The European Efforts in Material Development for 650°C USC Power Plants—COST522

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"Advanced Steam Power Plant" is one of three working groups within the frame of European COST 522 with the aim of developing and evaluating ferritic steels for steam conditions up to 650°C. Today’s state-of-the-art large fossil-fired steam turbines comprise live steam conditions of up to 610°C/300 bar and re-heat temperatures of up to 630°C. These ultra super critical steam parameters significantly increase plant efficiency and reduce fuel consumption and emissions of CO₂.

Ferritic materials should be used for thick-walled components to maintain high operational flexibility of such large plants. Rotors, casings, bolts, tubes/pipes and waterwalls are the critical components under current investigation. The class of the 9–12% Cr steels offers the highest potential to meet the required property level for critical components. Therefore a significant effort to increase the application temperature of these steels was the focus of study within the European COST 501 programme and has led to improved materials for 600°C application of forged and cast components and for pipework. These 600°C materials are already being successfully utilised in a number of advanced European power plants. Further potential for improvement in creep strength seems possible after taking into account the oxidation resistance for T>600°C.

A large number of new ferritic–martensitic compositions, which have been designed on the basis of the positive outcomes attained in previous studies as well as on the results obtained with advanced thermodynamic calculation tools are under investigation in the new COST 522 programme. Full-size cast and forged components have been manufactured from the most promising compositions and now are being evaluated by intensive mechanical testing.

KEY WORDS: advanced materials; 9–12Cr steels; COST522; USC power plants; creep strength.

1. Introduction

The ready availability of energy at an economical price is a major factor affecting the success of manufacturing industry, upon which the general well-being and the standard of living of the population depend. Energy production, on the other hand, is faced with the introduction of increasingly stringent emission regulations to safeguard health and to preserve the environment for future generations. Coal, oil and natural gas will remain the primary sources of fuel for the next twenty to thirty years.

But the reserves of oil and natural gas are unlikely to be sufficient to satisfy fully the projected increase in power demands. Therefore, coal may be the only fuel available in substantial quantities by the middle of the 21st century. This fact is driving utilities to increase their power plant efficiency.

Countries in which the largest increases in electricity generation capacity will occur (India and China, among others) have large indigenous deposits of coal. Therefore the demand for coal-fired power plant will continue to expand. In Europe, coal or lignite will also play an important role in the foreseeable future and, although the requirements for new plant will be limited, there will be a substantial market for up-grading or replacing existing plants.

The thermal efficiency is influenced by several factors, and the adoption of supercritical conditions by increasing steam temperatures and pressures plays a key role. The application of steam parameters of 600°C to 650°C/300 bar offer improvements of 8 to 10% and a corresponding CO₂ reduction compared to 540°C/180 bar.¹ These advanced steam parameters require materials with adequate creep strength and resistance to oxidation. Experience with Austenitic materials was unsatisfactory in showing considerable restrictions in the operational flexibility of plants. The class of the 9–12% Cr steels offers the highest potential to meet the required property level for critical components in steam power plants.

2. Research Programmes in Europe

Since the late seventies, research efforts have been focused world wide on further development of ferritic–martensitic 9 to 12% Cr steels. Serious endeavors in this regard are ongoing in Japan, US and Europe.² The most relevant research programmes in these countries are summarised in Fig. 1.

In Europe the R & D efforts have been concentrated in
International Projects on Advanced Steam Power Plants

**JAPAN**
- Development and plant operation: EPDC
  - 1981 - 1993
    - Turbine and boiler manufacturers, steelmakers, R&D organisations
    - Materials development
    - Component manufacture
    - Pilot plant operation (50 MW)
  - 1994 - 2000
    - Target: 300 bar, 630°C / 630°C
    - Power plant orders

1000 MW, 241 bar, 593°C, 593°C com. 97
1050 MW, 250 bar, 600°C, 610°C ordered

**USA**
- Development: EPRI
  - 1981 - 1993
    - Basic studies (1978-1980)
    - Turbine & boiler man. (1986-1993)
  - EPRI project 1403 (USA, J, EU)
    - Thick-walled pipe steels
    - Standardisation achieved
    - Trial components in service

400 MW, 285 bar, 580°C, 580°C, 580°C com. 97
530 MW, 300 bar, 600°C, 600°C ordered

**EUROPE**
- Development: COST
  - 1981 - 1997
    - Turbine and boiler manufacturers, steelmakers, utilities, R&D
    - Interaction with VGB, Brite-EuRam, Marcklo, ECCE etc.
    - All major power plant components
    - Targets: 300 bar, 600°C / 600°C
      - 300 bar, 600°C / 620°C

The new COST 522 programme started in April 1998 and has a planned duration of 5 years. It involves 16 European countries and co-ordinates well over 100 research projects involving over 70 different organisations across Europe, including all of the main utilities, manufacturers, materials suppliers and research establishments. The overall COST 522 programme will focus on the development of suitable materials, coatings and surface treatments for the following:
- Steam power plants with inlet temperatures of up to 650°C
- Gas turbines with combustion temperature of up to 1450°C and NOx emissions <10 ppm.

Accordingly, the new COST 522 action is divided into different sub-projects:
- Steam Power Plant
- Gas Turbines
- Ancillary Components for Plants with Advanced Processes.

The steam power plant project aims to develop materials for highly loaded components at steam inlet temperature of up to 650°C where efficiencies of approx. 50% may be achieved by the use of ferritic–martensitic steels. Additional objectives are the improvement of the lifetime prediction methods, the preparation of material models to characterise the creep and LCF behaviour, and the improvement of the plant simulation techniques and the monitoring of operating conditions.

The steam power plant working group is sub-divided into a “Turbine” and a “Boiler” group, but a close collaboration between these two groups allows for synergy whenever possible. The organisation of the working group is shown in Fig. 2.
3. Materials Development for 600–620°C Application/
COST 501

Within COST 501 a series of advanced steels for forgings, castings and pipe/tube application as given in Table 1 was qualified.

There is a significant gain in application temperature for these new rotor, cast and pipe materials, as compared to traditionally used materials, Figs. 3 and 4.

The improved creep rupture strength does not, however, prejudice other design-relevant material properties, such as fracture toughness or low cycle fatigue behaviour. Additionally, the new materials provide benefits in medium-load and peak-load power plant operation on account of their favourable physical properties, including reduced thermal expansion as compared to low alloyed steels and subsequent shorter start-up times.4)

These advanced cast and forged COST steels are currently being applied in several advanced European power plants to achieve elevated steam parameters, Table 2.

The experience of the qualified manufacturers of these plant components has been positive throughout. The acceptance of the new rotor alloys of the 1W–1Mo and the 1.5 Mo types has also been demonstrated by the number of manufactured and installed power plant components. More than 800 forgings with a total delivery weight of approx. 3 000 tonnes have already been produced in Europe in these new steel grades, including steam turbine rotors and shaft ends, gas turbine rotor discs and various other forged components. Encouraged by the results, the newly developed cast steel grades are now already in use in more than 14 European power plants. Six foundries have successfully

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Table 1. Compositions of improved ferritic steels developed in COST 501.

| Steel Type | C | Cr | Mo | W | V | Ni | Nb | N | B | Status |
|------------|---|----|----|---|---|----|----|---|---|--------|
| Forged Steels |   |    |    |   |   |    |    |   |   |        |
| Type F     | 0.1| 10 | 1  | 1 | 0.2| 0.7 | 0.05| 0.05 | - | Applied in operating power stations |
| Type E     | 0.1| 10 | 1.5| 0.2| 0.6 | 0.05| 0.05 | - | Trial rotor manufactured |
| Type B     | 0.2| 9  | 1.5| 0.2| 0.1 | 0.05| 0.02| 0.01| - |        |
| Cast Steels |   |    |    |   |   |    |    |   |   |        |
| 10CrMoWVNbN | 0.1| 10 | 1  | 0.2| 0.8 | 0.07| 0.05 | - | Applied in operating power stations |
| 10CrMoWVNbN | 0.1| 10 | 1  | 0.2| 0.8 | 0.07| 0.05 | - |        |
| Tube/Pipe Steel | E911 | 0.1| 9  | 1  | 0.2| 0.3 | 0.05| 0.07 | - | Applied in operating power stations, application for ASME/ASTM |

Table 2. European advanced steam power plants.

| Steam Plant | Fuel    | Output MW | Live Steam bar°C | Reheat Steam°C | Thermal Efficiency % |
|-------------|---------|-----------|-------------------|-----------------|----------------------|
| Skaerbaek   | Gas     | 400       | 200/582           | 580/580         | 49 **\(*)\)          |
| Nordjylland | Coal    | 400       | 200/582           | 580/580         | 48 **\(*)\)          |
| Avedøre     | Biomass, Coal | 530 | 300/582           | 600             | 47 \(*)\)            |
| Schkopau A, B | Lignite | 450       | 285/545           | 560             | 40                   |
| Schw. Pumpe A, B | Lignite | 800       | 264/542           | 560             | 40.6                 |
| Boxberg Q, R | Lignite | 900       | 260/540           | 580             | 41.7                 |
| Lippendorf R, S | Lignite | 900       | 268/554           | 583             | 42.3                 |
| Niederaußen K | Lignite | 1050     | 265/576           | 600             | >43                 |
| Isogo 1     | Coal    | 600       | 251/600           | 610             | >43                 |
| Westfalen D (Design) | Coal | 350       | 283/600           | 620             | >43                 |

**\(*)\) air cooling and double reheat  \*) air cooling
produced some 350 castings with the weight ranging from 1 to 60 tonnes. In order to confirm the long-term properties of the improved steel grades for 600°C application and to establish a comprehensive database for these materials, a programme was launched with the support of VGB in Germany involving the investigation of commercial components. The test programme includes 24 heavy components manufactured from the new cast and forged steels (W-bearing and W-free) and produced by different suppliers employing the use of different production routes.

Creep tests, tensile and LCF tests at different temperatures have been performed with durations >30 000 h. These tests reveal a strong correlation between these production components and the trial components tested within COST. Parallel with the ongoing mechanical tests, extensive microstructural investigations have been carried out within the metallography and alloy design working group of COST 501 in order to firstly ascertain the causes for the differences in properties observed, and secondly, to provide support for further alloy modifications. Based on these microstructural efforts and on the careful evaluation of already available long term test data, an alloy concept for the further modification of cast and forged steels for 620°C application was formulated. The main characteristics consist of a reduced Ni-content, the addition of Co, B and N and the increase of Cr for oxidation resistance in a C–Cr–Mo–W–Nb–V matrix. After investigation of five different alloy compositions for forgings and five for castings with testing times >30 000 h, two favourite alloy compositions have been identified, Table 3.

Type FB2 is based on the positive results in the Boron containing trial rotor within the previous round of COST 501, but with reduced C-content and the addition of Co. Type CB2 is similar to the forged melt FB2 with a higher B-content. The creep rupture strength of the two alloys is compared in Fig. 5. The expected rupture strength for 625°C/100 000 h is 100 MPa for FB2 resp. 85 MPa for CB2.

Under the current COST 522 action, a full-size pilot rotor has been manufactured in FB2 for which investigations are currently running. Simultaneously, a 5 t pilot valve with composition CB2 has been cast and is currently being tested including fabrication weldments. First results of rupture strength are given in Fig. 6. The test data of three different positions in the pilot valve are within the 20% scatterband of the trial melt and have reached times of >15 000 h.

### Table 3. Favourite test melts of 9–12% Cr-steels for 620°C application.

| Parameter | Forgings: Type FB2 | Castings: Type CB2 |
|-----------|--------------------|--------------------|
| Chemical Composition (wt%) | | |
| C         | 0.13               | 0.12               |
| Si        | 0.05               | 0.20               |
| Mn        | 0.82               | 0.88               |
| Cr        | 9.32               | 9.20               |
| Mo        | 1.47               | 1.49               |
| Co        | 0.06               | 0.06               |
| Ni        | 0.16               | 0.17               |
| V         | 0.20               | 0.21               |
| Nb        | 0.05               | 0.06               |
| N         | 0.019              | 0.02               |
| B         | 85                 | 110                |
| Heat treatment °C | 1100 / 570 / 710   | 1100 / 730 / 730   |
| 0.2% Limit MPa  | 714               | 547                |
| FATT50 °C   | 14                 | 32                 |

4. Current Development Status for 650°C Application/COST 522

The results available so far from the previous activity show it to be unlikely that any of the trial materials investigated have the potential to fulfil the requirements for an application at 650°C. Therefore further improvement of these ferritic–martensitic grades is necessary with respect to creep strength, but keeping in mind the increased oxidation...
occurring at this temperature level.

On the basis of the promising compositions FB2 and CB2, modifications were made in the C-, Cr-, Co-contents. It was found that the relevant alloying aspects with respect to creep strength may be valid for both, forged and cast materials. Therefore, the new compositions for forged and cast trial melts show a strong similarity. Seven forged trial melts of approx. 150 kg, forged into bars and heat treated to simulate the core position of a heavy forging have been produced. In addition, six cast trial melts have been fabricated as plates of 100 mm thickness and were given a common heat treatment.

For the forged and cast trial melts, an extended test programme has been initiated, which will include metallographic investigations, short-term and long-term mechanical properties, oxidation tests, evaluation and qualification of filler metals for the new cast steels and the investigation of production welds on the components. The most promising alloys after testing times of 10,000 h are summarised in Table 4.

As of the present date, the new alloys do not show a further improved creep rupture strength values compared to the 620°C alloys, but do offer the potential for a higher oxidation resistance caused by their increased Cr content. The creep tests are planned to reach 100,000 h. The determination of long term oxidation resistance is currently running.

5. Summary

(1) The 9–12% Cr steels have been much improved in the last 15–20 years. The result is that today’s thermal power plant can be built with steam parameters of 610°C/300 bar and re-heat temperatures of up to 630°C.

(2) By concentrating the European efforts in the COST 501/522 programmes, in which some 70 organisations from 16 countries have taken part, materials with improved properties have been able to be successfully manufactured and tested.

(3) The recently developed materials with improved properties are already being utilised in several European power plants and will be further put to use in power plants currently under construction. The manufacturing experience gained with the new materials has been positive throughout.

(4) The further development of ferritic–martensitic materials for application temperatures of up to 650°C is the target of the sub-project “Steam Power Plant” in the 5-year programme COST 522. The chances for further improvement to the 9–12% Cr materials are promising.

(5) New alloy compositions have been identified with the potential to improve the oxidation behaviour at $T > 600°C$. Further effort is necessary to gain the targeted creep rupture strength of 100 MPa for 100,000 h at 650°C. The European COST family is taking on this challenge.

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REFERENCES

1) K. H. Mayer, W. Bendick, R. U. Husemann, T.-U. Kern and R. B. Scarlin: New Materials for Improving the Efficiency of Fossil-fired Thermal Power Stations, VGB Power Tech e.V., Essen, Germany, (1998), 27.
2) M. Staubli, K. H. Mayer, T.-U. Kern and R. Vanstone: Proc. 5th Int. Charles Parsons Conf., IOM Communications Ltd., London, (2000).
3) M. Staubli, W. Bendick, J. Orr, F. Deshayes and C. Henry: Proc. 6th COST Conf., Liège, Forschungszentrum Jülich, Jülich, Germany, (1998).
4) T.-U. Kern, R. B. Scarlin, R. W. Vanstone and K. H. Mayer: Proc. 6th COST Conf., Liège, Forschungszentrum Jülich, Jülich, Germany, (1998).
5) R. Hanus, K. H. Schönfeld: Proc. 5th Int. Parsons Conf., IOM Communications Ltd., London, (2000).
6) K. H. Mayer, R. Blum, P. Hillenbrand, T.-U. Kern and M. Staubli: Proc. 7th Liège COST Conf., Forschungszentrum Jülich, Jülich, Germany, (2002).
7) R. W. Vanstone, H. Cerjak, V. Foldyna, J. Hald and K. Spiradek: Proc. 5th Liège COST Conf., Kluwer Academic Publishers, Dordrecht, Netherlands, (1994).
8) T.-U. Kern, M. Staubli, K. H. Mayer, K. Escher and G. Zeiler: Proc. 7th Liège COST Conf., Forschungszentrum Jülich, Jülich, Germany, (2002).