICK SECTION COMPONENTS AND STEAM LINES

For thick section boiler components and steam lines there are two goals for the materials development. An improved ferritic/martensitic 9-12%Cr steel is desirable to expand the present temperature range for ferritic steels up to app. 650 °C. A Ni-based superalloy with a 100,000 hour rupture strength of 150 MPa at 700 °C is needed to allow construction of outlet headers and main steam lines with acceptable wall thicknesses.

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Ferritic pipe steels

The task of improving the 9-12%Cr steels on top of the impressive developments in the last two decades has proved to be very difficult. In the last five years worldwide research has resulted in a large number of new alloys being announced, and from short-term tests they seemed very promising. However, in long-term tests the steels show sigmoidal creep behaviour and so far no ferritic alloy has demonstrated long-term creep strength better than steel P92. In AD700 an attempt was made to improve the creep rupture strength of 9-12% Cr steels. Seven trial melts were manufactured and mechanical properties were obtained up to 12.000 hours. Six of the seven melts turned out to be weaker than P92 and only one melt, a 9%Cr5Co2WVNbN, showed creep rupture data similar to P92. In parallel, tests were made on steel NF12. Short-term data demonstrated a major improvement, but longer term data showed a dramatic drop in strength also for this steel (Figure 5).

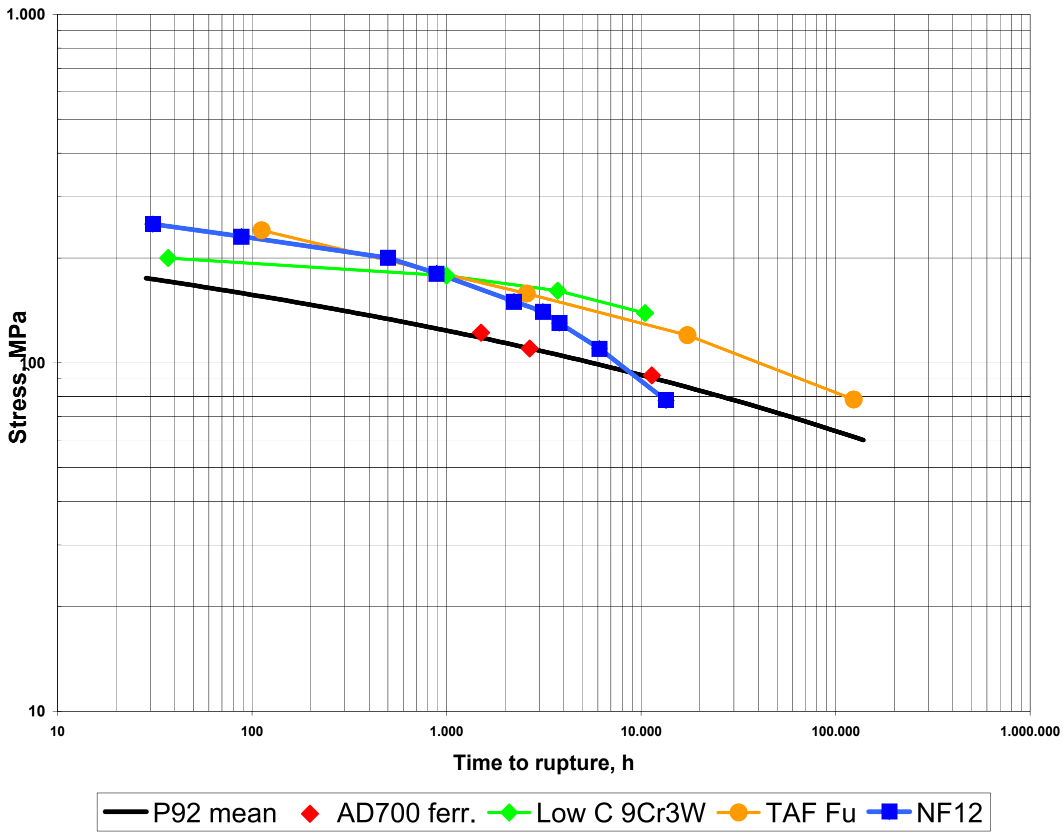

Fig. 5. Ferritic steels 650 °C

Systematic microstructure investigations of new ferritic steels showing sigmoidal creep behaviour have demonstrated that precipitation of the complex Z-phase nitride (Cr(V,Nb)N) takes place in the steels at the expense of the strengthening MX carbonitrides, which dissolve. This mechanism is responsible for the reduction in creep strength, and it seems that high Cr steels are more prone to Z-phase formation than low Cr steels. In order to be able to improve the strength, a fine-tuning of the composition is needed based on a thorough understanding of recent developments. Recent advances in microstructure characterisation techniques and thermodynamically based microstructure models may prove to be the only way to go further in the development of improved ferritic steels [7].

A potentially interesting new ferritic steel is the low carbon 9Cr3Co3WVNbN steel currently under development at the NIMS in Japan. This steel is strengthened only by nitrides and Laves phase precipitates, and the unstable $M_{23}C_6$ carbides are not present. Creep tests up to about 10.000 hours at 650 °C show no signs of sigmoidal creep behaviour, see fig. 5. If the low C steels can maintain microstructure stability up to long times, this idea may serve as an important platform for future developments of ferritic steels. The low Cr content will, however, lead to poor steam oxidation resistance, and a surface coating will be needed. At the moment, it does not seem to be possible to obtain high creep strength together with high oxidation resistance at the same time in ferritic steels.

Nickel base piping
NIMONIC® alloy 263 or an improved version of INCONEL® alloy 617 may meet the demands for outlet headers and steam lines at 700 °C steam temperature. Long-term creep data and demonstration of fabricability – pipe production, hot bending and welding – are needed before a 700 °C power plant can be realised. Alloy 263 is under investigation in the AD700 project, and the improved version of alloy 617 is investigated by the German national project MARCKO DE2. Alloy 617 pipes were manufactured in late 2002.

The precipitation hardened Nimonic alloy 263 chemical composition, see table 5, had only limited stress rupture data available as its designed purpose was for industries that do not require 100,000 hour creep data. Therefore, the biggest experimental effort expended on this alloy is in creep testing of commercially available 15 mm diameter bar.

Table 5. Composition of Nimonic alloy 263 (Note: Ti + Al : 2.4 – 2.8)

C	Ni	Cr	Mo	Co	Al	Ti	Mn	Fe	Cu	B
0.04 0.08	Bal	19.0 21.0	5.6 6.1	19.0 21.0	0.6 Max	1.9 2.4	0.60 Max	0.7 Max	0.2 Max	0.0005 Max

The failed tests up to now along with running tests are shown in Figure 6. These data suggest that the alloy will easily meet the creep criteria. This will enable the design of components with relatively small thicknesses and thereby reduce production costs.

A vital demonstration of the viability of this alloy in the context of the AD700 programme is the ability to manufacture in thick section and extrusion trials on a produced 2 tonne ingot are imminent. This NIMONIC® alloy 263 ingot has been put through the normal pipe production route to produce 4.5 meter steam pipe with dimensions 310 mm OD x 66 mm wall thickness shown in Figure 7. Welding trials have been successfully performed and long term creep rupture data for base material as well as cross-weld specimens and microstructural stability test are ongoing and will complete the characterisation of this nickel alloy.

In the German MARCKO DE2 project, mechanical testing and welding trials are established on alloy 617. Both tube and pipe products are available and a review of the existing creep data base, covering creep rupture data for more than 20 heats with testing times above 100.000 h, resulted in an update of creep strength values for both tube and pipe products. Figure 8 shows the ASME creep rupture data of alloy 617 and the proposed revised data obtained in the MARCKO DE2 project as well as the extrapolated creep rupture data of alloy 263 based on 20,000 hours testing.

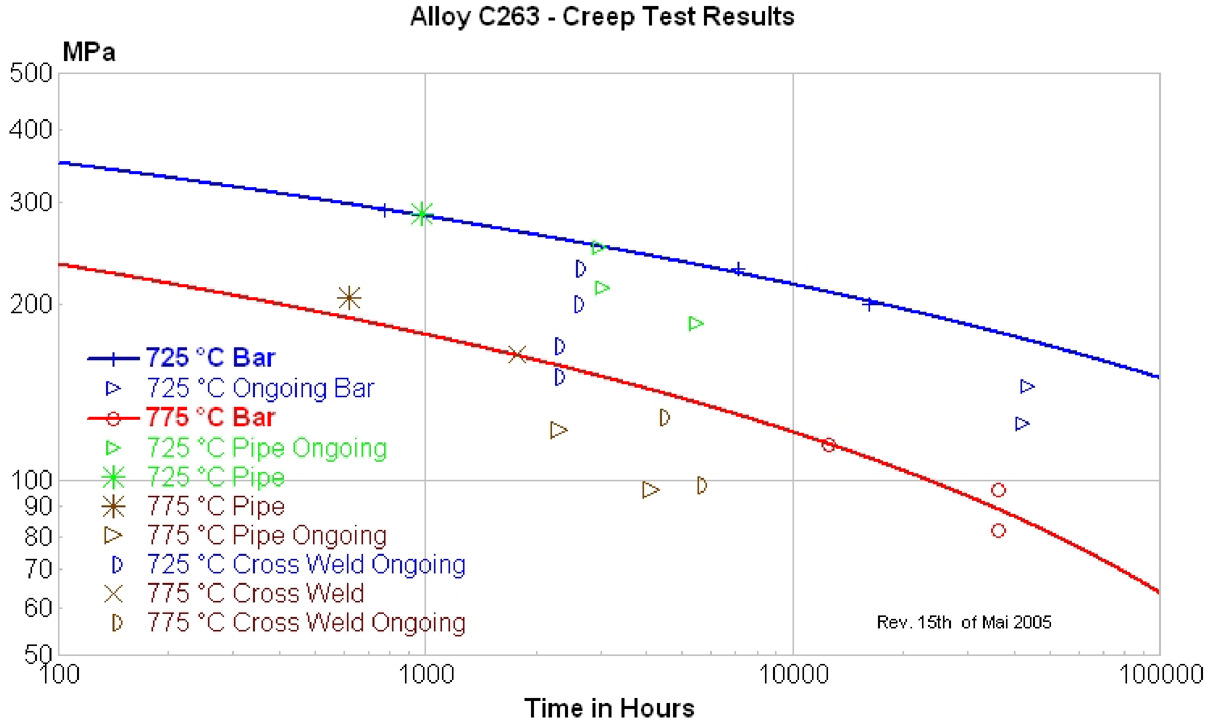

Fig. 6. Nimonic alloy 263 creep results

Fig. 7. Extruded NIMONIC® alloy 263 steam pipe

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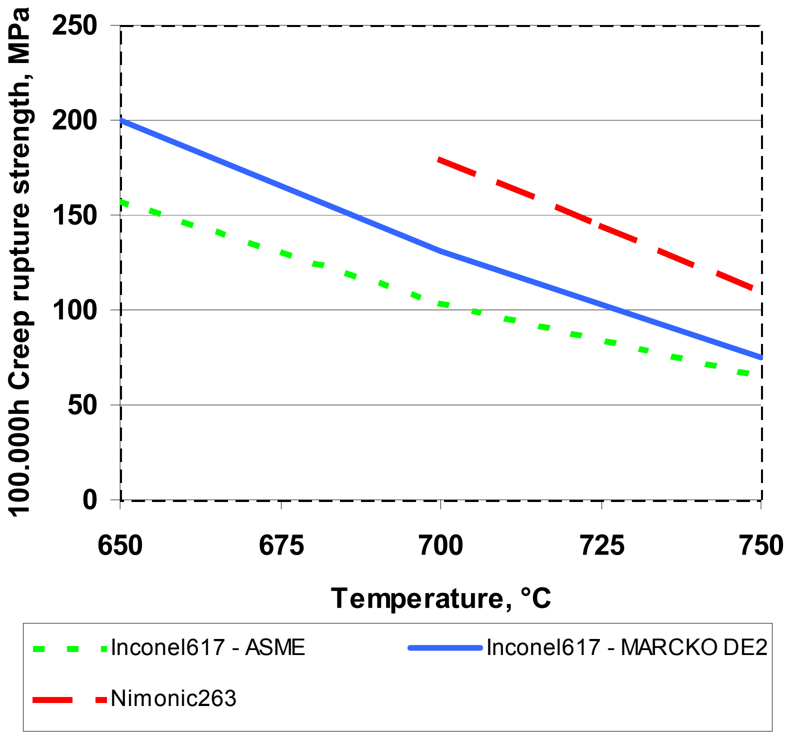

Fig. 8. Super alloy rupture strength

4. TURBINE MATERIALS

In addition to the factors already described, the selection of a first generation of candidate alloys in the AD700 project was influenced by the requirement to produce very large components so that experience of the project participants in producing large forgings in, for example alloys 706 and 718, and large castings in, for example, alloy 625 was taken into account. The selection was also influenced by the extent of data already available on the alloy, albeit generally not in the appropriate product form, for example the large body of data on tubes and pipes in alloy 617.

All these considerations, a review of the literature and of other data available to the project, led to the selection of nine alloys for investigation: alloys 155, 230, 263, 617, 625, 706, 718, 901 and waspaloy. In a couple of cases, alloys were selected in more than one heat treatment condition.

4.1 INVESTIGATION OF CANDIDATE ALLOYS

The main focus of the initial investigation was the identification of the best candidate alloys for the large rotor and casing components. The smaller components such as blading and bolting are equally important, but it was recognised that the product forms required for these components, bar and possibly investments castings, were already available for the gas turbine industry and could be applied to steam turbines with relatively little effort, perhaps limited to additional materials characterisation to establish those materials parameters required for steam turbine design. The nine candidate alloys were produced in various product forms, conventional castings, centri-spun castings, and bar or forgings. One alloy was also investigated in a powder metallurgy form.

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A first series of investigations was intended to confirm reported or expected short-term properties and to gain indications of response to ultrasonic testing and welding. These investigations included room temperature and elevated temperature tensile testing, creep testing at 700°C to target durations of 300-3,000 hours, and ageing trials at 650 and 700°C. The ageing trials involved impact and tensile testing after exposure for durations of 300, 1000 and 3000 hours. Welding trials were carried out on testpieces in each alloy. The weldments were around 35 mm in thickness and all were made with the same, alloy 617, consumable. Ultrasonic inspection was carried out on samples of the test materials to establish attenuation properties. Where possible, these investigations were carried out on already available materials but in many cases materials were manufactured specifically for the project.

The mechanical property investigations yielded results which were generally consistent with expected values. In terms of tensile properties castings were generally weaker than wrought products. The properties of centri-spun castings were similar to those of conventional castings. There was some concern that the low proof strength of the castings might lead to poor resistance to thermal cycling. A low cycle fatigue test programme mounted on these alloys has indicated that although relatively low strains lead to endurances of around 100 cycles, the gradient of the endurance curves is shallow so that the strains for endurance of around 5000 cycles are acceptable for steam turbine applications (Figure 9).

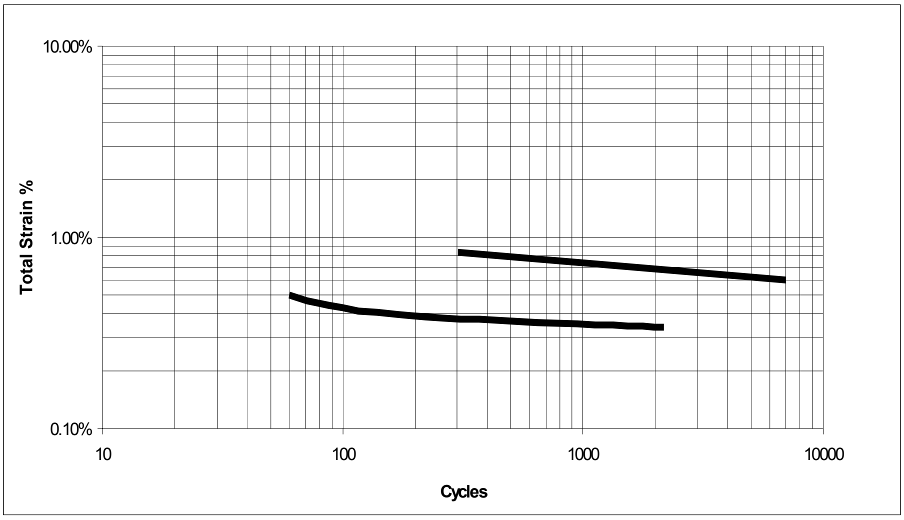

Fig. 9. Upper and lower bounds to low cycle fatigue endurance data obtained from tests on cast alloys 263, 617 and 625

Nearly all of the alloys responded to long term ageing through increased tensile strength but reduced impact strength. The reductions in impact strength were large enough to be of concern and prompted further investigation. In alloy 617, values of Charpy-V impact strength were observed to fall to as low as 10J. However when fracture toughness tests were carried out on this embrittled material, values of fracture toughness in excess of $70MPam^{0.5}$ were measured, values which are considered acceptable for steam turbine applications. The kinetics of embrittlement were very similar in all of the alloys. There was little difference in ageing response at 650 and 700 °C and most of the embrittlement appears to be complete after 1000 hours so that the differences between properties measured after ageing for 1000 hours and 3000 hours were relatively small (Figure 10).

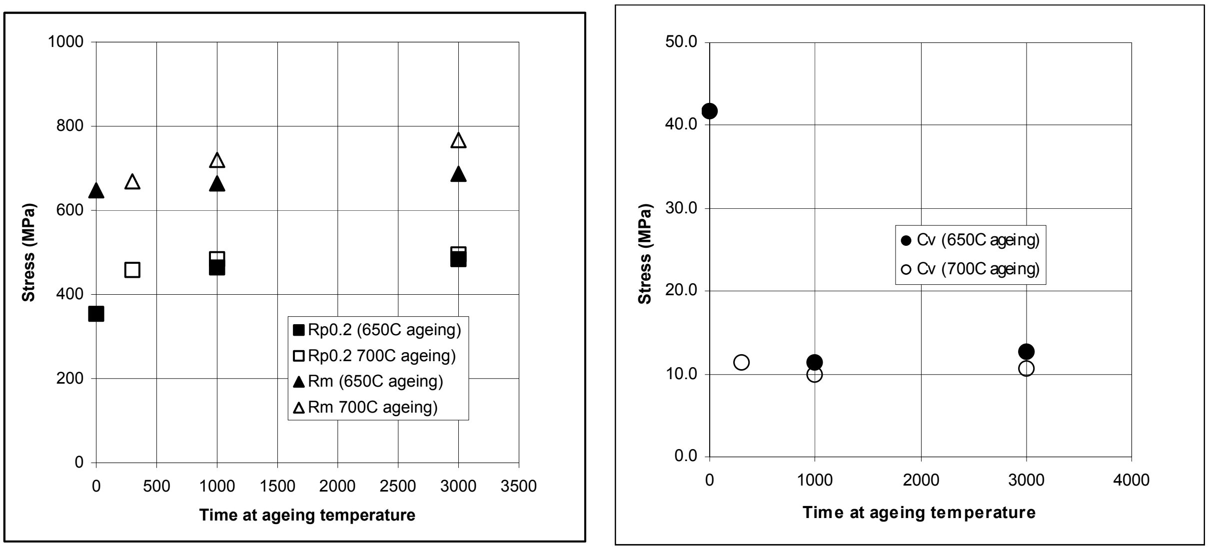

Fig. 10. Kinetics of long term ageing in alloy 617

The creep tests indicated properties generally in line with expectations. However the creep properties of the powder metallurgy product, in alloy 625, were disappointing. Investigation showed that premature, low ductility creep failures occurred at prior particle boundaries due to the presence of nitrides. However process improvements have been identified which may overcome this problem. One notable success was the development of a modified heat treatment for alloy 718. The alloy normally undergoes a two-stage ageing treatment involving ageing at around 720°C and then 620°C. An increase in the temperature of these ageing treatments by 30-40°C has resulted in a significant increase in long term creep strength. Figure 11 shows the creep master curve of the modified heat treatment [8].

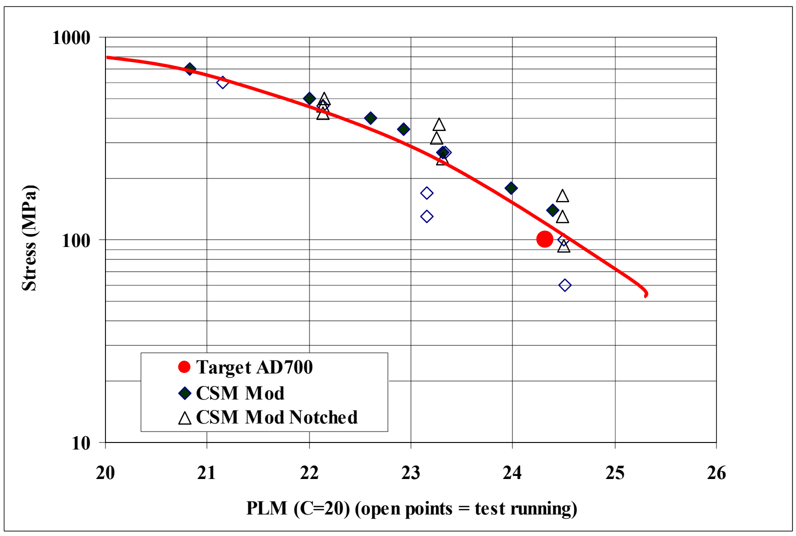

Fig. 11. Larson-Miller master curve of the modified heat treatment specimens [6]

The welding trials indicated potential weldability for all of the alloys. No heat affected zone cracking was observed in any case. The ultrasonic investigations showed that the wrought alloys could be inspected by ultrasonics but very clearly showed this would not be possible in cast components. Attenuation levels were so high that in some cases no back wall echo was observed even after ultra-

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sonic path lengths less than 100 mm. Therefore volumetric inspection of castings will be carried out by radiography.

4.2 ALLOY SELECTION FOR FULL SCALE OR MODEL COMPONENT PROTOTYPE DEMONSTRATION

The first round of investigations confirmed that a number of alloys were potentially suitable for application to steam turbine components. The next stage in the project was the selection of alloys for manufacture of full scale prototypes or of components which realistically simulate full scale components.

Even if the properties of castings are poorer than those of forgings, there are strong drivers for their application to valve chest and turbine casings arising from their lower costs and more flexible geometries. Castings require good weldability for the upgrading process arising from defects in the casting itself, but also due to the requirement to join castings to other components. This is especially true in the AD700 concept where the limited size of nickel alloy castings, coupled with the desire to restrict their application to the highest temperature parts of the turbine, means that welded joints in turbine casings, either between two nickel alloy castings, or between nickel alloy castings and steel castings, is likely to be required. The weldability of alloys used in the solution treated condition is generally high due to the relatively low levels of hardening elements such as Ti and Al. Furthermore the absence of phase changes during the welding process means that these nickel alloys require no PWHT to modify the microstructure in the heat affected zone and that they can tolerate any PWHT that is appropriate to the steel base material in dissimilar joints. Taking into account all available data and experience, alloys 617 and 625 were selected for further casting development.

Very similar factors drove the selection of alloys for forging development. Again limited size and high cost mean that welded constructions will be necessary, again favouring the solution treated alloys. For these reasons alloys 617 and 625 were also selected for further forging development. However two additional alloys were also selected. It is unlikely that alloy 718 in its standard form has adequate long term creep strength, but, with the heat treatment modification developed in the first round of investigations, it may provide a lower cost alternative to 617 and 625. Therefore this alloy was also selected for continued development. Finally, in case longer term testing showed unexpected reductions in the creep strength of these first three alloys, a fourth alloy, expected to have even higher strength, alloy 263, was also selected.

The initial round of investigations had also revealed that waspaloy is an excellent alloy for application to smaller, non-welded components such as blading and bolting.

4.3 CASTING MANUFACTURE

Model castings (step blocks with sections up to 200 mm) were successfully manufactured in alloys 617 and 625 (Table 6). Additional blocks were also cast for the manufacture of similar metal joints. Joints 70 mm in depth and 500 mm long were successfully manufactured and inspected using dye pentrant and radiographic techniques. In the case of both alloys, the joints were manufactured using matching consumables. These castings and welded joints were sectioned and are currently being subjected to an extensive and long term testing programme. Investigation of dissimilar joints is planned later in the project.

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Table 6. Details of castings for long term property investigation

617 and 625 casting geometry: Stepped block 300 mm in length with sections of 50, 100 and 200 mm

617 and 625 casting weight: 750 kg

Heat treatment: 617: 1170 C/water quench
625: 1200 C/water quench

Cast analysis:

Alloy	C	Ni	Fe	Cr	Mo	Co	Nb	Ti	Al	Mn	Si	P	S	Others
617	0.06	bal	0.6	21.6	9.2	12.2	<0.01	0.53	1.09	0.27	0.34	<0.01	0.001	N, 0.021 Cu, 0.02
625	0.02	bal	0.5	21.9	8.4	0.2	3.59	0.3	0.3	0.16	0.18	0.005	0.002	N, 0.033 Cu, 0.08

A full scale valve chest (delivery weight about 3.5 tonnes) has also been manufactured in alloy 617 (Figure 12). Further work is planned on this casting to confirm its properties are similar to those of the castings already under investigation. A second prototype casting is also being planned.

4.4 ROTOR FORGING MANUFACTURE

In both of the principal candidate alloys, 617 and 625, full scale HP rotor forgings 700 mm in diameter have been successfully manufactured. Careful selection and control of heat treatment parameters is necessary to avoid excessive grain growth which leads to poor ultrasonic inspectability. A first attempt to manufacture the 617 forging was unsuccessful but success was achieved on the second attempt after further heat treatment trials and adoption of a modified heat treatment practice. The final result has been sound forgings in a fully solution treated condition but with minimum detectable defect sizes over a path length of around 1.5m of better than 3 mm diameter flat bottomed hole equivalent. These forgings have been sectioned and are currently being tested in a long term test programme. More recently, an even larger forging of diameter around 1000 mm suitable for IP rotor forgings, has been manufactured (Figure 13). These forgings will also be investigated to confirm their properties are similar to those already under investigation.

Fig. 12. 617 valve chest casting after removal from mould and shot peening (courtesy of Goodwin Steel Castings)

Fig. 13. 617 forging during automatic ultrasonic inspection (courtesy of Saarschmiede)

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Model forgings have been manufactured in alloys 718 and 263, heat treatment parameters being controlled to simulate as far as possible the larger forgings manufactured in alloys 617 and 263. These forgings have also been sectioned for investigation. Details of all forgings investigated in this testing programme are given in Table 7.

Welding development has focussed on the two primary candidates and on the requirement for dissimilar joints. Different welding processes and filler metals have been investigated and an optimum solution has been defined. This involves manufacture of the joint using a narrow-gap TIG process and a nickel based filler metal. Manufacture of a full scale joint to demonstrate this solution has been successfully completed and a full investigation of weldment properties is in progress.

Table 7. Details of forgings for long term property investigation

Alloy	C	Ni	Fe	Cr	Mo	W	Co	Nb	Ti	Al	B	Zr	Mn	Si	P	S	Others
263	0.052	bal	0.34	19.5	5.8		19.5		2.21	0.48	<0.005		0.04	0.09	<0.005	<0.002	Cu, <0.10
617	0.060	bal	0.35	22.8	9.0	0.02	11.9	0.003	0.48	1.15	0.0002	0.005	0.02	0.05	0.005	0.001	Cu, 0.013; N, 0.004; V, 0.005
625	0.030	bal	2.17	21.9	9.1	0.03	0.02	3.7	0.20	0.19	0.004	0.010	0.01	0.02	0.002	0.001	Cu, 0.012; N, 0.006; V, 0.01
718	0.023	54.1	bal	18.8	3.0	<0.01	0.04	5.0	0.93	0.46	0.004		0.01	0.09	0.009	0.0006	

Alloy	Dimensions	Heat treatment (Hold temp, C/ hold time, h/ cooling medium)		
		Solution treatment	Ageing 1	Ageing 2
263	600mm diameter x 100mm	1150/10/air	800/8/air	
617	700mm diameter x 800mm	1100/3/water		
625	725mm diameter x 1230mm	1100/6/water		
718	730mm diameter x 320mm	1065/1/air	760/8/furnace	650/12/air

Alloy	Rp0.2	Rm	A	Z
	MPa	MPa	%	%
263	615	912	21	18
617	359	772	48	45
625	363	763	57	52
718	1155	1340	19	21

4.5 CANDIDATE MATERIALS FOR BLADING, BOLTING AND VALVE COMPONENTS

As previously stated, the identification of the optimum alloy selection and manufacturing route for blading and bar products such as bolts received a lower priority in the early stages of the programme. It is clear there are many alloys with properties more than sufficient for the requirements of steam turbine applications. However a significant decision was required over the manufacturing route for blading. The conventional route involves machining of blades from bar. However as the value of the alloy and the difficulty of machining rises, then the attraction of a near-net shape process grows. For example, investment castings have been applied very successfully in gas turbines. However cost estimates showed that this route was marginally less attractive than the conventional route, at least for the relatively low volumes anticipated during the early stages of exploitation of this technology. Therefore work is now focussing on development of all the properties needed for application of blades machined from bar.

Bolting materials will inevitably be machined from bar and materials with appropriate properties are already available. Selection of the optimum alloy is likely to depend on the particular requirements of a particular steam turbine design.

Wear resistance is an important issue for valve components and hard-facing solutions are applied in conventional steam turbines. The wear performance of these conventional solutions, as well as more advanced solutions, is currently under investigation.

4.6 INVESTIGATION OF ROTOR FORGING AND CASTING MODEL AND FULL-SCALE PROTOTYPES

The materials manufactured as full scale prototypes or as model components for rotor forgings or castings have been sectioned and are currently under investigation. The objective is to provide a basis for full validation of all allowable stresses used in steam turbine design and to investigate all potential failure mechanisms. In the as-received condition tensile, fracture toughness, long term creep (>30,000 hours), fatigue crack growth, creep crack initiation and growth, low cycle fatigue, creep-fatigue and steam oxidation properties are all being investigated. To investigate the influence of service exposure on properties, tensile, fracture toughness, fatigue crack growth, low cycle fatigue and creep-fatigue tests are being repeated on material aged for 1000 hours at 650°C.

Weldments are being investigated to define cross-weld, heat affected zone and weld metal properties. Cross-weld tensile, long term creep and low cycle fatigue tests are in progress. The heat affected zone fracture toughness, creep crack initiation and growth and fatigue crack growth properties are under investigation. Finally the weld metal properties are being assessed through fracture toughness, creep crack initiation and growth, fatigue crack growth, low cycle fatigue, creep-fatigue and steam oxidation tests.

This programme of testing has been in progress for over 25,000 hours and its results will be presented in future papers. However the results already available have revealed no unexpected behaviours or parameters which would create major difficulties for steam turbine design.

5. CONCLUSION

Alloys have been identified which meet the requirements for boilers and steam turbines operating at 700-720°C. Good progress is being made in application of these alloys to a series of prototype components to demonstrate the feasibility of manufacture. A comprehensive materials testing programme has been launched to investigate these prototype components and is addressing all critical properties and potential failure mechanisms. Currently the test programme is confirming the expected properties and has identified no technical obstacles to design and manufacture of boiler and steam turbines.

The results of this project have placed the European power generation industry and its supply chain in a powerful position for exploitation of this technology which on its own has a significant potential for mitigation of carbon emissions. When coupled with emerging technologies for carbon capture and sequestration, this technology can also facilitate the transition to zero-emission coal-fired power generation.

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