Development of SFR Fuel Cladding Tube Materials

International Conference on Fast Reactors and Related Fuel Cycles (FR09), Kyoto, Japan

8 December 2009

Sung Ho Kim, Chan Bock Lee, and Dohee Hahn

KAERI Korea Atomic Energy Research Institute

Outline

I Core Environment of SFR

II SFR Fuel Cladding Development Program

III Alloy Design for SFR Cladding Materials

IV Evaluation of New Alloys

V Evaluation of Fabrication Process

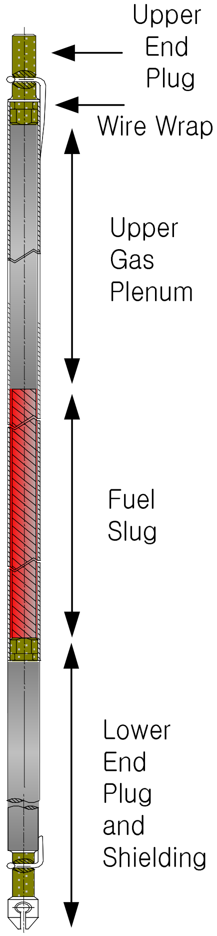
VI Summary

I Core Environment of SFR

I.1 Fuel Rod and Assembly

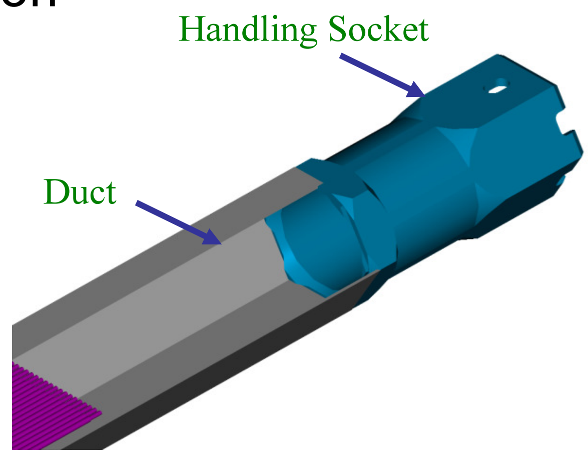
I.2 Core Environment & Design Requirements for Cladding Tube

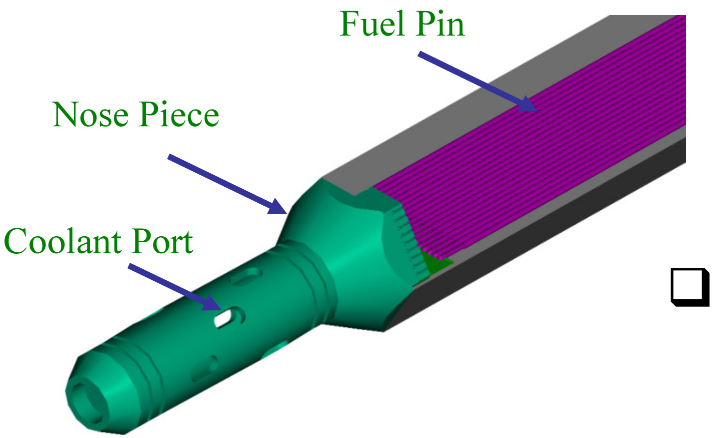
I.1 Fuel Rod & Assembly



❑ Fuel cladding tube dimension

- Outer diameter : 8.5 mm
- Thickness : 0.53 mm
- Length : 3500 mm





❑ SFR fuel materials

- Fuel : Metallic
- Cladding material : FM steel
- Duct material : FM steel

❑ Fuel assembly

- No. of rod : 271
- No. of fuel rod : 267
- Length : 4500 mm

I.2 Core Environment & Design Requirements

❑ Core Environment

- Inlet temperature : 370^{o}C
- Outlet temperature : 545^{o}C
- Fuel temperature : 650^{o}C
- Fast neutron fluence : 200 dpa
- Hoop stress (end of life) : 70MPa
- 3-4 cycles (1 cycle : 18 month) : 50,000 hrs

❑ Design Requirements of Cladding Tube

- Thermal strain : < 1%
- Total strain : < 3%
- Swelling : < 5%

II

SFR Fuel Cladding Development Program

II.1 Target

II.2 Long-term Development Plan

II.3 Short-term Development Plan

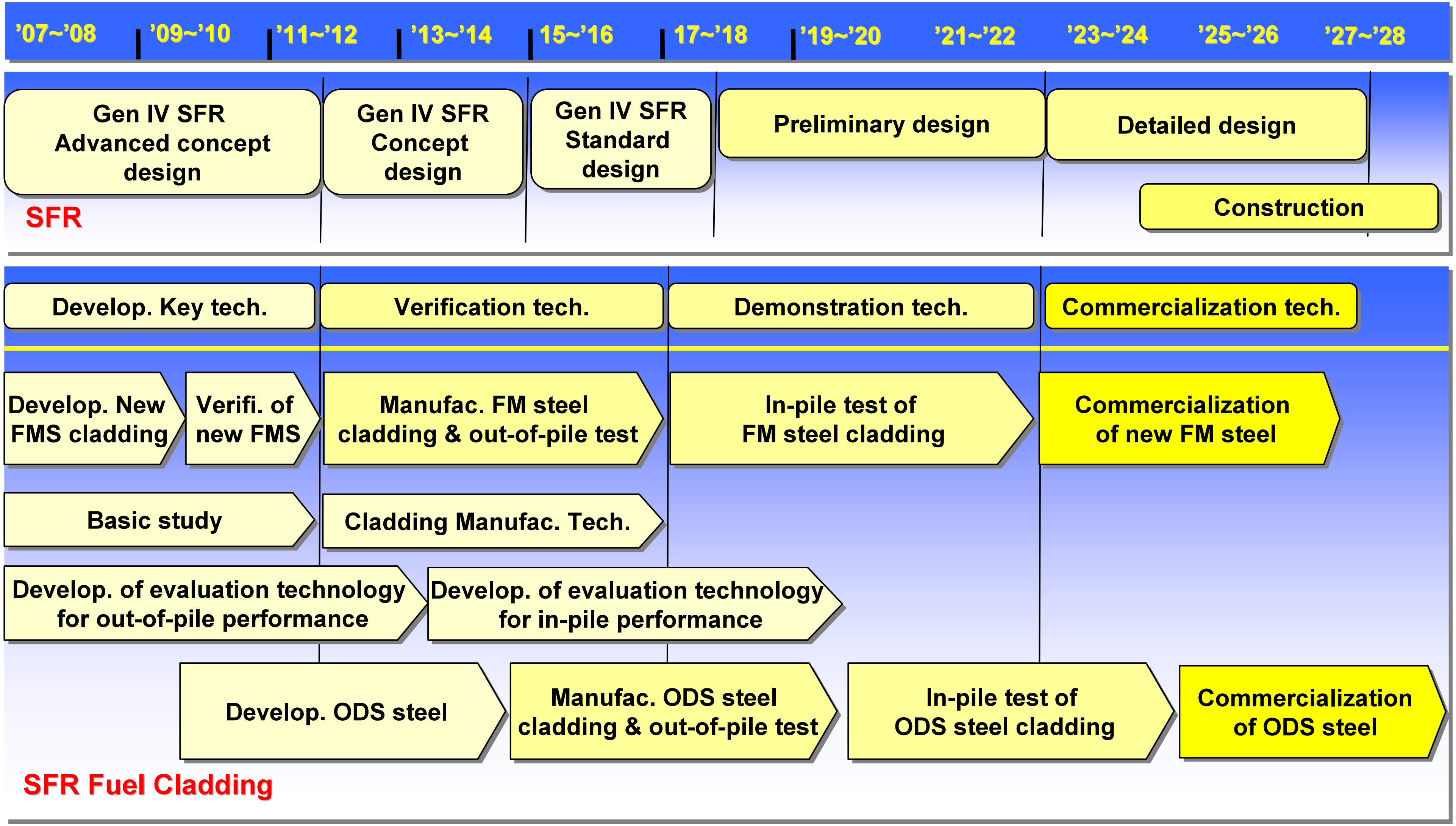
II.1 Target

◆ **Development of new cladding having higher creep rupture strength**

◆ **Development of barrier materials for applying to cladding tube**

	KALIMER 600	New Target
Max. allowable temp. of cladding tube	630°C	Above 650°C
Max. fluence of cladding tube	200 dpa	250 dpa
Limitation in cladding temp. by eutectic melting (°C)	650°C – 700°C	No. (Apply barrier to cladding tube)

II.2 Long-term Development Plan



’07~’08 | ’09~’10 | ’11~’12 | ’13~’14 | 15~’16 | 17~’18 | ’19~’20 | ’21~’22 | ’23~’24 | ’25~’26 | ’27~’28

SFR

- Gen IV SFR Advanced concept design
- Gen IV SFR Concept design
- Gen IV SFR Standard design
- Preliminary design
- Detailed design
- Construction

SFR Fuel Cladding

- Develop. Key tech.
- Verification tech.
- Demonstration tech.
- Commercialization tech.

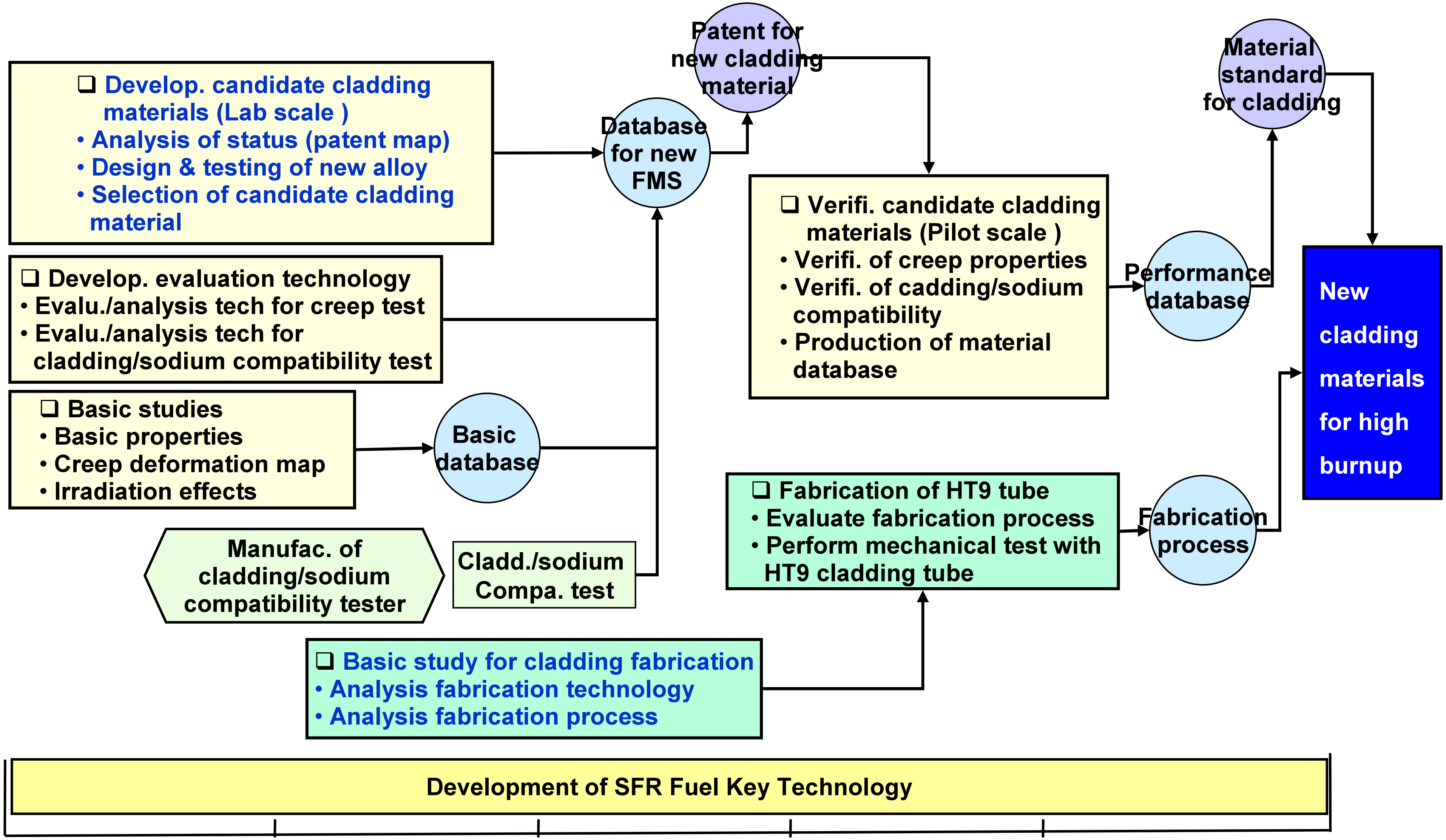
- Develop. New FMS cladding
- Verifi. of new FMS
- Manufac. FM steel cladding & out-of-pile test
- In-pile test of FM steel cladding
- Commercialization of new FM steel

- Basic study
- Cladding Manufac. Tech.

- Develop. of evaluation technology for out-of-pile performance
- Develop. of evaluation technology for in-pile performance

- Develop. ODS steel
- Manufac. ODS steel cladding & out-of-pile test
- In-pile test of ODS steel cladding
- Commercialization of ODS steel

II.3 Short-term Development Plan



☐ Develop. candidate cladding materials (Lab scale)
- Analysis of status (patent map)
- Design & testing of new alloy
- Selection of candidate cladding material

☐ Develop. evaluation technology
- Evalu./analysis tech for creep test
- Evalu./analysis tech for cladding/sodium compatibility test

☐ Basic studies
- Basic properties
- Creep deformation map
- Irradiation effects

Manufac. of cladding/sodium compatibility tester

Cladd./sodium Compa. test

Basic database

Database for new FMS

Patent for new cladding material

☐ Verifi. candidate cladding materials (Pilot scale)
- Verifi. of creep properties
- Verifi. of cadding/sodium compatibility
- Production of material database

Performance database

Material standard for cladding

☐ Fabrication of HT9 tube
- Evaluate fabrication process
- Perform mechanical test with HT9 cladding tube

Fabrication process

☐ Basic study for cladding fabrication
- Analysis fabrication technology
- Analysis fabrication process

New cladding materials for high burnup

Development of SFR Fuel Key Technology

2007

2011

III

Alloy Design for SFR Fuel Cladding Materials

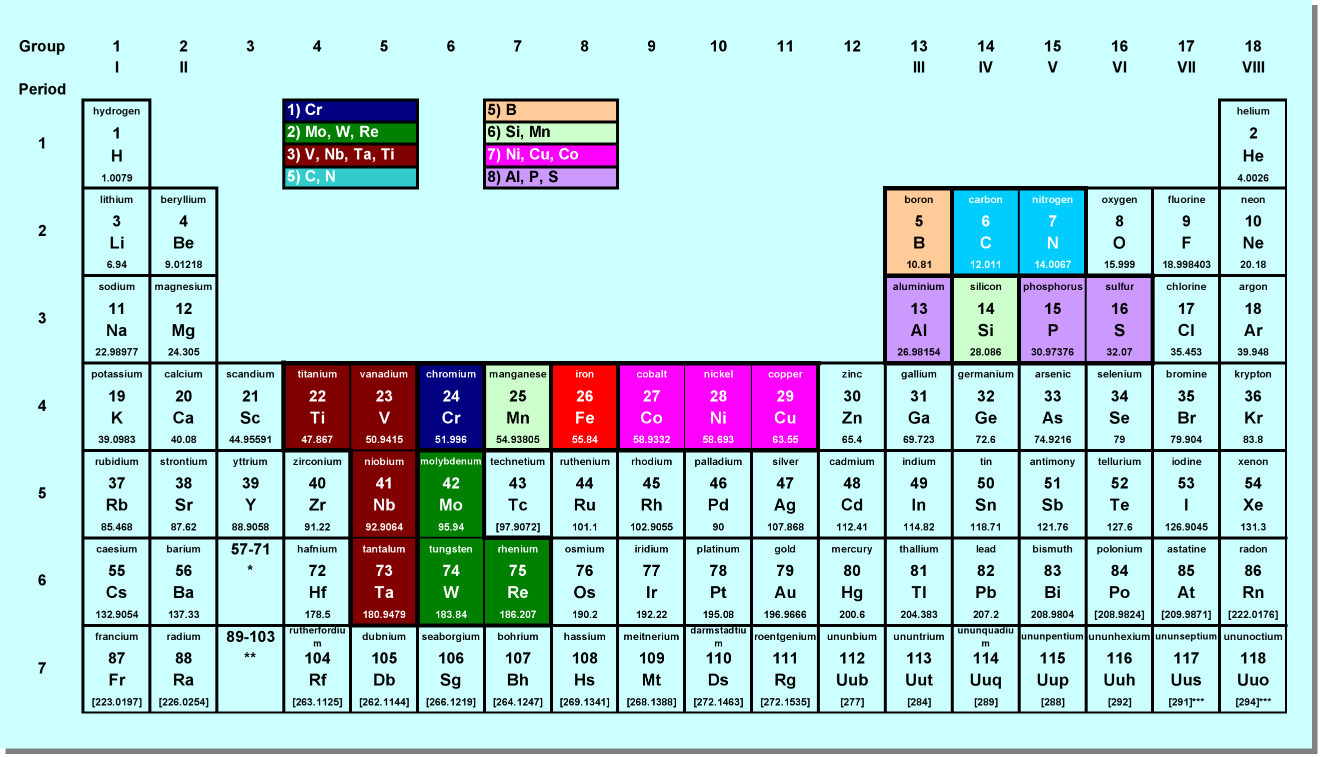
III.1 Evaluation of Minor Alloying Elements

III.2 Strengthening Mechanism of FM Steels

III.3 Alloy Design

III.4 Fabrication Process

III.1 Evaluation of Minor Alloying Elements



1) Cr
2) Mo, W, Re
3) V, Nb, Ta, Ti
5) C, N

5) B
6) Si, Mn
7) Ni, Cu, Co
8) Al, P, S

Group Period	1 I	2 II	3	4	5	6	7	8	9	10	11	12	13 III	14 IV	15 V	16 VI	17 VII	18 VIII
1	hydrogen 1 H 1.0079																	helium 2 He 4.0026
2	lithium 3 Li 6.94	beryllium 4 Be 9.01218											boron 5 B 10.81	carbon 6 C 12.011	nitrogen 7 N 14.0067	oxygen 8 O 15.999	fluorine 9 F 18.998403	neon 10 Ne 20.18
3	sodium 11 Na 22.98977	magnesium 12 Mg 24.305											aluminium 13 Al 26.98154	silicon 14 Si 28.086	phosphorus 15 P 30.97376	sulfur 16 S 32.07	chlorine 17 Cl 35.453	argon 18 Ar 39.948
4	potassium 19 K 39.0983	calcium 20 Ca 40.08	scandium 21 Sc 44.95591	titanium 22 Ti 47.867	vanadium 23 V 50.9415	chromium 24 Cr 51.996	manganese 25 Mn 54.93805	iron 26 Fe 55.84	cobalt 27 Co 58.9332	nickel 28 Ni 58.693	copper 29 Cu 63.55	zinc 30 Zn 65.4	gallium 31 Ga 69.723	germanium 32 Ge 72.6	arsenic 33 As 74.9216	selenium 34 Se 79	bromine 35 Br 79.904	krypton 36 Kr 83.8
5	rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.9058	zirconium 40 Zr 91.22	niobium 41 Nb 92.9064	molybdenum 42 Mo 95.94	technetium 43 Tc [97.9072]	ruthenium 44 Ru 101.1	rhodium 45 Rh 102.9055	palladium 46 Pd 90	silver 47 Ag 107.868	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.6	iodine 53 I 126.9045	xenon 54 Xe 131.3
6	caesium 55 Cs 132.9054	barium 56 Ba 137.33	57-71 *	hafnium 72 Hf 178.5	tantalum 73 Ta 180.9479	tungsten 74 W 183.84	rhenium 75 Re 186.207	osmium 76 Os 190.2	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.9666	mercury 80 Hg 200.6	thallium 81 Tl 204.383	lead 82 Pb 207.2	bismuth 83 Bi 208.9804	polonium 84 Po [208.9824]	astatine 85 At [209.9871]	radon 86 Rn [222.0176]
7	francium 87 Fr [223.0197]	radium 88 Ra [226.0254]	89-103 **	rutherfordium 104 Rf [263.1125]	dubnium 105 Db [262.1144]	seaborgium 106 Sg [266.1219]	bohrium 107 Bh [264.1247]	hassium 108 Hs [269.1341]	meitnerium 109 Mt [268.1388]	darmstadtium 110 Ds [272.1463]	roentgenium 111 Rg [272.1535]	ununbium 112 Uub [277]	ununtrium 113 Uut [284]	ununquadium 114 Uuq [289]	ununpentium 115 Uup [288]	ununhexium 116 Uuh [292]	ununseptium 117 Uus [291]***	ununoctium 118 Uuo [294]***

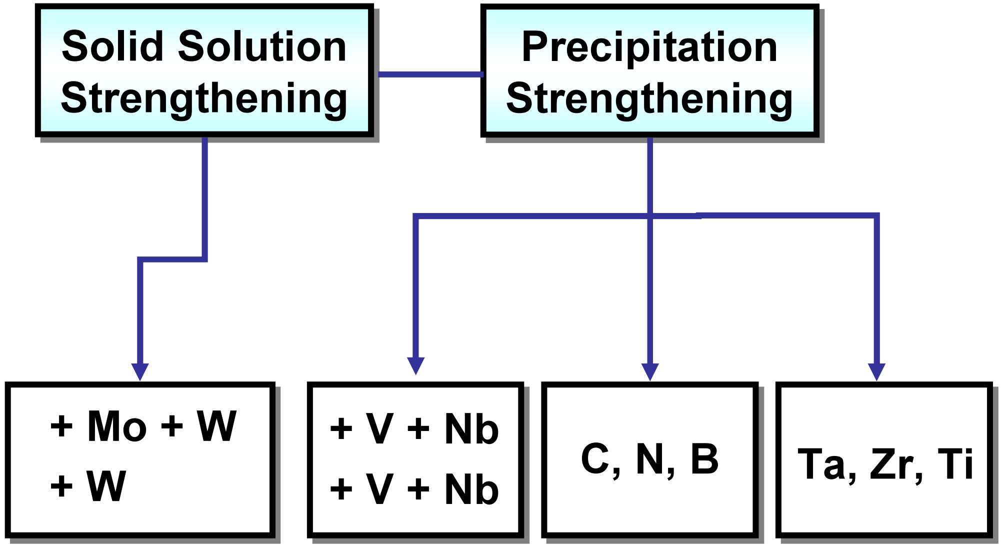
1) Cr: Precipitation hardening
2) Mo, W, Re: Solid solution hardening
3) V, Nb, Ta, Ti: Precipitation hardening
4) C, N: Precipitation hardening
5) B: Stabilization of precipitates
6) Si, Mn: Stabilization of precipitates
7) Ni, Cu, Co: Stabilization of microstructure
8) Al, P, S: Stabilization of microstructure

Evaluation of base data

- Crystal structure/atomic radius
- valence/Electronegativity/MP
- nucleus embrittlement
- Formation of δ-ferrite
- Phase transformation temp. (M_s, A_1)

III.2 Strengthening Mechanism of FM Steels

Strengthening mechanisms of FMS Steels



Solid Solution Strengthening

Precipitation Strengthening

+ Mo + W
+ W

+ V + Nb
+ V + Nb

C, N, B

Ta, Zr, Ti

- **Effect of B addition**
- **Optimization of C and N**
- **Optimization of Nb, V**
- **Effect of Ta addition**
- **Effect of Zr and Ti**

III.3 Alloy Design

❑ Chemical compositions

ID	Nominal composition	Remark
A	9Cr-2W-Nb-Ta-V1	Effect of V concentration
B	9Cr-2W-Nb-Ta-V2	“
C	9Cr-2W-Nb-Ta-V1-C1-N1	Effect of C and N concentration
D	9Cr-2W-Nb-V-Ti	Effect of Ti
E	9Cr-2W-Nb-V-Zr	Effect of Zr

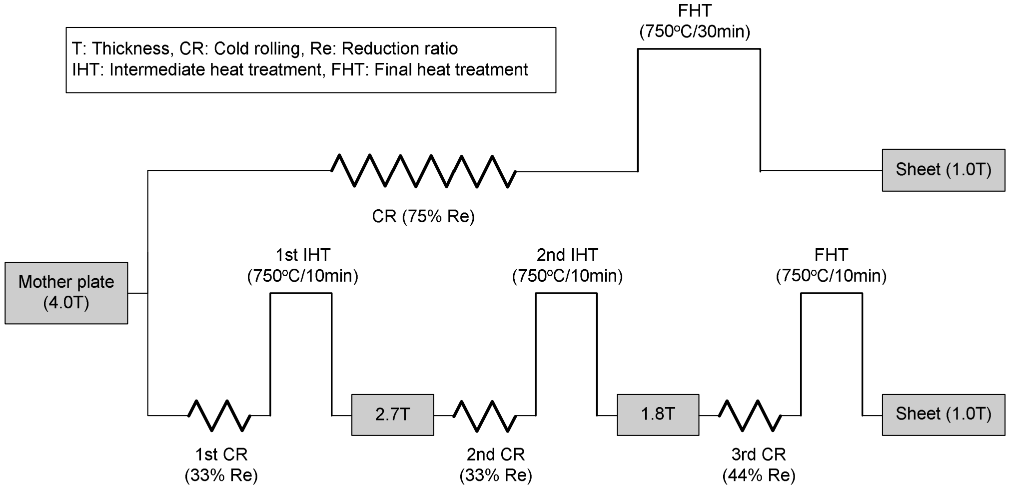
❑ Specimen manufacturing

- Vacuum Induction Melting (Ingot size : 30kg)
- Hot rolling (1150^{o}C)

❑ Heat treatment

- Normalizing : 1050^{o}C x 1 hour
- Tempering : 750^{o}C x 2 hours
- Air cooling was applied during all the heat treatment.

III.4 Fabrication Process



❑ Cold rolling and heat treatment

- Plate : normalized at 1050°C for one hour, tempered at 550°C for 2 hours
- Cold rolled from 4 mm to 1 mm
- One time cold rolling :
  - Reduction ratio : 75%
  - Heat treatment : 750°C for 30 min
- Three times cold rolling
  - Reduction ratio : 33% or 44%
  - Heat treatment : 750°C for 10 min

IV Evaluation of New Alloys

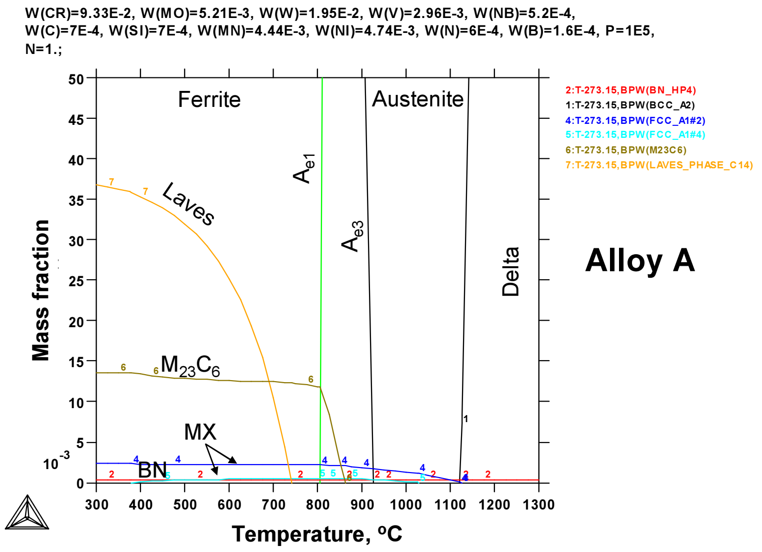
IV.1 Phase Equilibrium Diagram

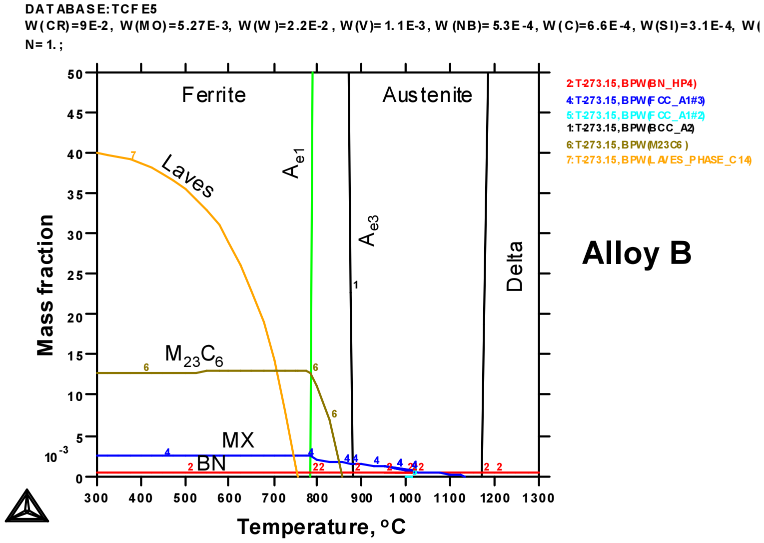
IV.2 Mechanical Properties

IV.1.1 Phase Equilibrium Diagram

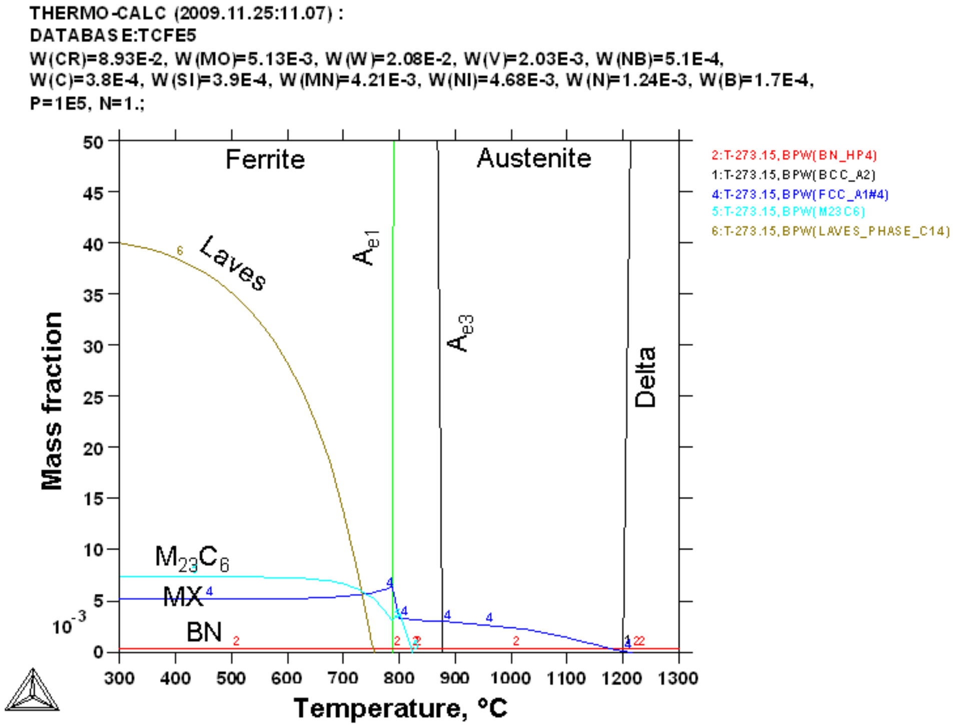
❑ Phase equilibrium of Alloy A & B

- Alloy A : high vanadium steel
- Alloy B : low vanadium steel
- Equilibrium phases : $M_{23}C_6$, MX, BN and Laves phase
- A_{e1} temperature : 805°C and 780°C in alloy A and B
  - Alloy A can be tempered at higher temperature.
  - More stable precipitates may be formed.
  - Creep resistance of Alloy A may be improved.
- V-rich MX phases
  - Formed in Alloy A
  - Not appeared in Alloy B





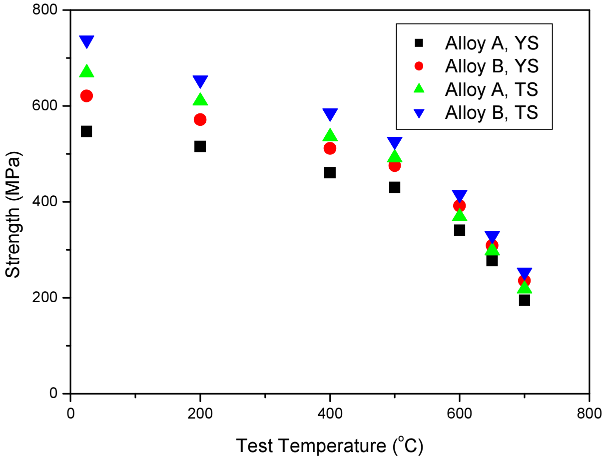
IV.1.2 Phase Equilibrium Diagram

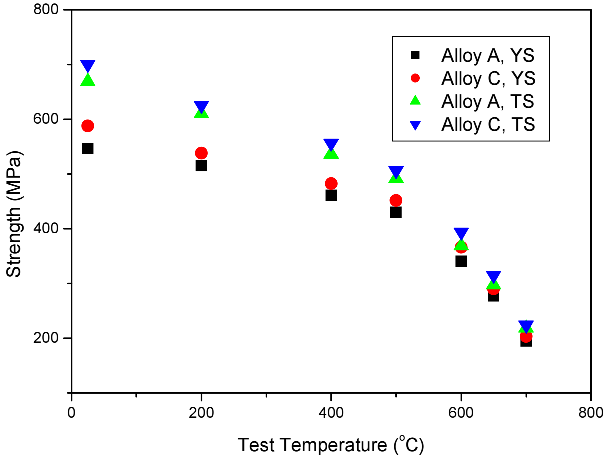


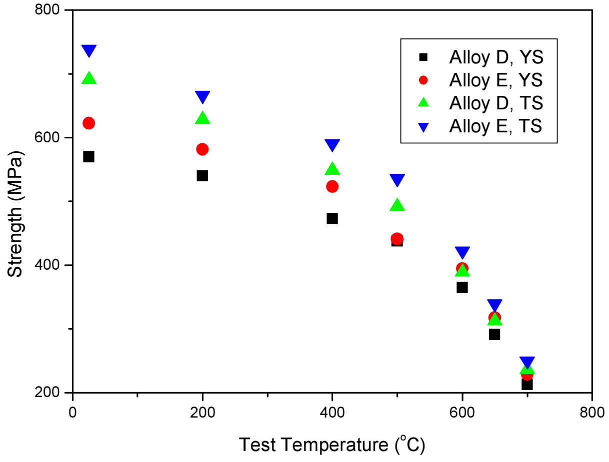
❑ Phase equilibrium of Alloy C

- Carbon concentration : decrease
- Nitrogen concentration : increase
- A_{e1} temperature : 780°C
- Mass fraction of $M_{23}C_6$ precipitates : reduce in Alloy C
- Mass fraction of MX precipitates : increase in Alloy C

IV.2.1 Tensile Properties



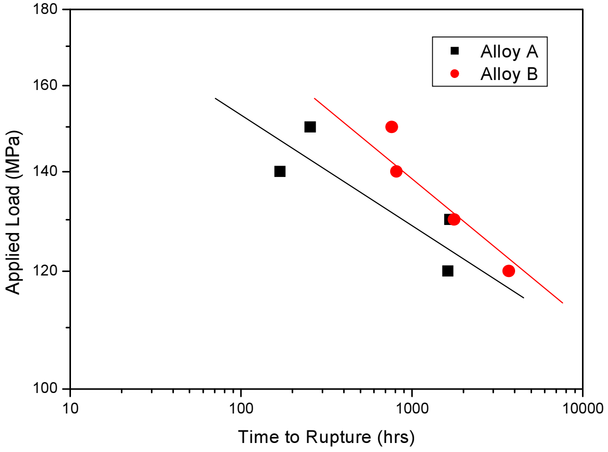


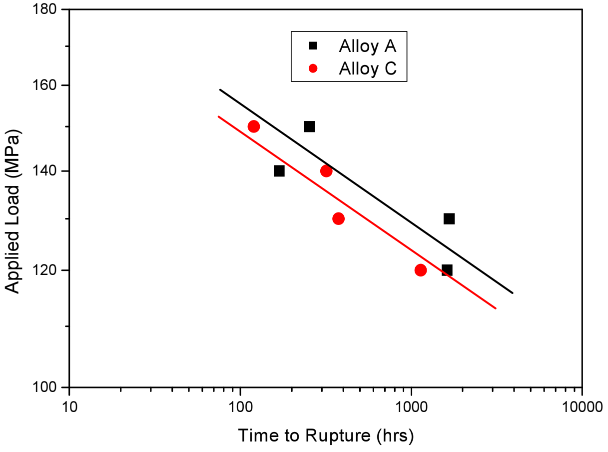


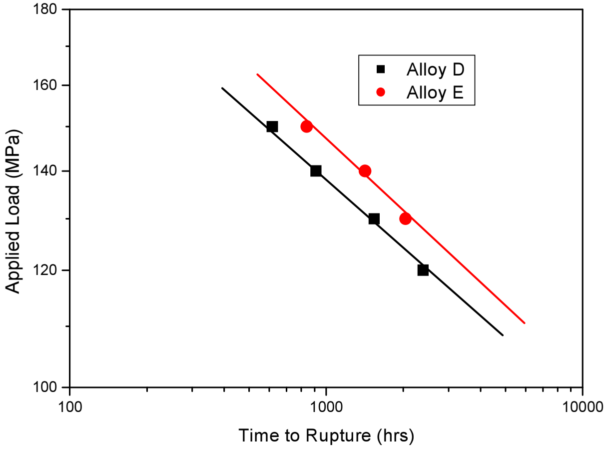
☐ Tensile test results

- Tensile test temperature : 650^oC
- V effect
  - Low V alloy : higher yield and tensile strengths
- C & N effect
  - Low C & high N alloy : higher yield and tensile strengths
- Ti of Zr effect
  - Zr addition : more effective in improving yield and tensile strengths

IV.2.2 Creep Properties



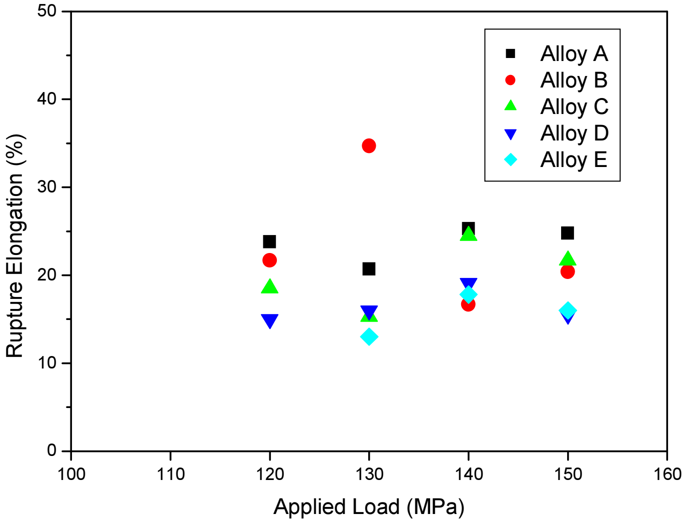




☐ Creep rupture test results

- Creep test temperature : 650^{o}C
- Applied stress : 120 ~ 150 MPa
- V effect
  - Low V alloy : higher creep rupture strength
  - Perform the creep test at low stress levels
- C & N effect
  - Low C & high N alloy : lower creep rupture strength
- Ti or Zr effect
  - Zr bearing alloy : higher creep rupture strength

IV.2.3 Creep Rupture Elongation



❑ Creep rupture elongation

- V effect
  - High V alloy : higher creep rupture elongation
- C & N effect
  - Low C & high N alloy : lower creep rupture elongation
- Ti or Zr effect
  - Similar creep rupture elongation
- Creep rupture elongation : 15 ~ 25%, not changed with applied load

V

Evaluation of Fabrication Process

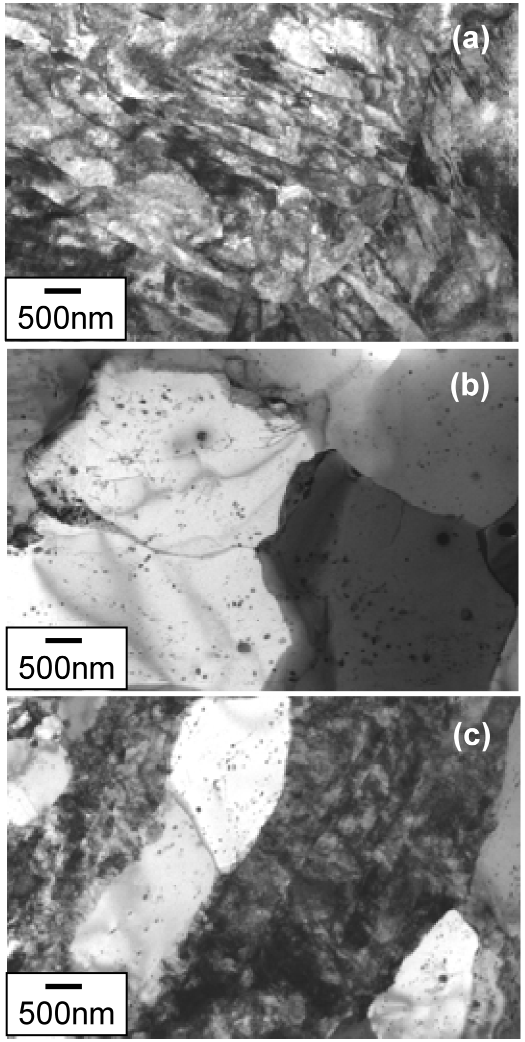
V.1 Microstructure

V.2 Mechanical Properties

V.1.1 Microstructure - Matrix

❑ Matrix microstructure

- Mother plate
  - Normalized at 1050^{o}C for 1 hour
  - Tempered at 550^{o}C for 2 hours
  - Typical tempered martensite structure
  - Lath width : 200 nm
- One time cold rolling
  - Reduction ratio : 75%
  - Tempered at 750^{o}C for 30 min
  - Fully recrystallized ferritic structure
  - Excess strain energy stored through cold rolling
  - Average grain size : 3 um
- Three times cold rolling
  - Reduction ratio : 33-44%
  - Tempered at 750^{o}C for 10 min
  - Recrystallized ferritic structure was observed.
  - Strain energy accumulated through first and second cold rolling : disappeared by intermediate heat treatment

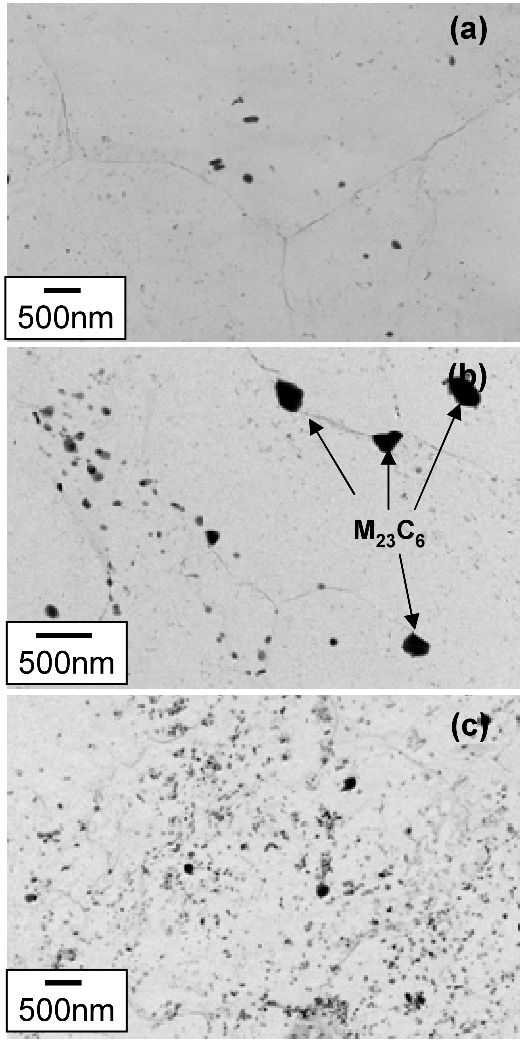


(a) Normalized
(b) One time cold rolling
(c) Three times cold rolling

V.1.2 Microstructure - Precipitates

❑ Precipitates microstructure

- Mother plate
  - $M_{23}C_6$ and V-rich MX fully dissolved
  - Tempering temperature was low enough to avoid the formation of $M_{23}C_6$ and V-rich MX
  - Nb-rich MX phase
  - 85Nb-9V-4Cr-2W (at%)
- One time cold rolling
  - Nb-rich MX phase : originally contained in the steel before cold rolling
  - $M_{23}C_6$ phase : 68Cr-25Fe-3Mo-4W (at%)
  - V-rich MX phase : 65V-12Nb-15Cr-8W
  - Size of V-rich MX : less than 100 nm
  - Size of $M_{23}C_6$: relatively large
- Three times cold rolling
  - Nb-rich MX, V-rich MX, $M_{23}C_6$ phase
  - Fine and uniform precipitates
  - High density of dislocations: provide favorable nucleation site for precipitates

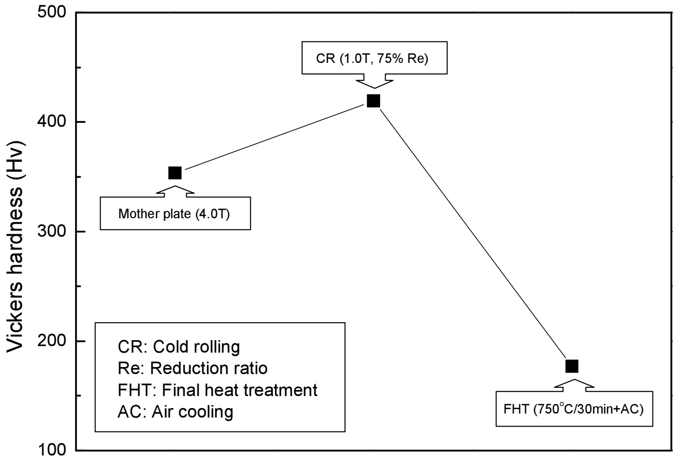


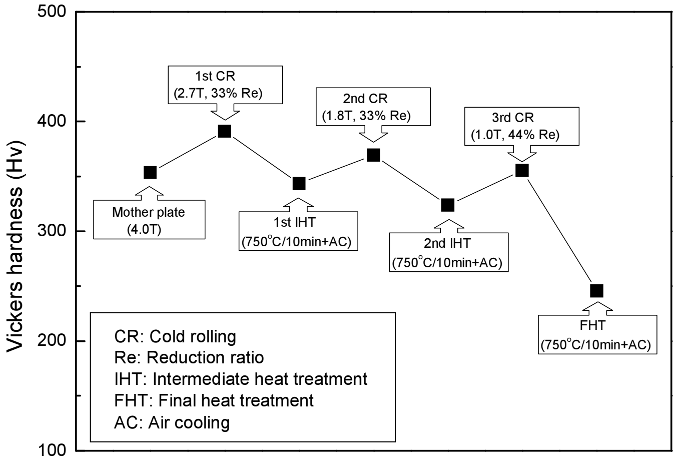
(a) Normalized
(b) One time cold rolling
(c) Three times cold rolling

V.2.1 Microhardness

❑ Microhardness test results

- Mother plate : 350 Hv
- One time cold rolling
  - Cold rolling : 419 Hv, heat treatment : 175 Hv
  - Significant softening : fully recrystallized grains
- Three times cold rolling
  - 1st cold rolling : 391 Hv, heat treatment : 344 Hv,
  - Heat treatment recovered mechanical properties degraded during cold rolling.
  - 2nd cold rolling : hardness increased, heat treatment : hardness decreased
  - Final cold rolling & heat treatment : 246 Hv
  - Formation and growth of recrystallized grains

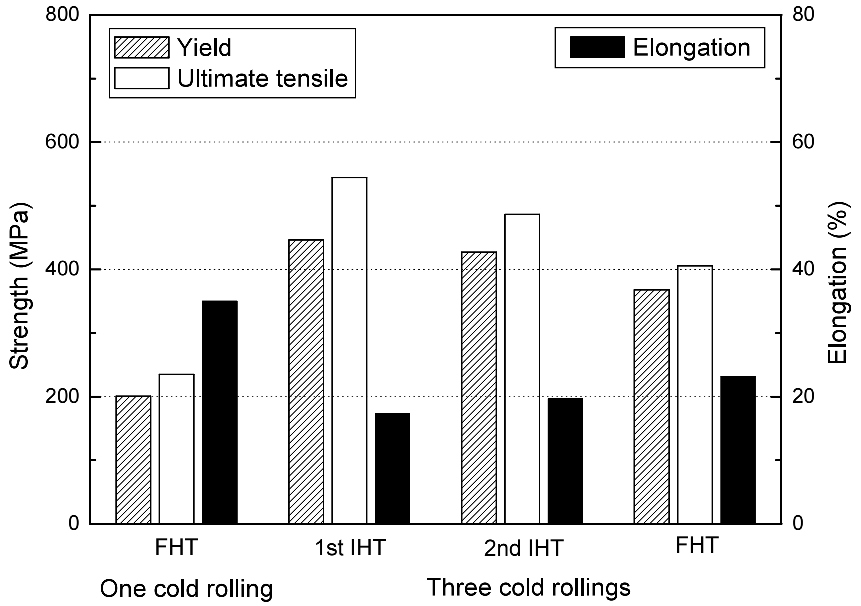




V.2.2 Tensile Properties

❑ Tensile test results

- Tensile test temperature : 650°C
- One time cold rolling
  - Yield, tensile strengths and elongation : 201 MPa, 235 MPa, and 35%
  - Fully recrystallized structure
- Three times cold rolling
  - First heat treatment : 446 MPa, 544 MPa, and 17%
  - Second heat treatment : yield and tensile strengths slightly reduced, elongation increased
  - Third heat treatment : 368 MPa, 405 MPa, and 23%
  - Partially recrystallized structure and finely distributed precipitates



Summary

☐ Alloy Design and Evaluation

- Increase of V concentration caused the increase of mass fraction of V-rich MX particles.
- The high V steel showed lower yield, tensile and creep rupture strengths.
- The high N and low C steel showed higher yield and tensile strengths, but revealed lower creep rupture strength than the low N and high C steel.
- The Zr addition was more effective than Ti addition in terms of yield, tensile and creep rupture strengths.

☐ Fabrication Process

- The 75% cold rolling and the final heat treatment led to a transition to a fully recrystallized structure with a formation of large inhomogeneous $M_{23}C_6$ carbides, resulting in a significant softening.
- However, three times cold rolling with an intermediate heat treatment after each cold rolling led to the formation of fine and uniform $M_{23}C_6$ carbides in a partially recrystallized structure, thus providing an enhanced tensile strength. These fabrication processes could be effective for fabricating a high strength ferritic/martensitic steels.