Advanced steels for thermal power
– status, challenges and progress

Pertti Auerkari
VTT, Espoo, Finland

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Introduction: drivers and trends

- Cost / economy
- Environment
  - reduce emissions
  - give up fossil
- Technical opportunities
- Opinion climate

Typical performance vs State-of-the-art

New opportunities and technology

Data IEA 2008

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Example: India

- **Significant growth**
  - coal, oil, gas
  - large now and in future

- **Modest growth**
  - nuclear, hydro
  - other renewables
  - remain small to 2040

- **Almost no growth**
  - biomass
  - large but stagnant

- Cf. Europe, China, …
Advanced steels for thermal power: what is new?

- Increasing efficiency = decreasing heat rate
- Development of technology
- Reduce fossil fuels - then what?

European best coal fired plants (adapted from Mayer & Masuyama, 2008)
New requirement: more flexibility & storage

- Increasing renewables → more cycling & ramping → need for more storage

- Need for improved technology:
  - process
  - design
  - materials

Data from Timpf & Fuchs 2012; and Jeschke, Henning & Schreier 2012
Advanced steels for thermal power: what is new?

- New processes and equipment
- New materials (steels/alloys, consumables…)
- New fabrication & related technology
- New experience (from new to established)

Drivers:
- policies < climate change, taxation etc.
- competitive options in trading, production, fuels,…
- grid connections/capacity (local, regional, wider)
- new opportunities
New processes and plant types: example

- **Conventional thermal (steam) plant**
  - pulverised fuel (coal, lignite) firing at ~1250°C
  - up to ~1100 MWe
  - efficiency ~38 to 44%
  - conventional to newer materials

- **New steam plant** (CFB as an example)
  - flexible fuels incl. biomass, firing at ~900°C
  - up to ~500 MWe
  - similar efficiency with comparable fuels
  - conventional to newer materials

- **Process** matters less than operating environment: e.g. P91 widely used in steam plants, gas turbines and chemical industry
New materials: e.g. 9-12% Cr steels

Steels for tubes & pipes:
- 1960’s - : X20 (DE), not so new anymore
- 80’s to ‘90’s- : P91 (US), P92 (JP)
- 2016? - : P93
- Numerous predecessors & sidesteps, parallel alloys for castings, forgings, …

Characteristics:
- tempered martensitic microstructure
- multiscale internal boundaries, precipitates, solid solution elements → strength, ductility
- fair oxidation resistance (Cr), compatibility in thermal cycles of operation
- strong influence by errors in heat treatments
- new until full range of service experience

Multiscale microstructure of tempered martensitic steel (Hayakawa 2000, Kimura et al. 2006)
Creep strength (EN 10216-2, 200 kh) compared to 10CrMo9-10 (P22)

- P92
- X11CrMoVNVb9-1-1
- X10CrMoVNb9-1
- X20CrMoV11-1
- 14MoV6-3

Potential loss in strength

P22 = 1
Fabrication & related technology

Processing & heat treatments
- Casting, forging, rolling, drawing, …
- PM heat treatment (aust. + tempering)
- Welding & PWHT, incl. DMW’s
- Repairs: weld repair & PWHT

Most common deviations in:
- temperature / time / env. of treatment
- material / material combination
  (- chemical composition)

Welds:
- potential weak links 😞
- mechanical fuses 😊
Risk of failures – power equipment

- **Risk of failures**
  - depend on application
  - shift in time?

- **Material impact**
  - only conventional
  - mixed with all sources
Experience on materials in service

X20CrMoV11-1 (EN 10216-2):

- In widespread use since 1970’s, also for superheaters/reheaters, not in ASME code < short-term toughness (welded)
- Generally good indicated long term performance in Europe, > 200 kh in plant
- No systematic indications of low ductility, suggested relatively late emergence of creep cavitation damage in inspections
- Established steel 😊 - to be replaced 😞

Specific features:
- 0.2%C, to be noted for welding
- Rupture strength ~96 MPa/560°C/200 kh
Experience on materials in service

P91 (X10CrMoVNb9-1 EN 10216-2):

- In widespread use since 1990’s, less for boiler internals than X20 (T91, lower Cr)
- Reported cases of early creep damage with high Al (Al:N), high operating temperatures
- No systematic indications of trouble when avoiding upper operating range ≥ 580°C
- Established steel, less long term experience

Specific features:
- 0.1%C, easier to weld than X20
- Rupture strength ~97 MPa/590°C/200 kh

WSF < 0.8 at high temperatures

s/UTS = stress/ tensile strength
P91 (X10CrMoVNb9-1):
- potential challenges from errors in welding, heat treatment, composition
- at least 30 years for ~ full service experience
- easier for industrial and biomass plants with modest operating temperatures

High Ni
(Kimura 2012)
Experience on materials in testing & service

P92 (X10CrWMoVNb9-2 EN 10216-2):

- Used since 1990’s, mostly for heavy sections of large plants
- Suggested cases of low creep ductility (composition, fabrication) for upper range of operating temperatures (>600°C)
- Mostly short to medium term operating experience, not yet a fully established steel

**Specific features:**
- 0.1% C, much more Laves phase than in P91 or X20
- Rupture strength ~101 MPa/600°C/200 kh

Kimura & Sawada 2015
Experience on materials in testing & service

P92 (X10CrWMoVNb9-2 EN 10216-2):

- Creep ductility and toughness can be low (below half the yield stress)
- Suggested reasons: local concentrated strain near prior austenite gb’s, cavitation from particle surfaces (MnS, Laves, BN, Al$_2$O$_3$)
- Suggested remedies:
  - reduction of impurities
  - adjusting composition
  - additional heat treatment

(Kimura & Sawada 2015)
Strength vs. ductility / toughness

Trends:
- increasing strength tends to be accompanied with lower ductility and toughness
- characteristic behaviour for given material class
- not entirely inevitable: exceptions by materials design, also general improvement through e.g. cleaner steels
- often poor correlation in short term (creep) testing

Heikkinen et al. 2015
Experience on materials in testing & service

P92

- Charpy V energy decreases with ageing but in PM less than in WM(?), and in any case less than in X20 → of concern?
- Much of ageing and creep testing short-term, typically $< 10^4$ h → could be inconclusive
- Retards accumulation of valuable evidence, except for that from plant, and possibly welds

Shi 2011, Yan & Liu 2016
9Cr-3W-3Co-0.02Nd (P93?)

Element | Target | Improvement
--- | --- | ---
9Cr | Long-term creep strength, Solution strengthening | Creep strength of base metal
3W | Laves phase precipitation strengthening | 
0.01B | Suppression of coarsening of $M_{23}C_6$ on G.B. | 
0.01N (low-N) | Suppression of Z-phase and BN precipitation | 
0.02Nd | Suppression of S segregation | Creep ductility
3Co | Stability of martensite | Toughness
0.01B | Suppression of fine HAZ | Creep strength of welded joint

Hamaguchi et al. 2015
**9Cr-3W-3Co-0.02Nd (P93?) welded**

**Observations:**
- testing up to about 45 000 h, downward trend accommodated in the fitting model?
- P92 under- and Alloy82 over-matching?
- failure positions in longest tests: type IV avoided?
- often poor correlation in short term (creep) testing

Hamaguchi et al. 2015
Challenges:

- Early CF methods developed for aerospace Ni alloys with design life $\sim 10^4$ h $\rightarrow$ HT but no long tests

- For land-based equipment with design life of more than $2 \cdot 10^5$ h, long holds make slow testing of both conventional & new materials $\rightarrow$ more emphasis on modelling and monitoring of equipment condition

- Improved resistance to more extensive cycling, reduced minimum loads (not only a materials issue)
Conclusions - summary

• **HT steel evolution for pressure equipment** is gradual and requires
  - long term qualification for first introduction
  - status of new material until initial adjustments and further evidence have accumulated to show trusted limits of application
  - dealing also with new challenges like those from cyclic/intermittent service, cost bias from subsidies, etc.

• **Each new generation** of successful steels provides
  - improved thermal and resource efficiency
  - process-independent advantages for any equipment with suitable service conditions (temperature, loads, chemical environment)
Thank you