New Nano-Particle-Strengthened Ferritic and Martensitic Steels by Thermo-Mechanical Treatment

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Ferritic/Martensitic Steels For Elevated-Temperature Service

- **Steels developed for fossil-fired power plants**
  - **Advantages: thermal properties and economics**
  - **Limitations: upper temperature limit on strength**
    - **Steels limited to 550-600°C**
- **Steels proposed for nuclear applications—fission and fusion power plants**
  - **Advantages demonstrated for fast reactors in 1960s**
  - **Steels adopted for fusion applications**

Ferritic and Martensitic Steels for Fusion Reactor First Wall

- **Ferritic/martensitic steels were chosen because of advantages over austenitic stainless steels:**
  - **Thermal properties**
    - **Higher thermal conductivity**
    - **Lower thermal expansion**
  - **Lower void swelling during irradiation**

Choice of Steels for Fusion

- First steels were commercial Cr-Mo steels (HT9, mod. 9Cr-1Mo, 2¼Cr-1Mo) from power-generation industry
- Reduced-activation steels were developed for fusion for easier nuclear waste disposal
  - Mo, Nb, and Ni were eliminated—long-life isotopes
  - Cr-W steels were developed to replace Cr-Mo steels
  - 7-10Cr-2WVTa steels were developed in Japan, Europe, and the United States

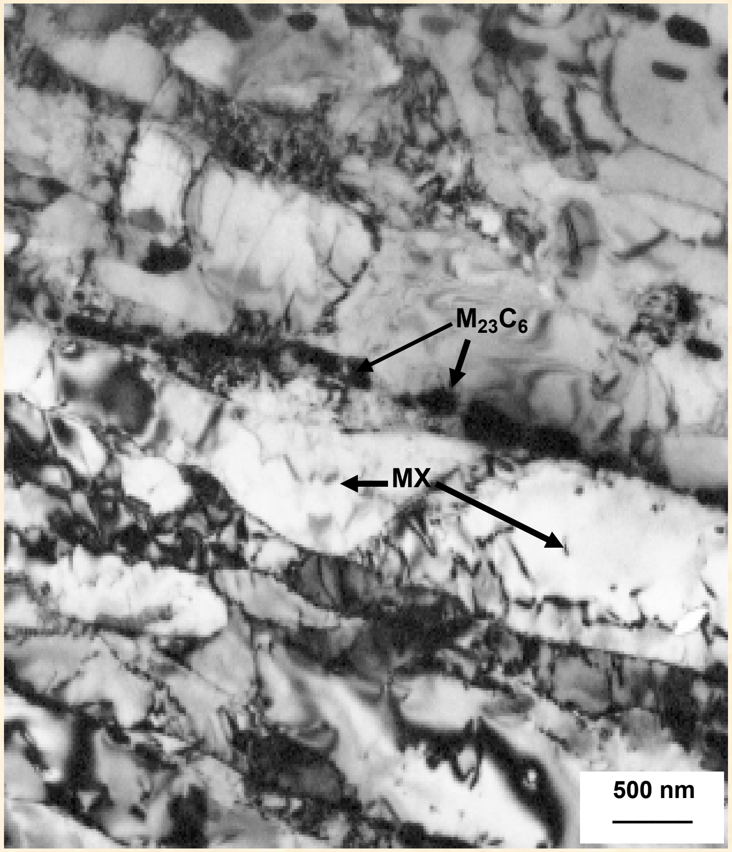
7-12% Cr Steels Have Tempered Martensite Microstructure

- **Austenitized and air cooled (normalized) to produce martensite**
- **Tempered to increase ductility and toughness**

Sandvik HT9: Normalized-and-tempered

Microstructure Limits Elevated-Temperature Strength of Steels

- **Large $M_{23}C_6$ particles pin subgrain boundaries**
- **Dispersion strengthening is by small MX particles (carbides, carbonitrides, and/or nitrides)**
- **Particles coarsen at elevated-temperatures**
- **Subgrain size increases and strength decreases**



HCM12A Steel (N &T)

New Steels Required For Higher Temperature Applications

- **Steels limited by elevated-temperature strength**
  - **Higher temperature operation required for better efficiency**
  - **Favorable properties of martensitic steels make them preferred candidates**
- **Present best <u>potential</u> replacement: Oxide dispersion-strengthened (ODS) steels**
  - **Fabricated by expensive/complicated mechanical alloying and powder metallurgy techniques**
  - **In development since 1960s**

Strength Of Steel Is Determined By Composition And Microstructure

- **Deformation creates and moves dislocations through matrix**
- **Strength improved by hindering dislocation movement**
- **Composition determines precipitates and solid-solution strength**
- **Microstructure effects (dislocation obstacles):**
  - **Precipitates (small, high-number density)**
  - **Grain boundaries and subgrain boundaries**
  - **Dislocations**

High Strength Obtained From Large Number Of Small Obstacles

- **Conventional steels: strength obtained by heat treatment to produce tempered martensite strengthened by precipitates**
  - **Large precipitates and low number density**
- **ODS steels: strength from high number density of small oxide particles**
- **New steels: strength from high-number density of nano-sized precipitates**
  - **Conventional processing vs. expensive powder metallurgy techniques of ODS steels**
  - **Conventional processing to eliminate anisotropy that has plagued ODS steels**

Objective: Develop New Steels For Elevated-Temperature Service

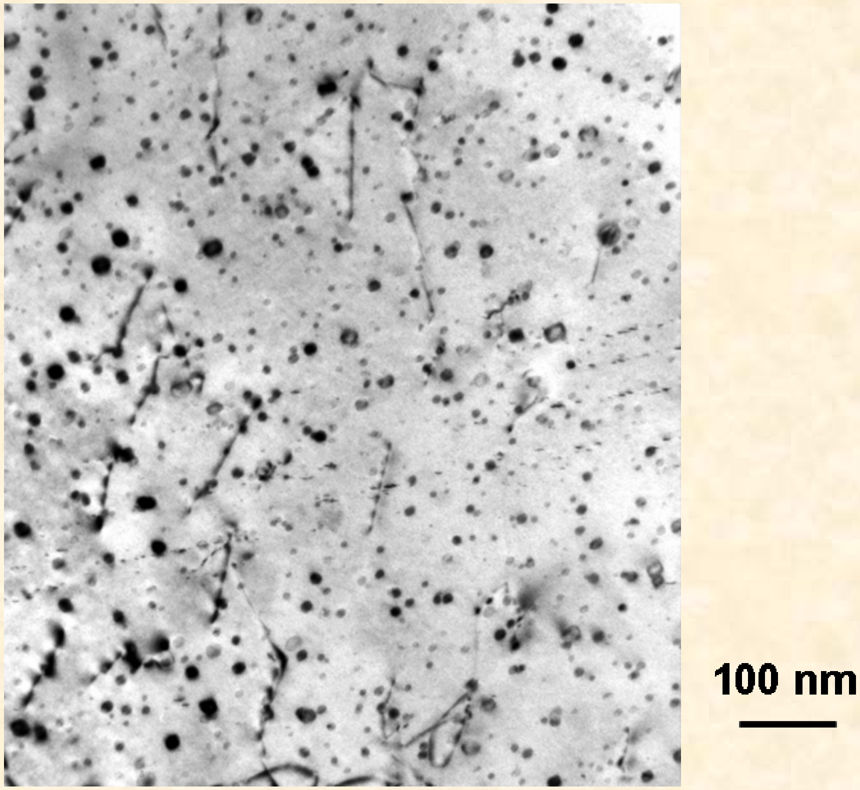
- **Use nitride (MX) precipitates for strengthening**
- **Obtain strength from high number density of small MX precipitate particles**
  - **maximize number of small MX particles**
  - **minimize number of large $M_{23}C_6$ particles**
- **Produce steels by conventional processing**
- **Creep strength adequate to 700ºC (or higher)**
- **Computational thermodynamics used to devise compositions and processing of new steels**

Thermo-Mechanical Treatment (TMT) Devised to Produce New Steels

- **Thermo-mechanical treatment:**
  - **Heat to high temperature (1100-1300ºC) to put all elements in solid solution in austenite**
  - **Cool to hot-rolling temperature (750-900ºC)**
  - **Hot roll to introduce dislocations that act as heterogeneous nucleation sites for MX precipitation**
  - **Anneal to grow precipitates to optimum size**
  - **Air cool to form high-strength martensite matrix**
- **Strength from distribution of nano-sized MX nitride and/or carbonitride precipitates**

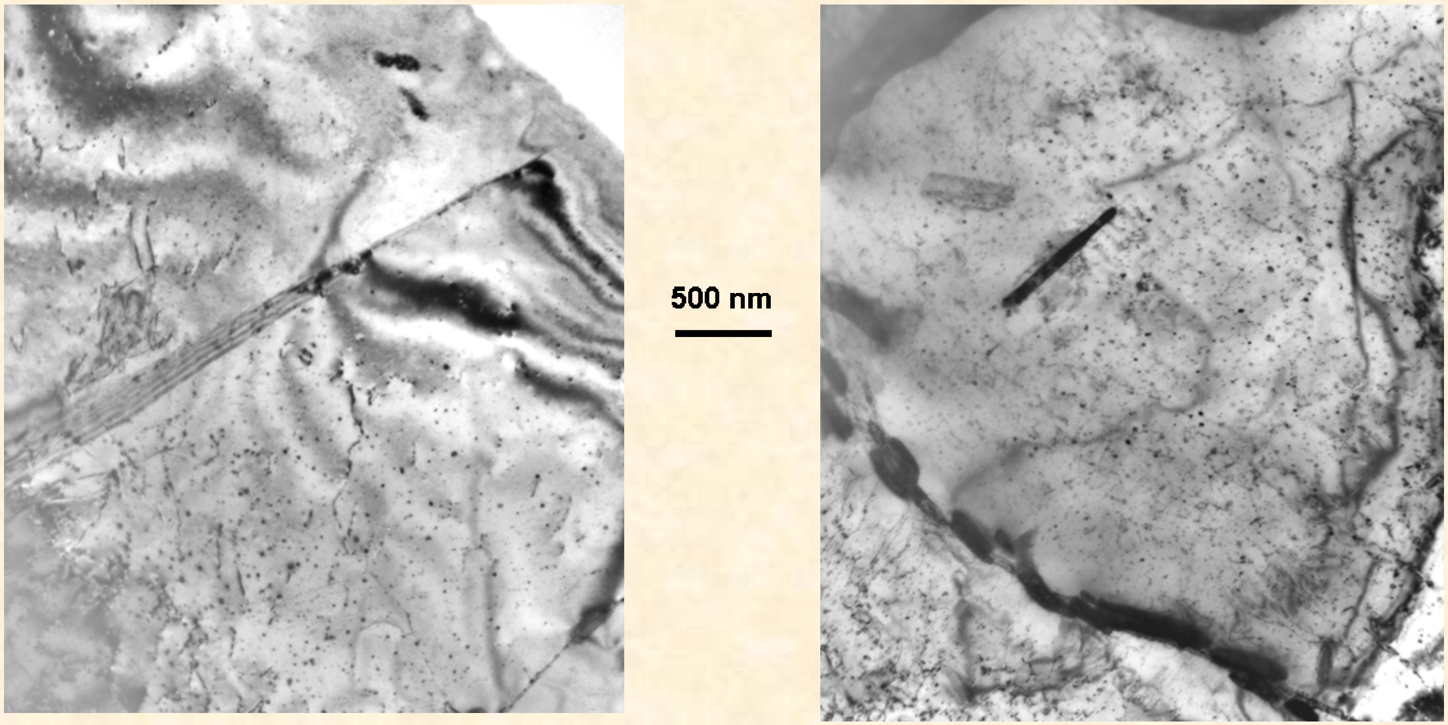
TMT Process Applied to Nitrogen-Containing Commercial Steel

- **Initial work: nitrogen-containing commercial steels (modified 9Cr-1Mo, etc.) were used**
- **Plates (25.4-mm thick) were available and processed by hot rolling**
- **Results used to verify capability of process**



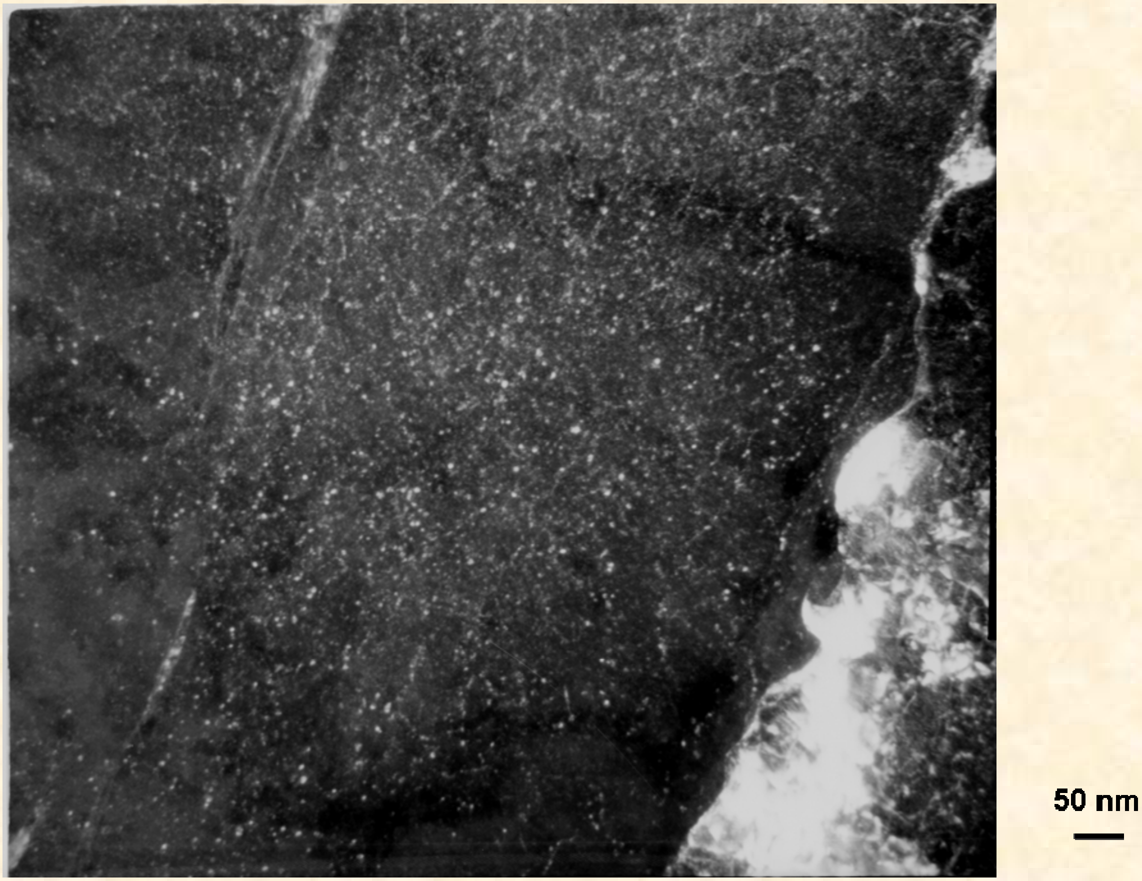
Modified 9Cr-1Mo—New TMT

Size and Number of Precipitates Depend on TMT Procedure



- **Commercial modified 9Cr-1Mo Steel after two variations of new TMT treatment**

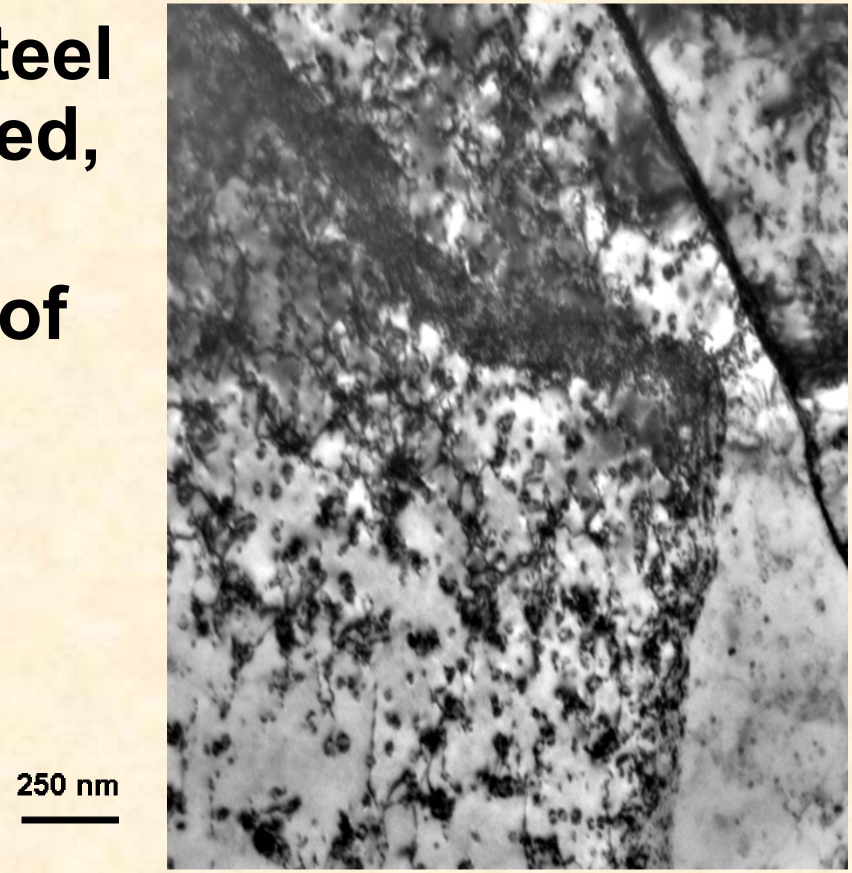
Precipitates Form On Dislocations During TMT



•Dark-field image—HCM12A (12CrWMoVNb steel)

New Steel With High Number Density of Small Particles Produced

- **Fe-9Cr-1MoNiVNbN steel 400-g ingot) was melted, cast, and TMT**
- **High number density of small precipitates**



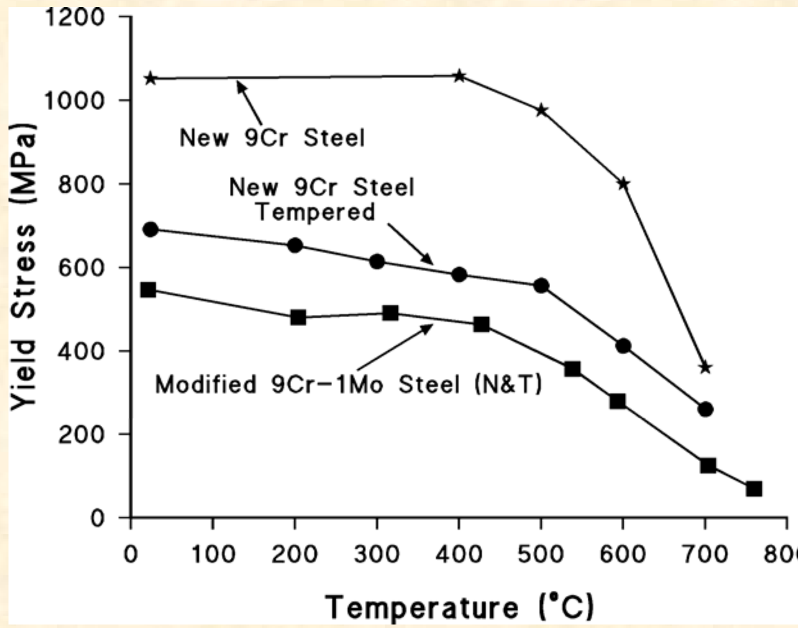
Size and Number of Precipitates Depend on TMT Processing Procedure

Experiment	MX Precipitates	
	Average Size (nm)	Number Density (m^{-3})
Modified 9Cr-1Mo—N&T	32	7.9×10^{18}
Modified 9Cr-1Mo—TMT1	7.2	8.9×10^{21}
Modified 9Cr-1Mo—TMT2	7.3	2.1×10^{21}
Modified 9Cr-1Mo—TMT3	8.0	1.9×10^{21}
Fe-9Cr-1MoNiVNbN—1	4.0	1×10^{22}
Fe-9Cr-1MoNiVNbN—2	3.3	7.2×10^{22}

- **High number density of nano-size particles obtained**

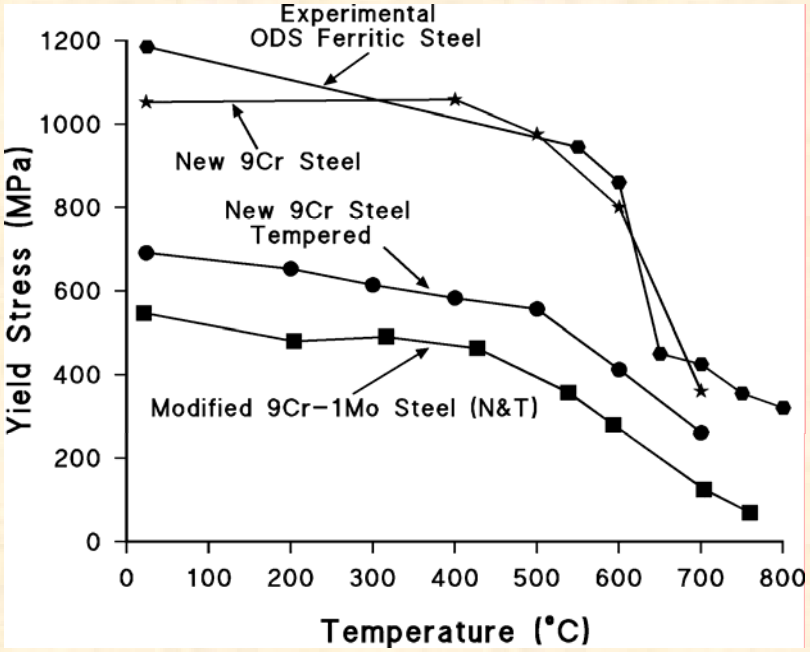
TMT of New Steel Composition Produced High Strength

- **Excellent strength from small ingot**
- **This despite inability to obtain nitrogen concentration desired**

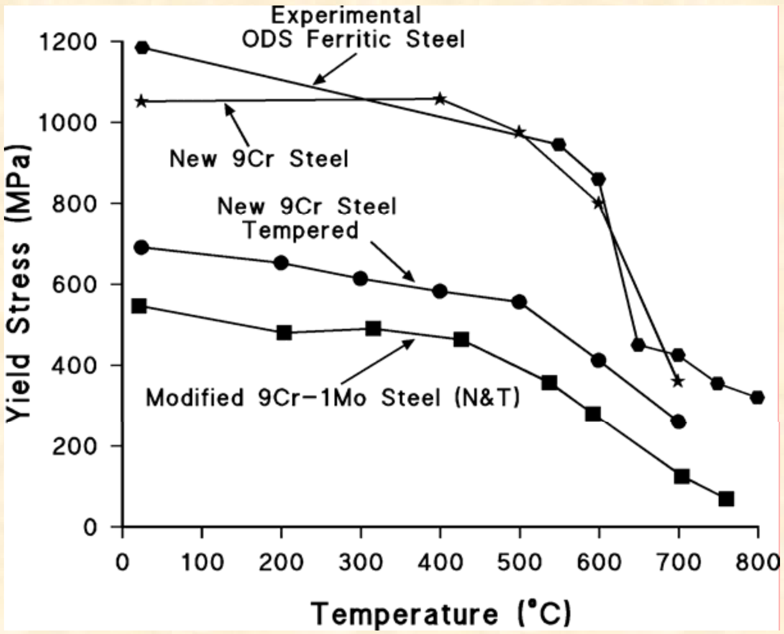


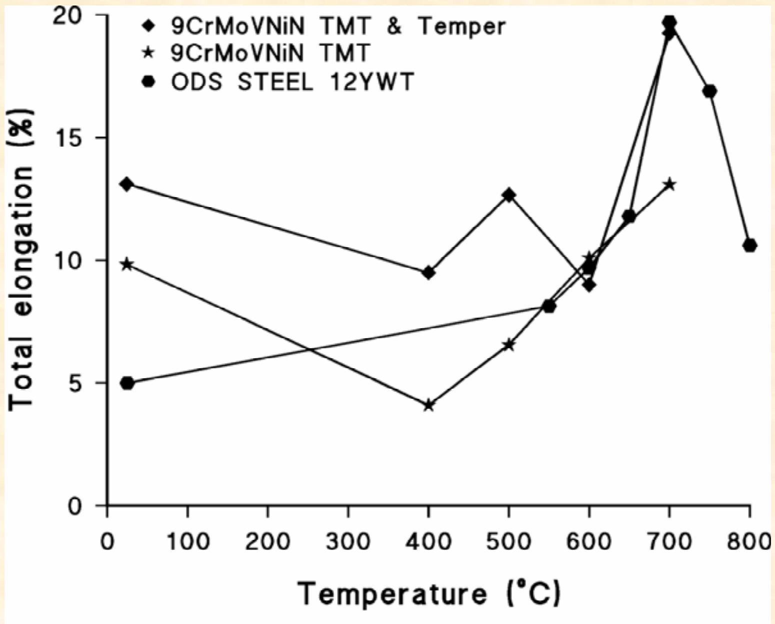
TMT of New Steel Composition Produced High Strength

- **Strength and ductility in tensile test are comparable to high-strength experimental ODS steel**



TMT of New Steel Composition Produced High Strength

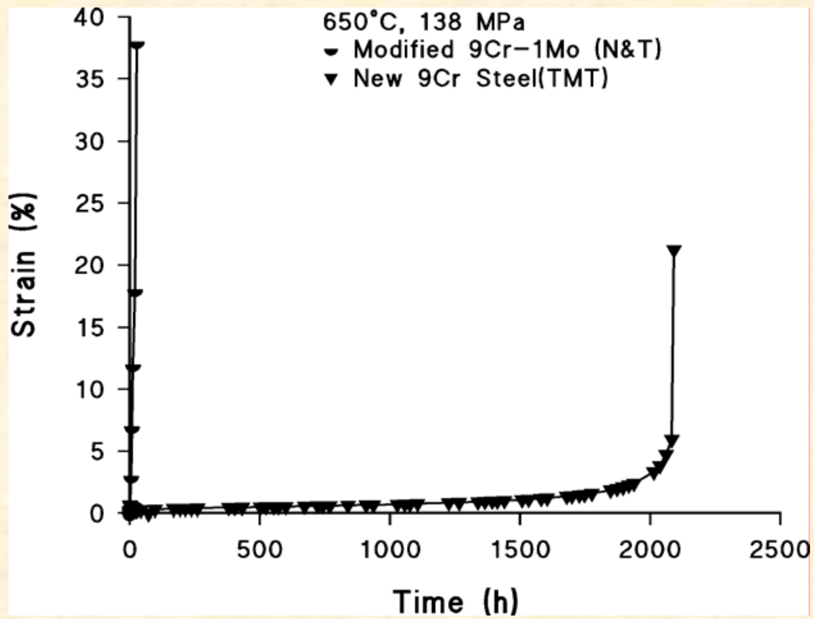




- **Strength and ductility comparable to high-strength experimental ODS steel**

Creep-Rupture Life Of Modified 9Cr-1Mo Steel Improved By TMT

- **Rupture life increased by ≈80 times by TMT**
- **Excellent ductility for high strength**



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Summary

- **Process to produce nano-particle-strengthened martensitic steels are being developed**
  - **Present steels limited to 550-600ºC**
  - **New steels should have use temperature >700ºC**
  - **Steels developed for fossil-fired power plants and future nuclear fission and fusion power plants**
- **Initial work demonstrated possibilities:**
  - **Microstructures contain high number density of small precipitate particles**
  - **Steels show large increase in strength relative to steels produced by conventional heat treatment**
  - **Strengths are comparable to strong ODS steel**