เอกสารประกอบการสอน

Physical Metallurgy III

(ALLOY STEELS)

PANYA BUAHOMBURA

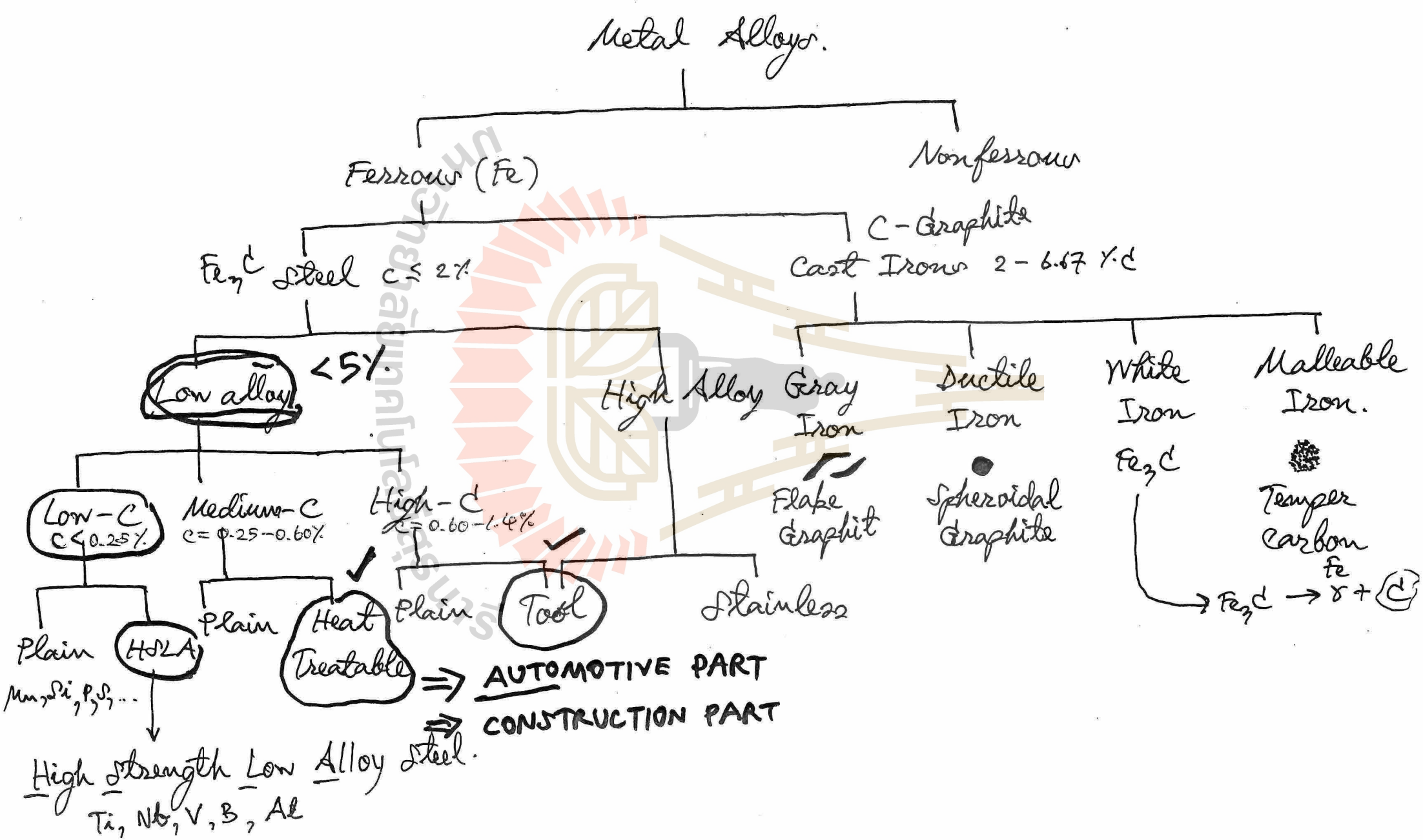
SCHOOL OF METALLURGICAL ENGINEERING

ALLOY STEELS.

PANYA BUAHOMBURA

S.U.T.

Classification scheme for the various ferrous alloys.



ALLOY STEELS.

① LIMITATIONS OF PLAIN-C STEELS.

- LOW HARDENABILITY (Depth & Distribution of Hardness)
- LOW CORROSION RESISTANCE
- SOFTENING WITH INCREASING TEMPERATUR
- NEED TO TEMPERED TO REDUCE INTERNAL STRESS OF HARDENED STEEL

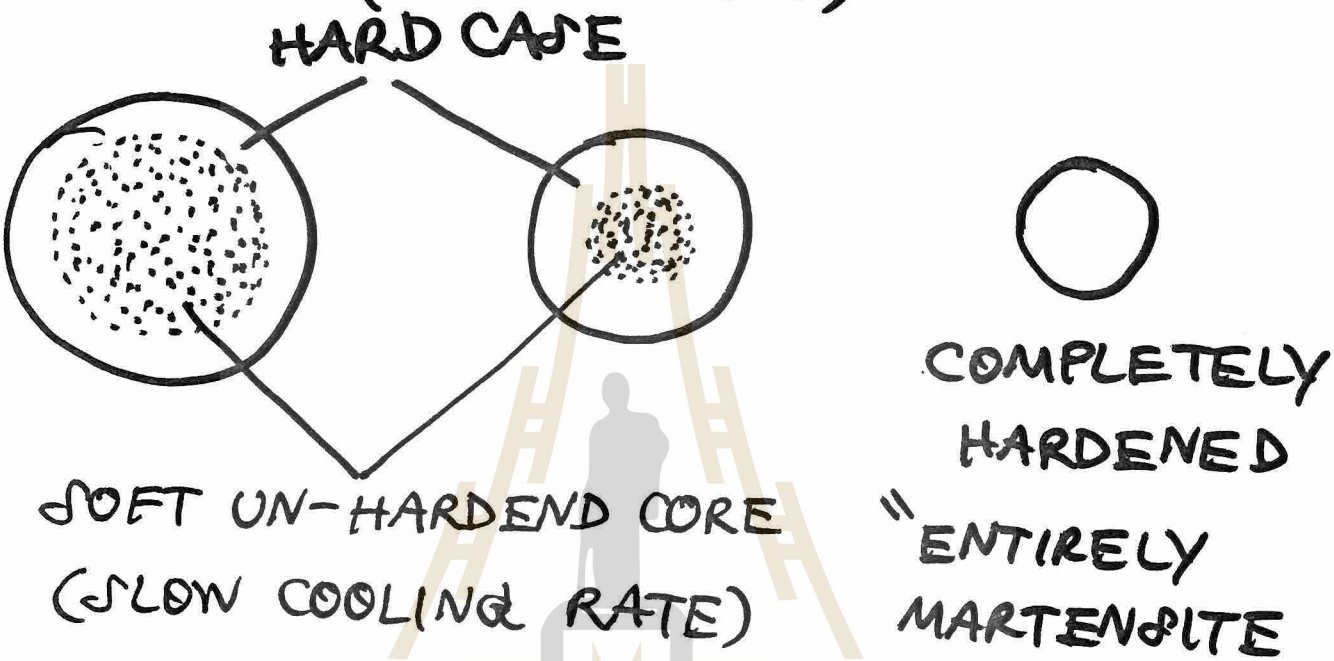
→ NEED TO ALLOYING FOR IMPROVING PROPERTIES.

⇩

"ALLOY STEELS."

● HARDENABILITY.

"PROPERTY WHICH DETERMINED THE DEPTH AND DISTRIBUTION OF HARDNESS INDUCED BY QUENCHING." (RAPID COOLED)



* INCREASE HARDENABILITY BY ADDING ALLOYING ELEMENT TO STEEL

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REDUCE CRITICAL RATES OF AUSTENITE TRANSFORMATION

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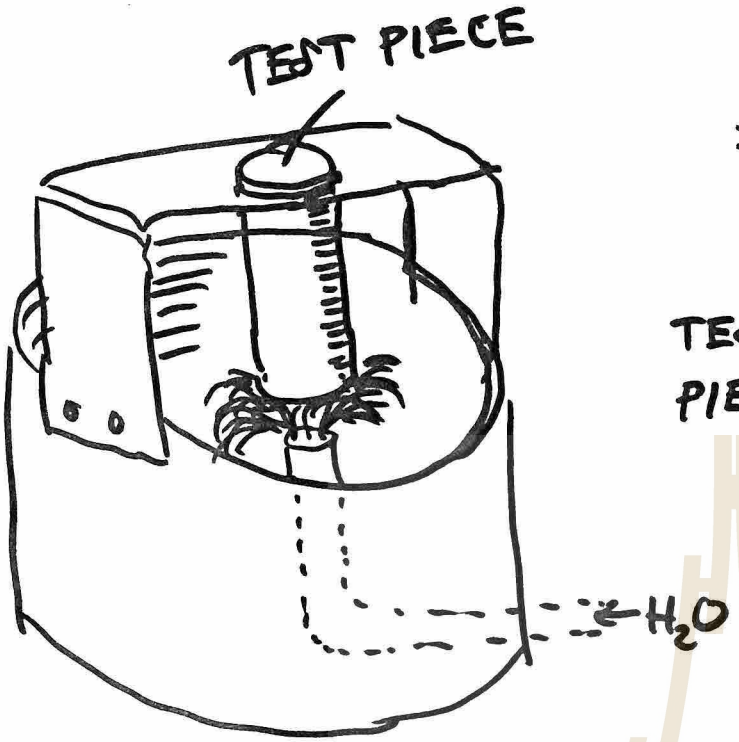
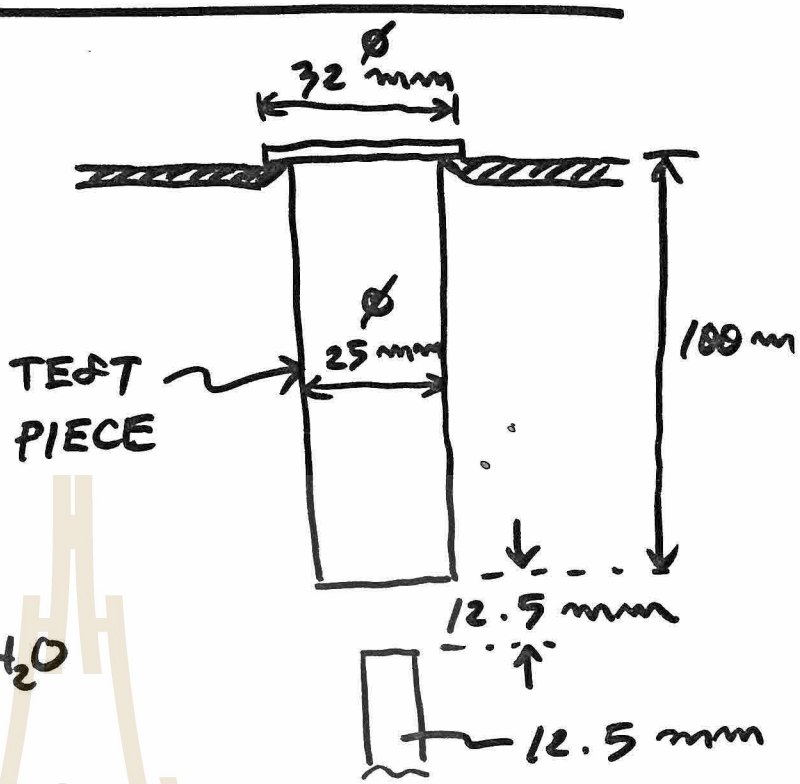
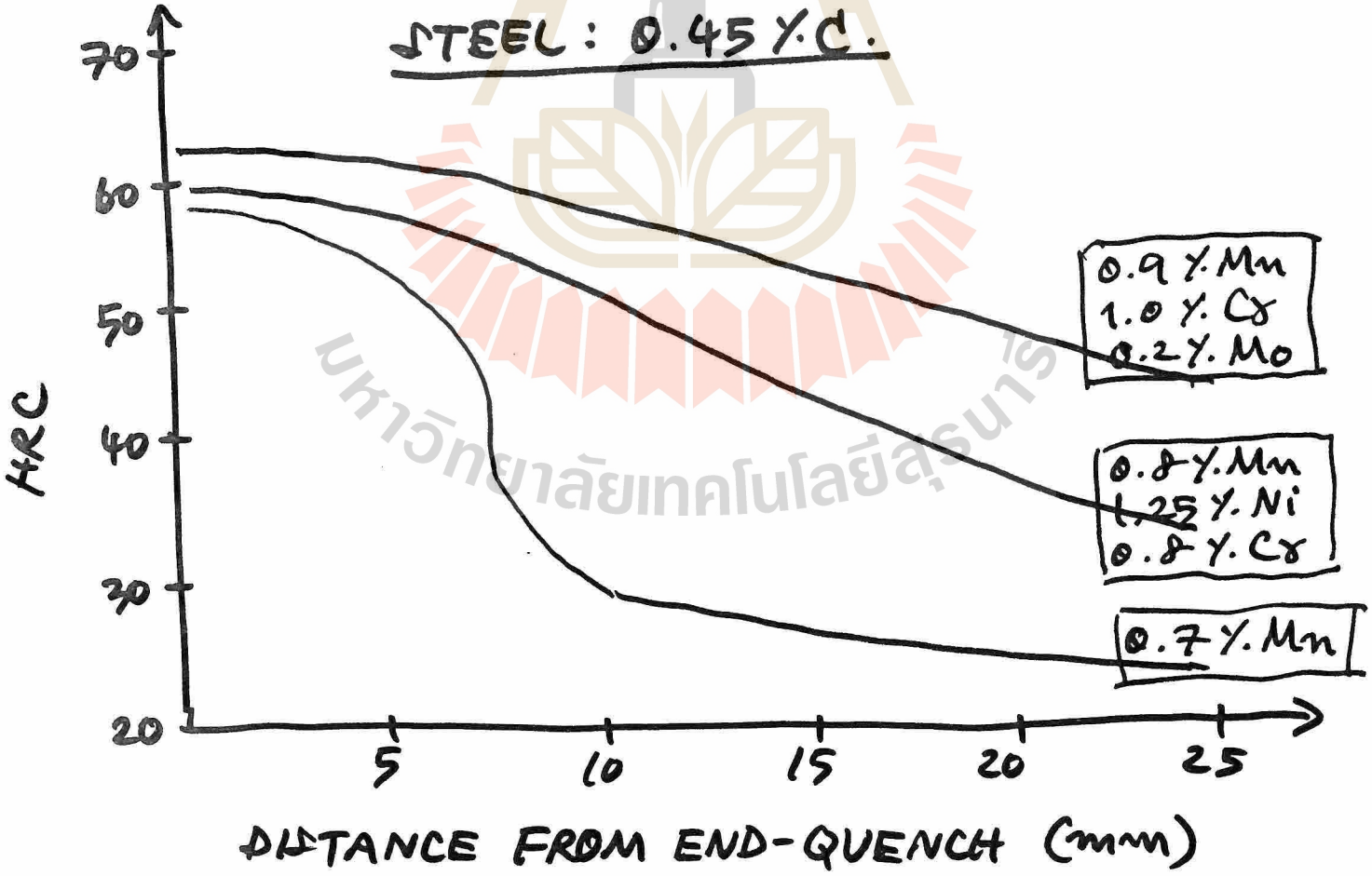
TO GET MATENSITIC STRUCTURE THROUGHOUT THICK SECTION EVEN LESS DRASTIC OIL OR AIR-QUENCHING

THE JOMINY END-QUENCH TEST.







PURPOSE OF ALLOYING.

(1.) INCREASE HARDENABILITY

(2.) IMPROVE STRENGTH AT R.T.

(3.) IMPROVE MECHANICAL PROPERTIES AT HIGH OR LOW TEMPERATURES

(4.) IMPROVE TOUGHNESS AT ANY MINIMUM HARDNESS OR STRENGTH

(5.) INCREASE WEAR RESISTANCE

(6.) INCREASE CORROSION RESISTANCE

(7.) IMPROVE MAGNETIC PROPERTIES

TWO GROUPS OF ALLOYING ELEMENTS IN CONSTITUENTS OF ANNEALED STEEL :—

<u>GROUP 1:</u> DISSOLVE IN α-FERRITE

<u>GROUP 2:</u> COMBINE WITH C TO FORM SIMPLE OR COMPLEX CARBIDES.

ALLOYING ELEMENT	GROUP ① DISSOLVED IN α	GROUP ② COMBINED IN CARBIDE
NICKEL	Ni	
SILICON	Si	
ALUMINUM	Al	
COPPER	Cu	
MANGANESE	Mn ⟷	Mn
CHROMIUM	Cr ⟷	Cr
TUNGSTEN	W ⟷	W
MOLYBDENUM	Mo ⟷	Mo
VANADIUM	V ⟷	V
TITANIUM	Ti ⟷	Ti

EFFECT OF ALLOYING ELEMENTS UPON α.

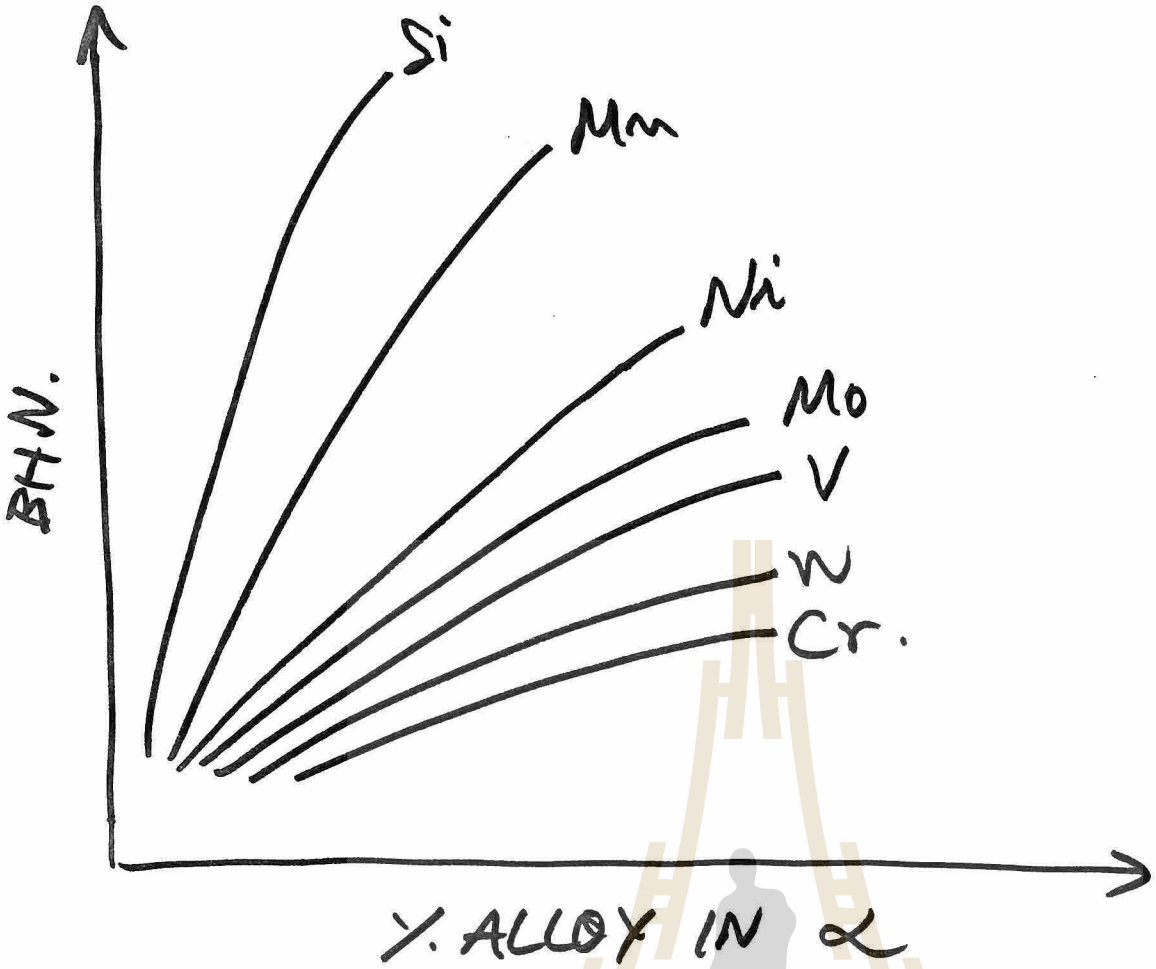
ANY ELEMENT DISSOLVED IN α

↙ IN CREASE STRENGTH

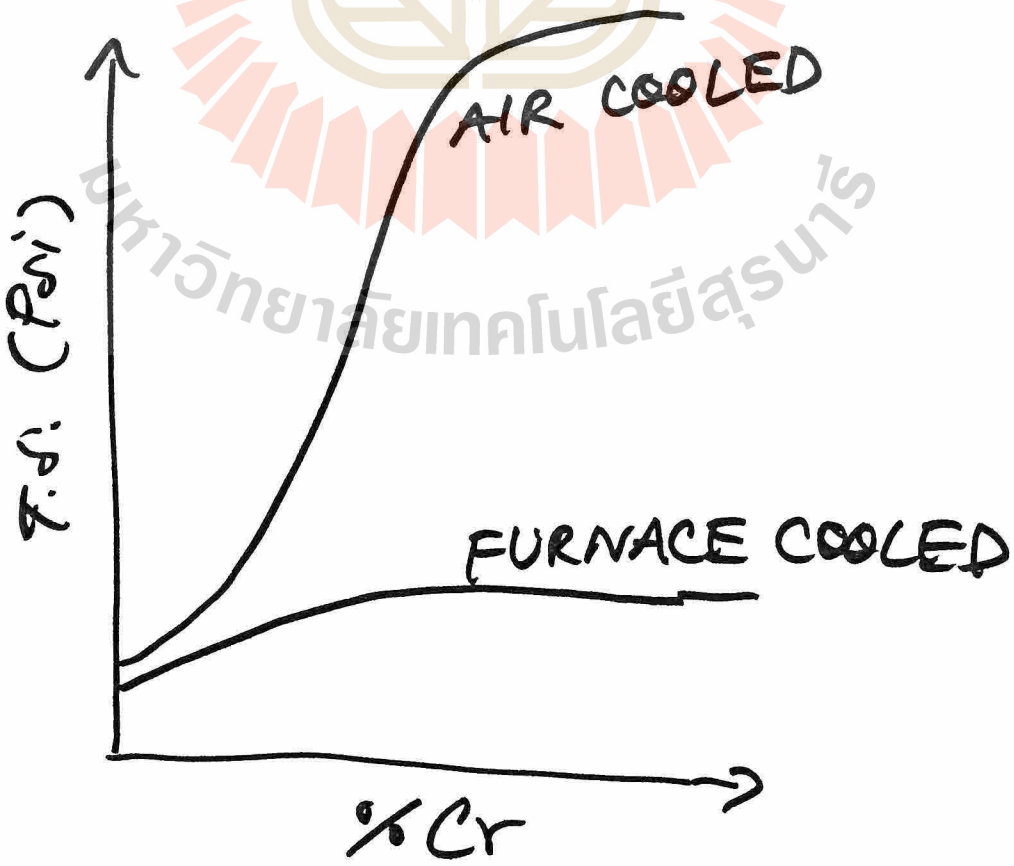
↘ INCREASE HARDNESS

BY SOLID SOLUTION STRENGTHENING

Q1: EXPLAIN HOW ALLOYING ELEMENTS THAT DISSOLVED IN α INCREASING ITS STRENGTH.



LOW-C CHROMIUM ALLOY.



EFFECT OF ALLOYING ELEMENTS UPON CARBID

CARBIDE ⇒ HARD & BRITTLE COMPOUND

e.g. Cr - CARBIDES, V - CARBIDES.

↑

HIGH HARDNESS & WEAR RESISTANCE

DEPEND ON :-

AMOUNT, SIZE & DISTRIBUTIONS.

INFLUENCES OF CARBIDE FORMING ELEMENT

↙ ↘

HARDENING TEMP. SOAKING TIME.

- COMPLEX CARBIDES.
  - DIFFICULT TO DISSOLVE IN γ
  - TEND TO OUT OF γ-SOLUTION

⇓

LOWER CARBON & ALLOY CONTENT

⇓

REDUCE HARDENABILITY.

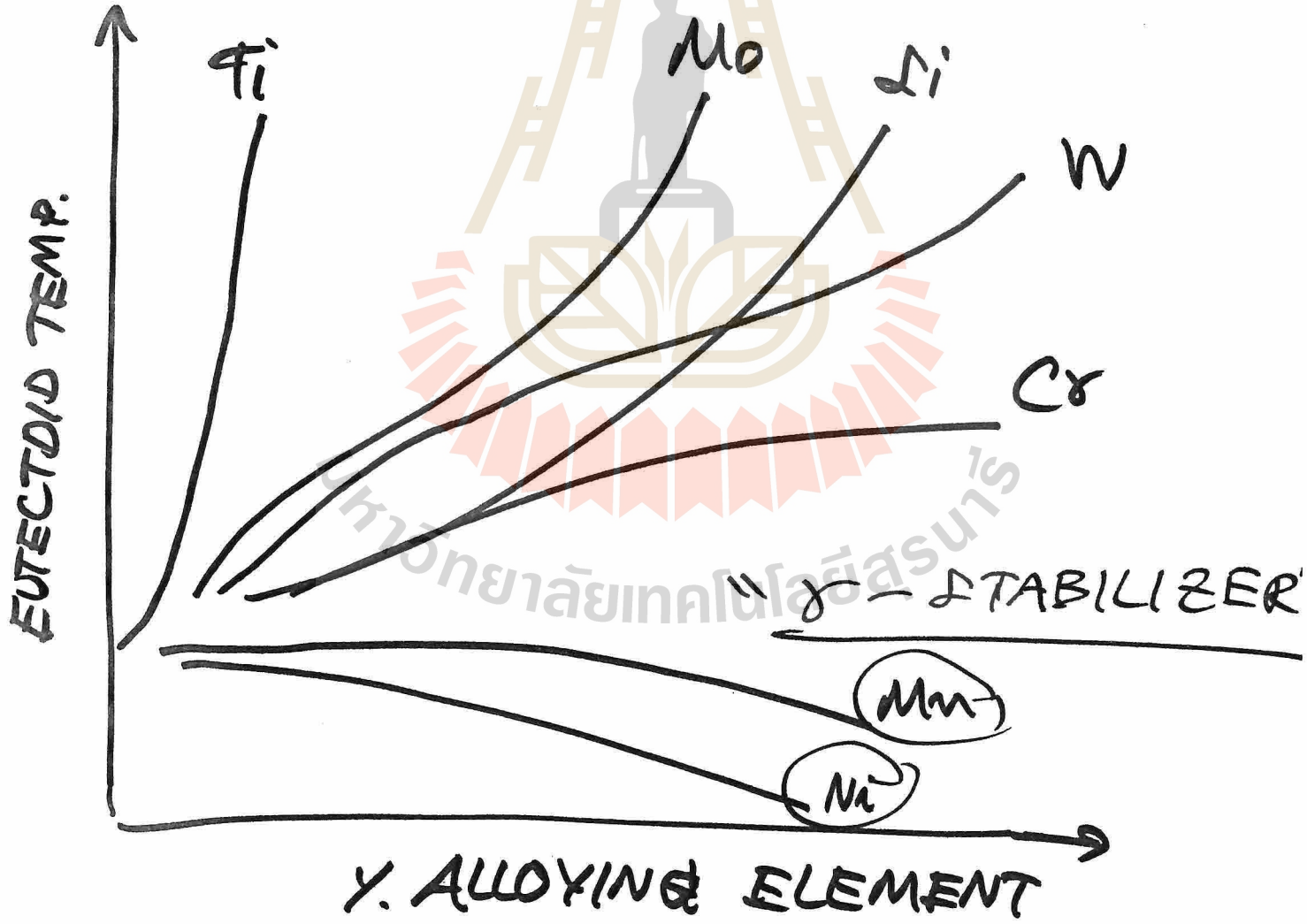
- UNDISSOLVED CARBIDE ACT TO REDUCE GRAIN GROWTH.

- IF DISSOLVE IN γ ⇒ INCREASE HARDENABILITY

INFLUENCE OF ALLOYING ELEMENTS ON $Fe-Fe_3C$ DIAGRAM.

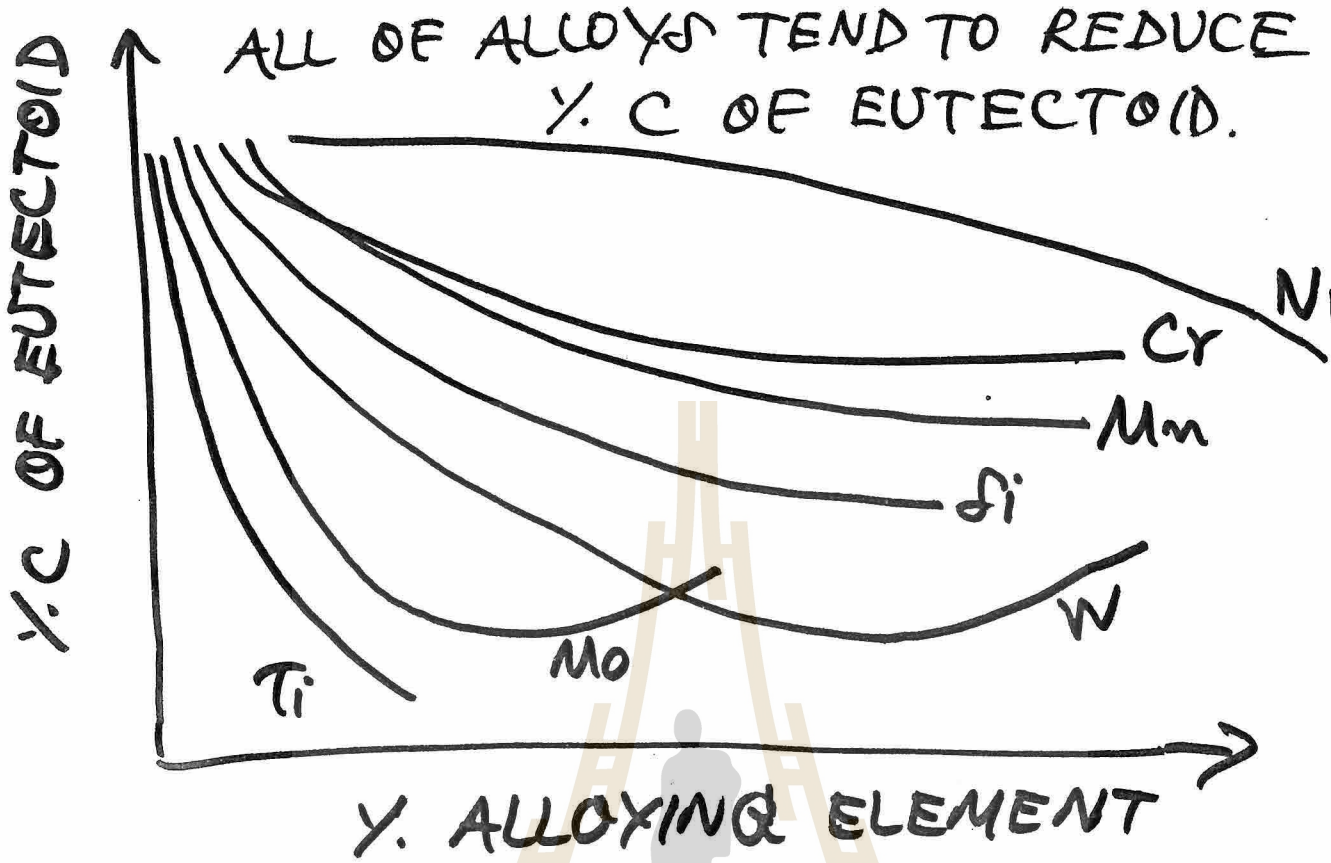
- CHANGING :—
  - CRITICAL RANGE
  - POSITION OF EUTECTOID POINT.
  - α AND γ FIELDS/AREAS

EFFECT ON EUTECTOID TEMPERATURE

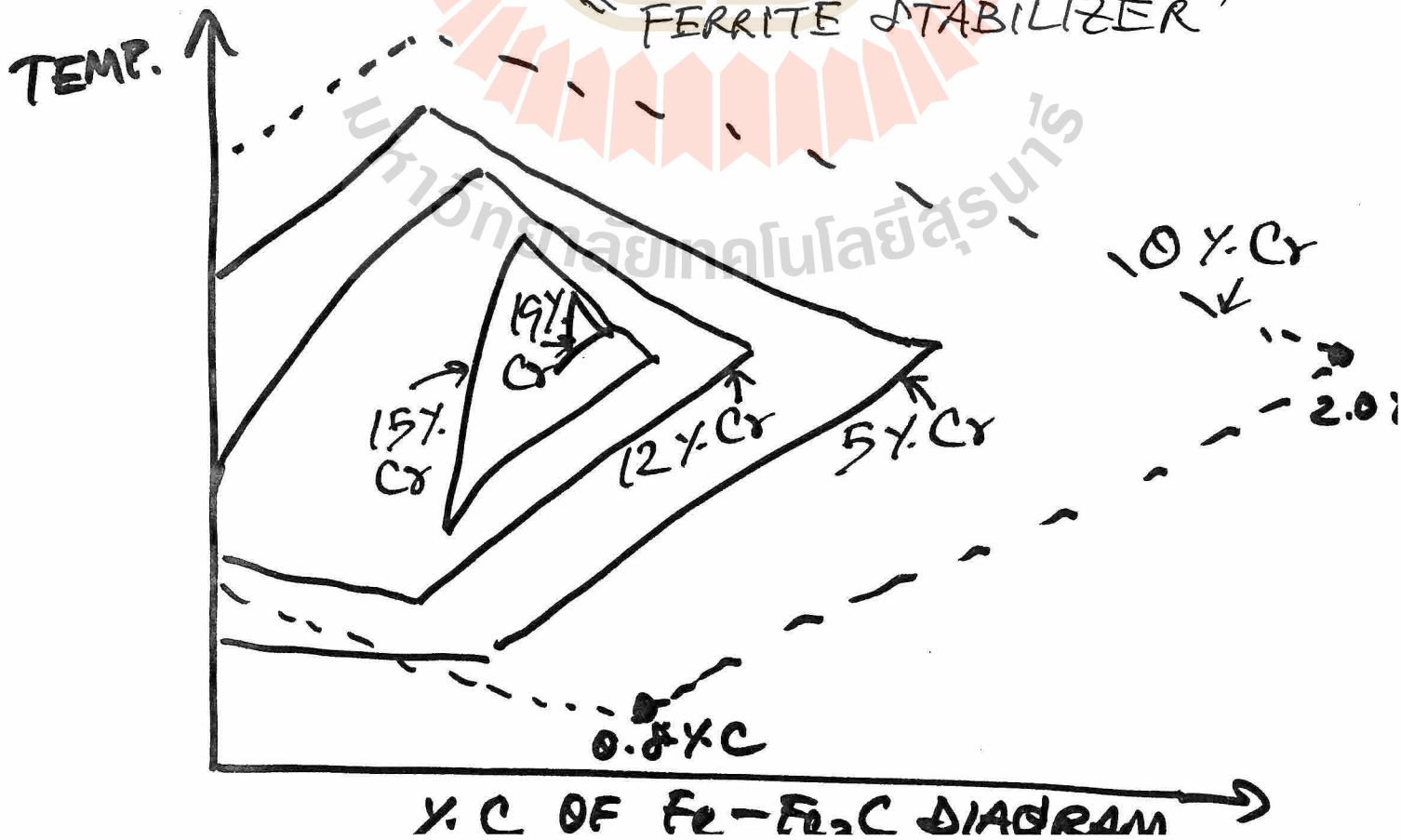


Mn & Ni LOWER EUTECTOID TEMP. & IF ARGE AMOUNT γ WILL BE RETAINED AT R.T..

EFFECT ON EUTECTOID COMPOSITIONS.

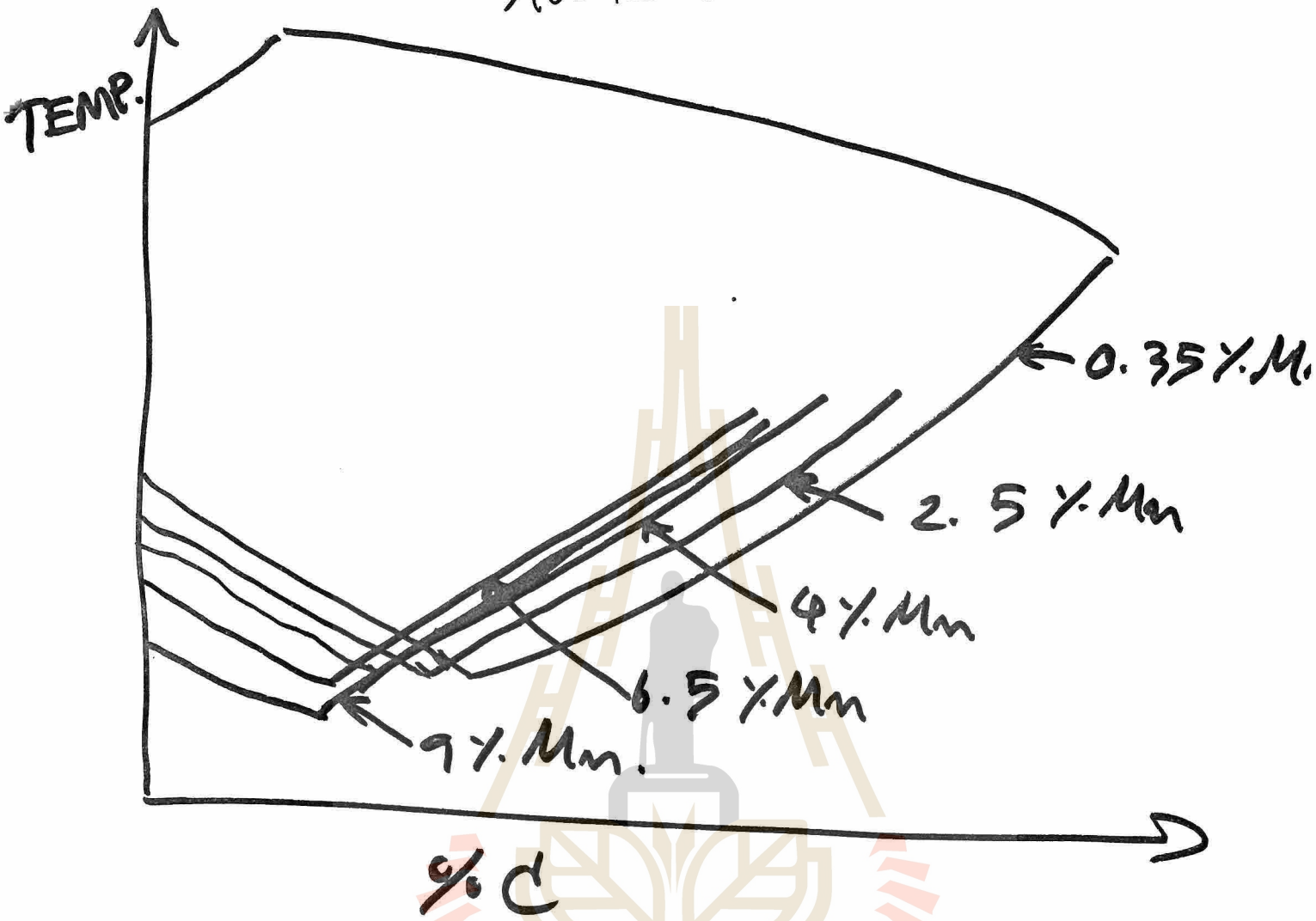


Mo, Cr, Si, Ti ⇒ REDUCE γ-FIELDS
BUT ENLARGE α AND δ-FIELDS.
"FERRITE STABILIZER"



Mn, Ni ⇒ ENLARGE γ-REGION.

"AUSTENITE STABILIZER"



EFFECT OF ALLOYING ELEMENTS IN TEMPERING

"TEMPERING" ⟹ SHOWN THAT HARDENED STEELS ARE SOFTENED BY REHEATING.

TEMPERING TEMP. ↑ ↓ HARDNESS.

<u>ALLOYS</u>. → RETARD SOFTENING RATE
→ HIGHER TEMPERING TEMP.
→ GIVEN HARDNESS

(i) ELEMENTS DISSOLVE IN FERRITE

Ni, Si, Mn

↓

LITTLE EFFECT ON HARDNESS OF TEMPERED STEEL

(ii) CARBIDE FORMING ELEMENTS

Cr, W, Mo, V

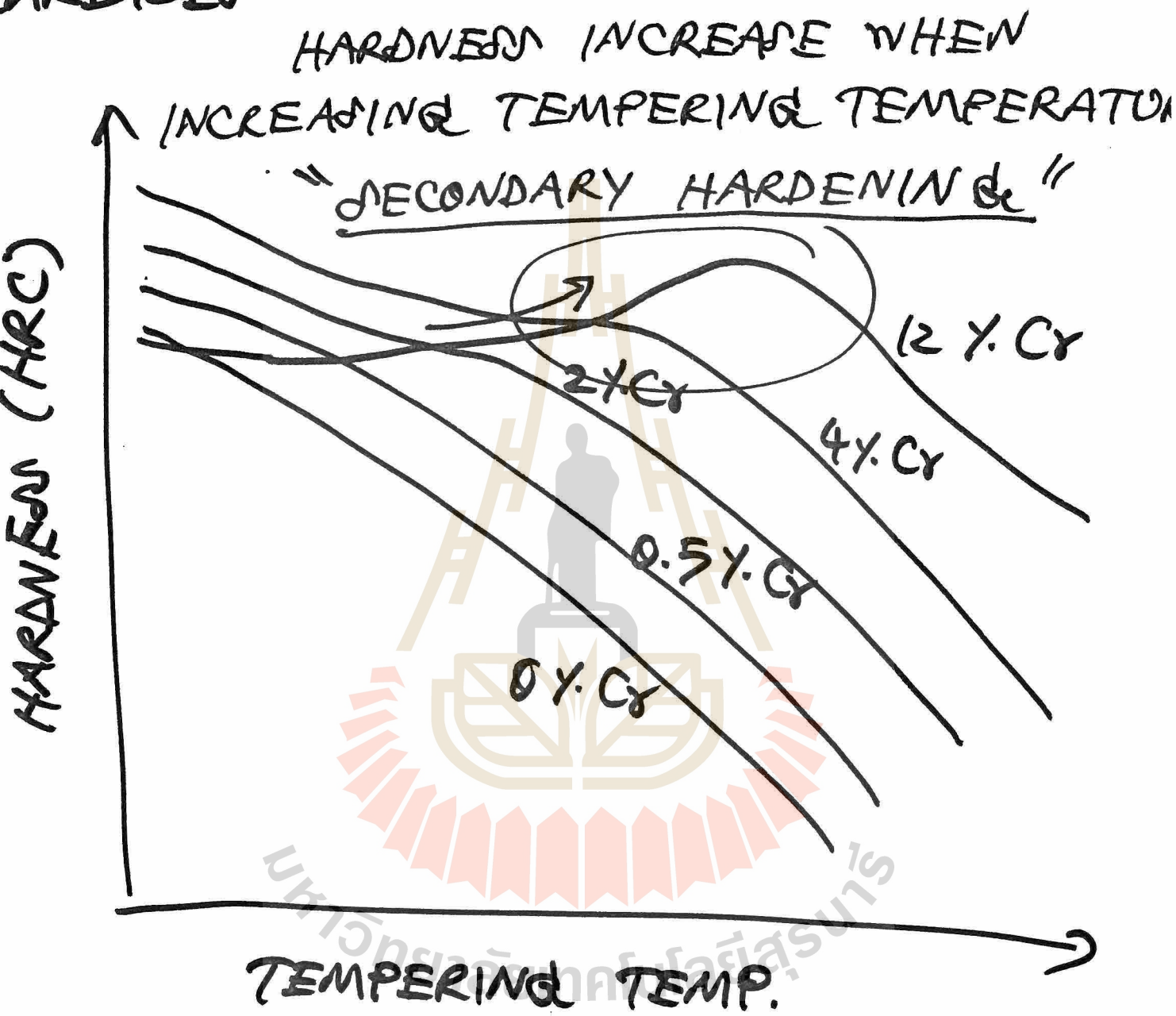
↓

LARGE EFFECT ON RETARDATION OF SOFTENING

⇓

IF LARGE AMOUNT ⟹ SHOW A RANGE WHICH HARDNESS INCREASE WITH INCREASING TEMPERING TEMPERATURE, KNOWN AS "<u>SECONDARY HARDNESS</u>"

SECONDARY HARDENING OCCUR DUE TO DELAYED PRECIPITATION OF FINE ALLOY CARBIDES



CLASSIFICATION OF ALLOY STEELS.

AISI 13XX (Mn-STEEL), Mn = 1.6-1.9 %.

AISI 23XX (3% Ni-STEEL), Ni = 3.25-3.75 %.

AISI 25XX (5% Ni-STEEL), Ni = 4.75-5.25 %.

AISI 31XX (Ni-Cr STEEL), Ni = 1.1-1.4 %.
Cr = 0.55-0.75 %.

AISI 40XX (Mo-STEEL), Mo = 0.2-0.3 %.

AISI 41XX (Cr-Mo STEEL), Cr = 0.8-1.1 %.
Mo = 0.15-0.25 %.

AISI 43XX (Ni-Cr-Mo STEEL), Ni = 1.65-2.00 %.
Cr = 0.4-0.9 %.
Mo = 0.2-0.3 %.

AISI 46XX (Ni-Mo STEEL), Ni = 0.7-2.0 %.
Mo = 0.15-0.30 %.

AISI 51XX (Cr-STEEL), Cr = 0.7-1.6 %.

AISI 61XX (Cr-V STEEL), Cr = 0.5-0.7 %.
V = 0.12-0.15 %.

AISI 86XX, 87XX, 88XX } LOW Ni-Cr-Mo STEEL, Ni = 0.4-0.7 %.
Cr = 0.4-0.6 %.
Mo = 0.15-0.30 %

* E = E.A.F. FURNACE , B = B.O.H. FURNACE .

AISI 92XX (Si-STEEL), Si = 1.80-2.20 %.

AISI E93XX (98XX) } HIGHER Ni-Cr-Mo STEEL , Ni = 3.0-3.5 %. (0.85-1.15 %)

Cr = 1.0-1.4 %. (0.7-0.9 %)

Mo = 0.08-0.15 %. (0.2-0.3 %)

AISI 94B30 (B-STEEL), SAME AS 98XX BUT ADDED BORON.

◉ Ni - STEEL (2XXX)

- Ni IS UNLIMITED SOLUBILITY IN γ-IRON AND HIGH SOLUBLE IN FERRITE (STRENGTH & TOUGHNESS THIS PHASE)
- Ni LOWER CRITICAL TEMP. & WIDEN THE TEMPERATURE RANGE FOR HEAT TREATMENT (WIDEN γ-AREA)
- RETARDS THE DECOMPOSITION OF γ
- DOES NOT FORM CARBIDES
- REDUCE %C OF EUTECTOID POINT.

★ UNHARDENED Ni-STEELS CONTAINS HIGHER % PEARLITE (THAN PLAIN C-STEEL

⇓

PEARLITE FORM AT LOW TEMP.

⇓

FINER PEALITE STRUCTURE & TOUGHER

⇓

INCREASE TOUGHNESS, PLASTICITY AND FATIGUE RESISTANCE

Ni-STEEL ⇒ SUITED FOR HIGH-STRENGT STRUCTURAL STEELS

↙ AS ROLLED ↘ LARGE FORGING

(BY DO NOT ADAPTED TO QUENCHING)

- 23XX (3% Ni) USED FOR :-
  - CARBURIZING OF DRIVE GEARS
  - CONNECTING-ROD BOLTS
  - STUDS
  - KINGPINS
- 25XX (5% Ni) ⇒ INCREASE TOUGHNESS
  - HEAVY-DUTY APPLICATIONS SUCH AS BUS & TRUCK GEARS, CAMS, CRANKSHAFT.

* 2XXX LARGELY REPLACED IN MANY APPLICATIONS BY LOWER-COST OF 86XX SERIES.

Cr - STEELS (5XXX)

- Cr FORM SIMPLE CARBIDES AS
  - → Cr_7C_3
  - → Cr_4C

  OR COMPLEX CARBIDES AS
  - → $(Fe,Cr)_3C$
- HIGH HARDNESS & GOOD WEAR RESISTANC
- Cr SOLUBLE UPTO 13% IN γ AND UNLIMITED SOLUBILITY IN α - FERRITE
- Cr > 5 % ⇒ HIGH TEMP. PROPERTIES AND CORROSION RESISTANCE

5XXX: C = 0.15 - 0.64%, Cr = 0.7 - 1.15%

i) 5XXX LOW CARBON
- USUALLY CARBURIZED

ii) 5XXX MEDIUM CARBON (OIL-HARDENING)
- SPRINGS, ENGINE BOLTS, STUDS, AXLE.

iii) 52100 (HIGH C & Cr), 1% C & 1.5% Cr
- HIGH HARDNESS & WEAR RESISTANCE
- BALL & ROLLER BEARING
- CRUSHING MACHINERY

- SPECIAL TYPE : 1 % C & 2-4 % Cr
  - EXCELLENT MAGNETIC PROPERTIES AS PERMANENT MAGNETS
- HIGH - Cr STEEL (Cr > 10 %)
  - HIGH CORROSION RESISTANCE (STAINLESS STEEL)

<u>Q2.</u>: WHAT EFFECT WOULD THE ADDITION OF 1 % Cr HAVE ON THE PROPERTIES OF A LOW C-STEEL ? AND A HIGH C-STEEL ?

TEMPERING.

HARDENED STEEL (QUENCHED STEEL)

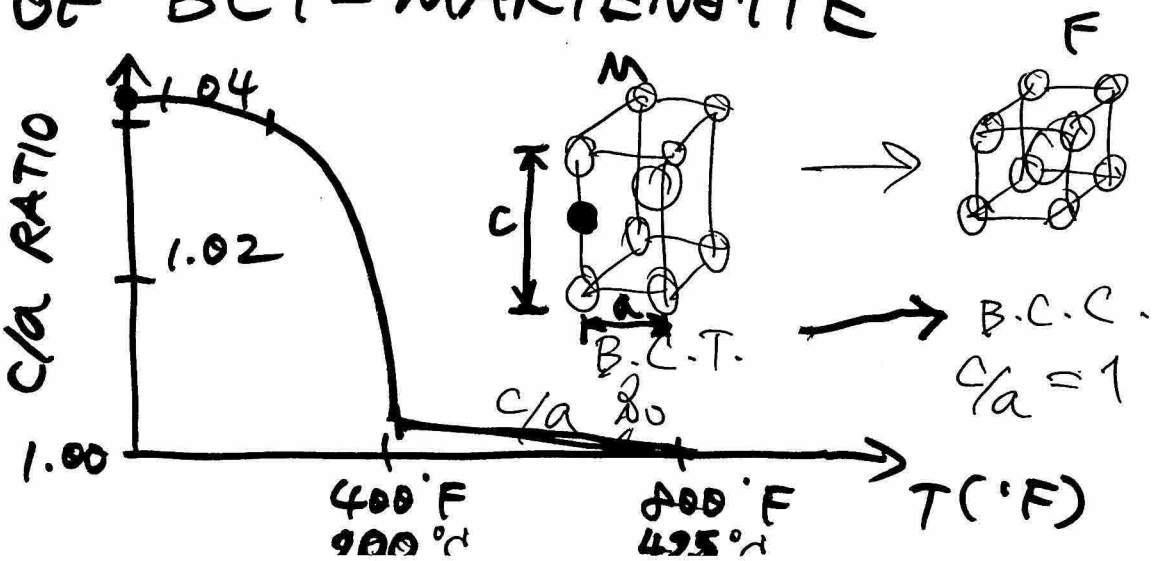
⇓

"MARTENSITE STRUCTURE"

HARD & BRITTLE, HAVE RESIDUAL STRESS, LOW DUCTILITY, CAN CAUSE DISTORTION & CRAC

TEMPERING;

- HEAT TO $T < A_1$
- MARTENSITE (B.C.T.) $\longrightarrow$ $\alpha + Fe_3C$ (SOFTER PHASE)
- RELIEVED STRESS
- INCREASE TOUGHNESS & DUCTILITY ↑
- STRENGTH & HARDNESS ↓
- REDUCE THE LATTICE DISTORTION OF BCT-MARTENSITE



STRUCTURE CHANGES DURING TEMPERING OF MARTENSITE (> 0.3 %C) HAVE 3 STAGES.

(1.) **1st STAGE:** T ~ 100 °C

MARTENSITE ⟶ LOW-C MARTENSITE (0.25%)

+

FINE-DISPERSED ε-CARBIDE (Fe_5C_2 ; MORE C THAN Fe_3C)

- TRANSFORMATION PROCEED SLOWLY
- SLIGHTLY INCREASE HARDNESS
- SLIGHTLY REDUCE BRITTLENESS

(2.) **2nd STAGE:** T ~ 250 °C

- MARTENSITE "NEEDLES" FORMED "TROOSTITE"
- RETAINED-γ ⟶ BAINITE
- SLIGHTLY INCREASE IN HARDNESS (DUE TO γ ⟶ HARDER BAINITE)

<3.> 3rd STAGE : ~ 350 °C ↑

AT 350 °C : ε-CARBIDE (Fe_5C_2) ⟶ CEMENTITE (Fe_3C)

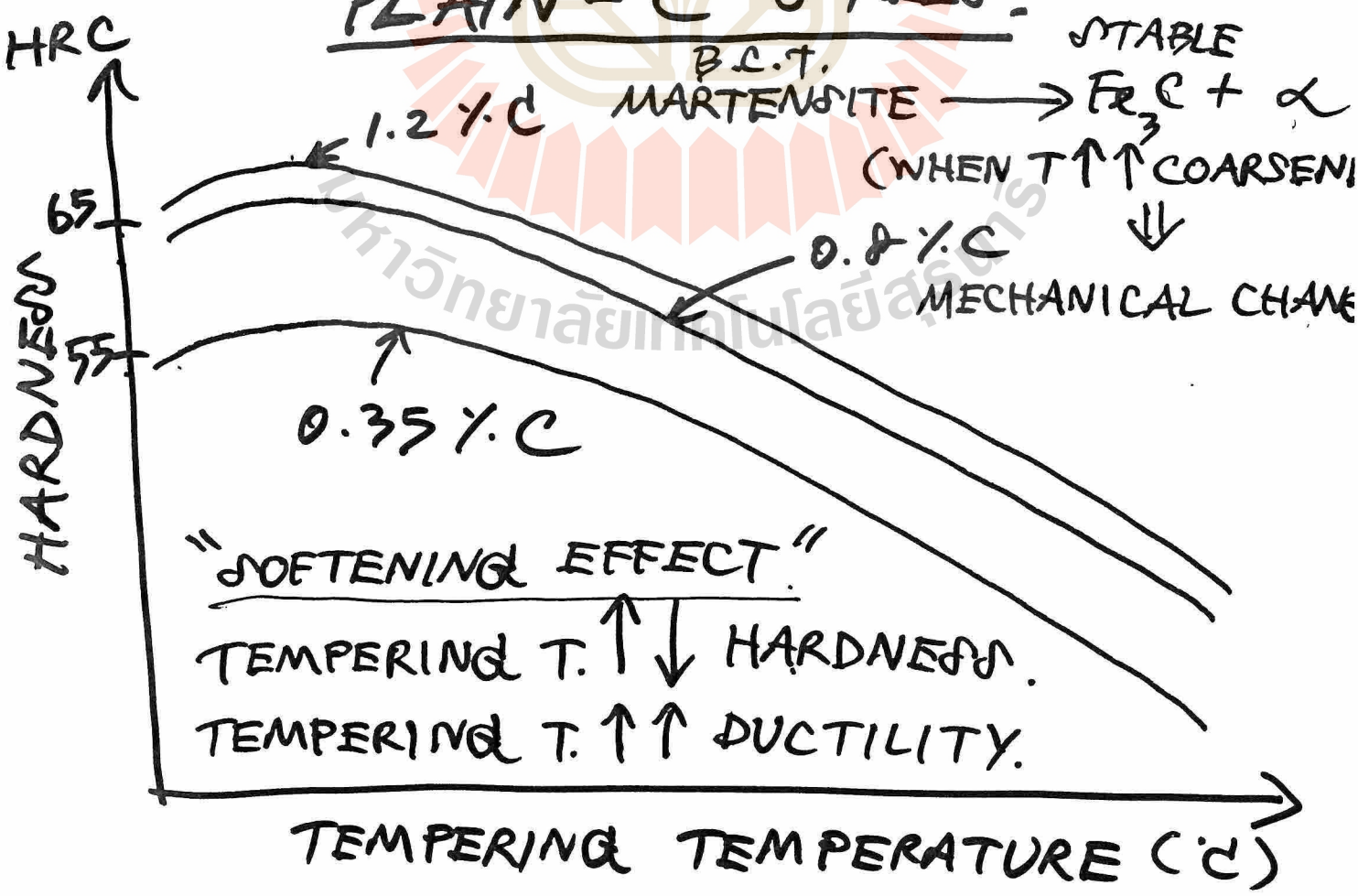
MARTENSITE (B.C.T.) —ต่อยู่ เป็นต้น→ Fe_3C + α-FERRITE (B.C.C.)

AT T > 500 °C :

PLATE-Fe_3C ⟶ "SORBITE" ROUNDED-Fe_3C IN α-MATRIX

— MORE DUCTILE BUT HARDNESS DECREASE

PLAIN-C STEES.



AUSTENITE-TO-MARTENSITE TRANSFORMATION OF EUTECTOID (0.8%C) STEEL.

AUSTENITIZING (γ-PHASE)

↓ QUENCHING

MARTENSITE
≈ 64 HRC

↓ TEMPERING

200°C
UPTO 400°F

ε-CARBIDE
+
LOW-C MARTENSITE
(≈ 60-64 HRC)

200°C-400°C
400-750°F

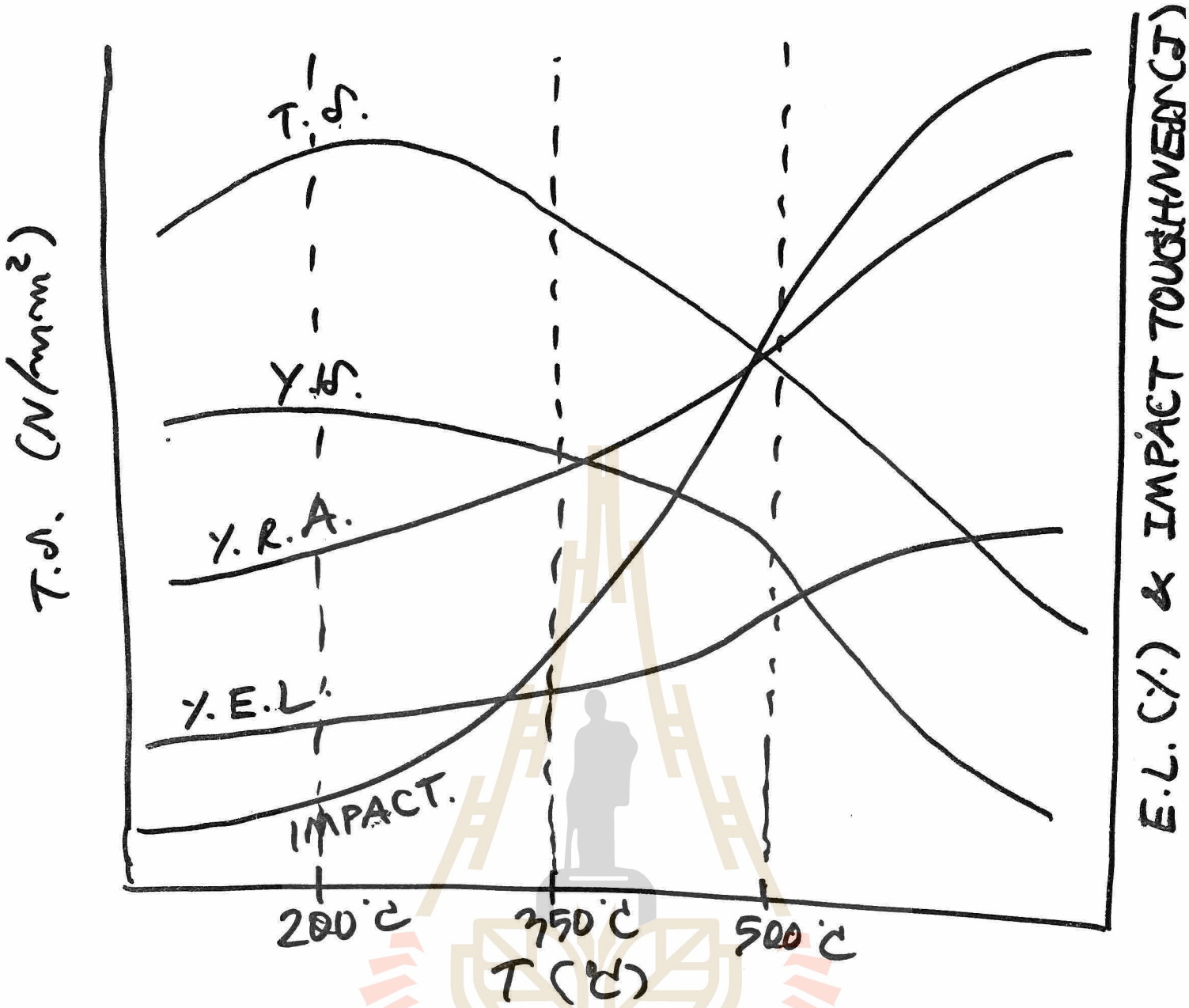
↓

TROOSTITE
(≈ 40-60 HRC)

400-650°C
750-1,200°F

→ SORBITE
(≈ 20-40 HRC)

"TEMPERED MARTENSITE".

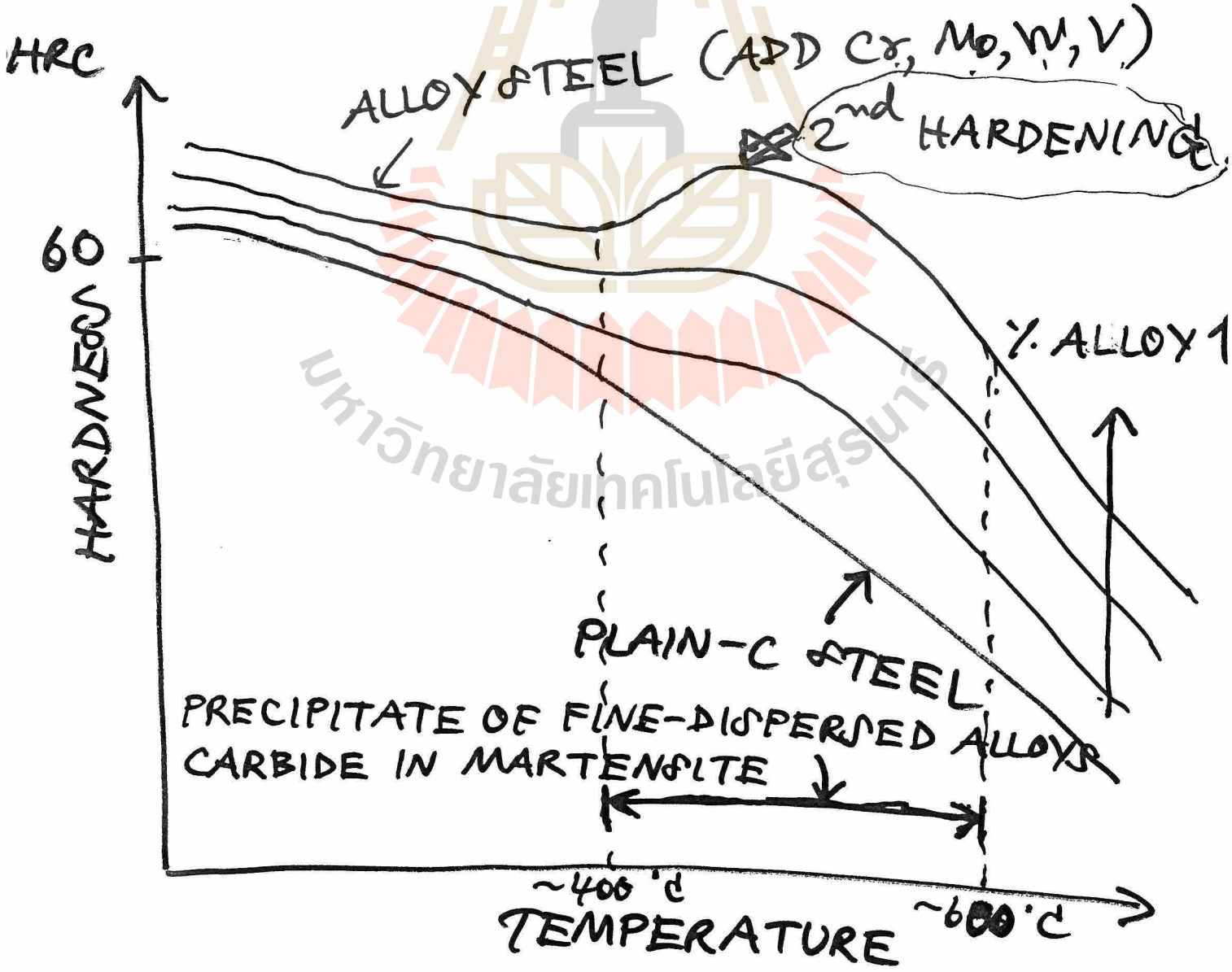


PLAIN-C STEEL (0.5%C, 0.7%Mn)
Ø 25 mm, WATER QUENCHED FROM
830 °C.

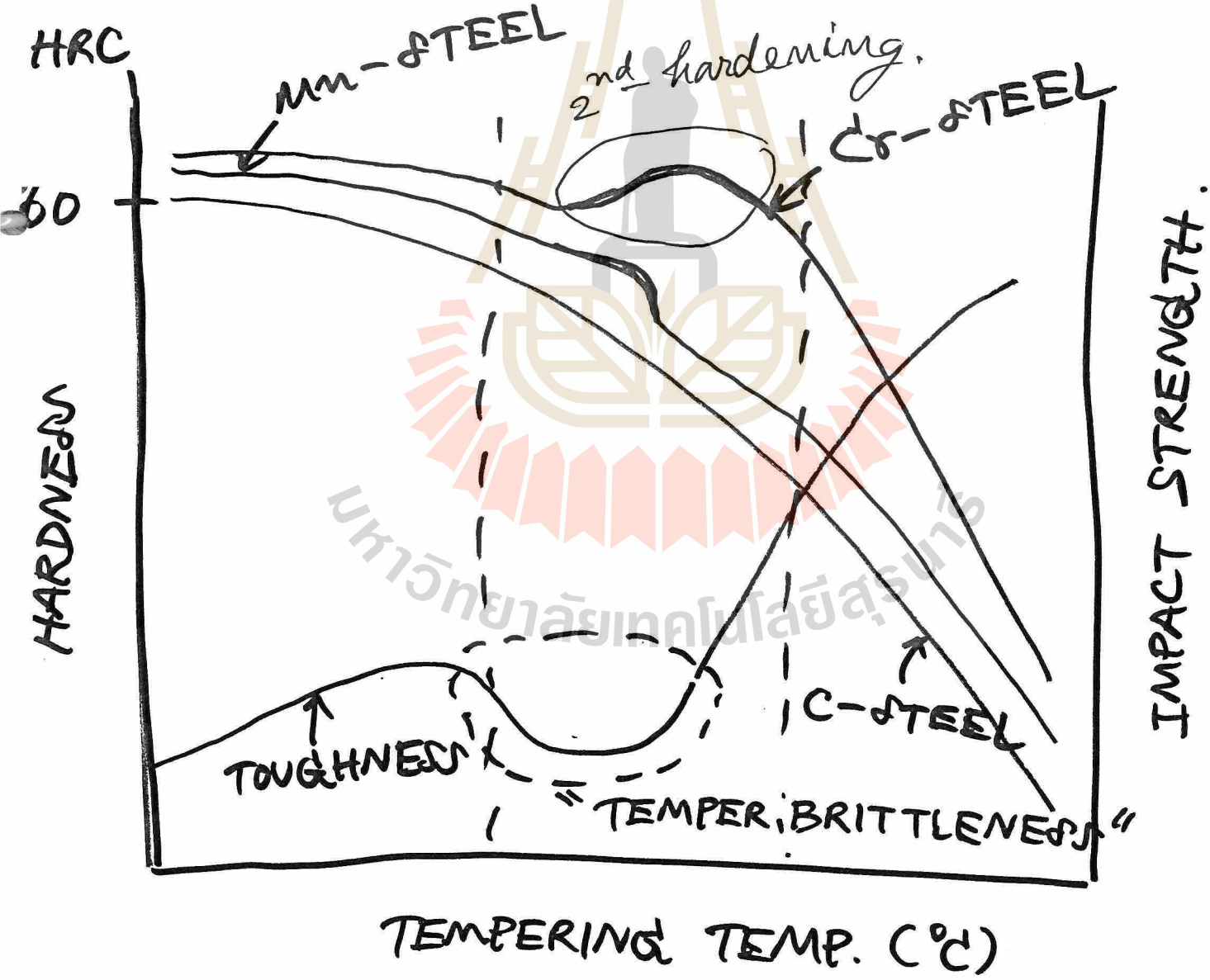
EFFECT OF ALLOYS ON TEMPERING.

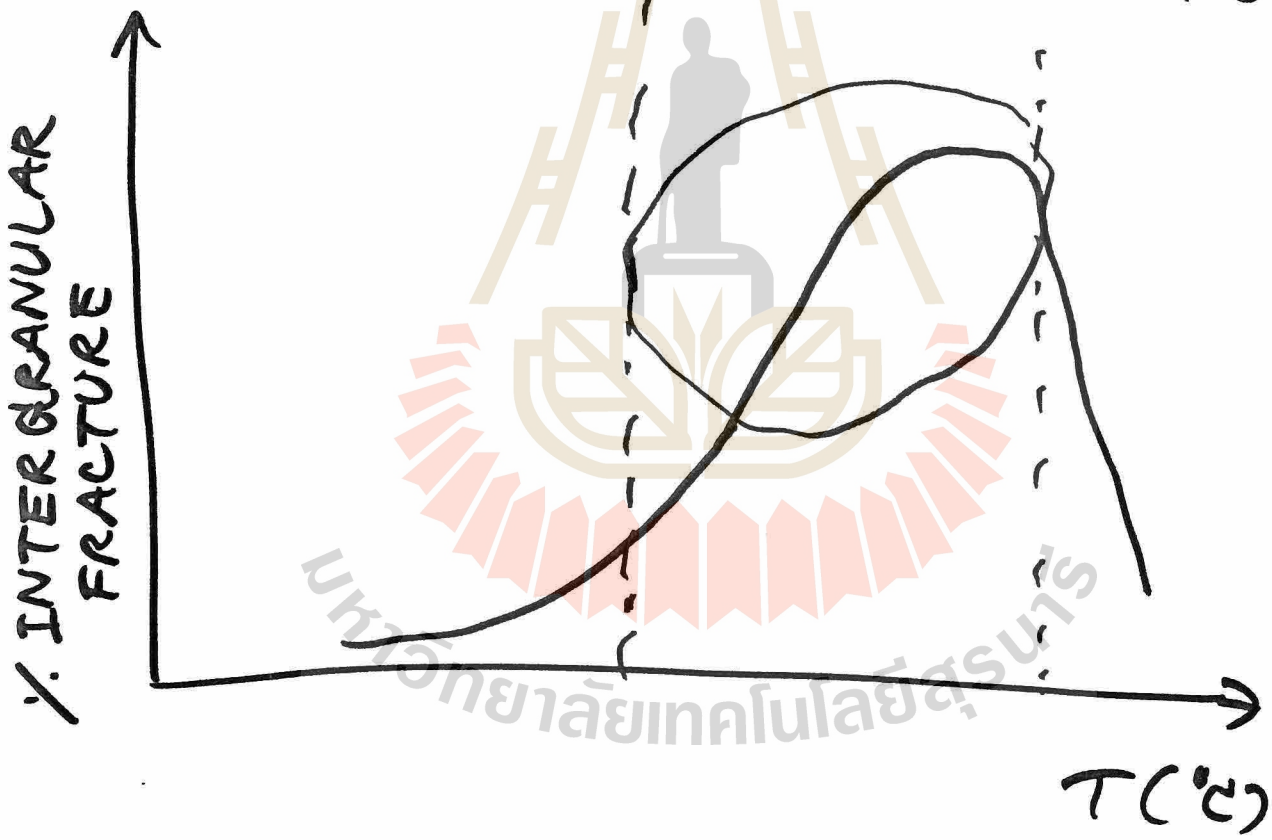
ADD Cr, Mo, W, V (STABLE CARBIDE STABILIZER)

- RESIST TO SOFTENING EFFECT
- IF LARGE AMOUNT → RE-HARDENING EFFECT (INCREASING IN HARDNESS) ON TEMPERING KNOWN AS "SECONDARY HARDENING" AT T ≈ 400 – 600 °C (500 – 650 °C)



FOR ALLOY, WHICH HIGH %Mn, %Cr & %P SUSCEPTIBILITY TO "TEMPER BRITTLENESS" ON TEMPERING IN RANGE OF 2nd HARDENING DUE TO PRECIPITATE & SEGREGATE OF CARBIDE ALONG GRAIN BOUNDARY DURING SLOW COOLING ⇒ DECREASE TOUGHNESS





TEMPER BRITTLENESS

⇓

CAUSE TO INTERGRANULAR CRACK

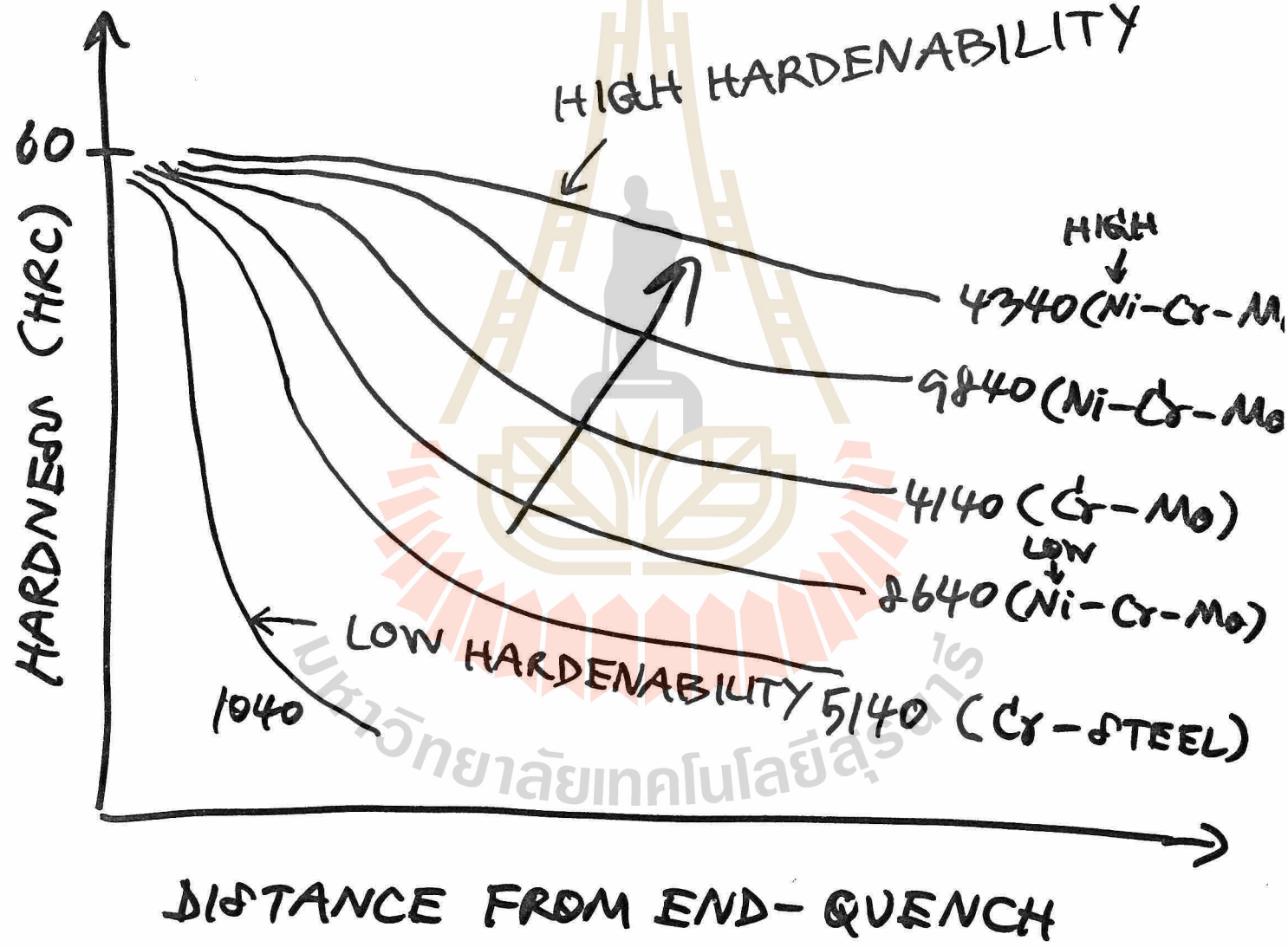
(BRITTLE FRACTURE)

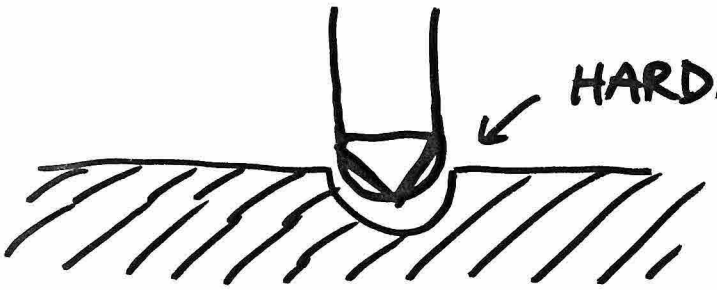
LOW TOUGHNESS.

HARDENABILITY (NOT HARDNESS)

⇓

"PROPERTY WHICH DETERMINED THE DEPT & DISTRIBUTION OF HARDNESS INDUCED BY QUENCHING FROM AUSTENITE"

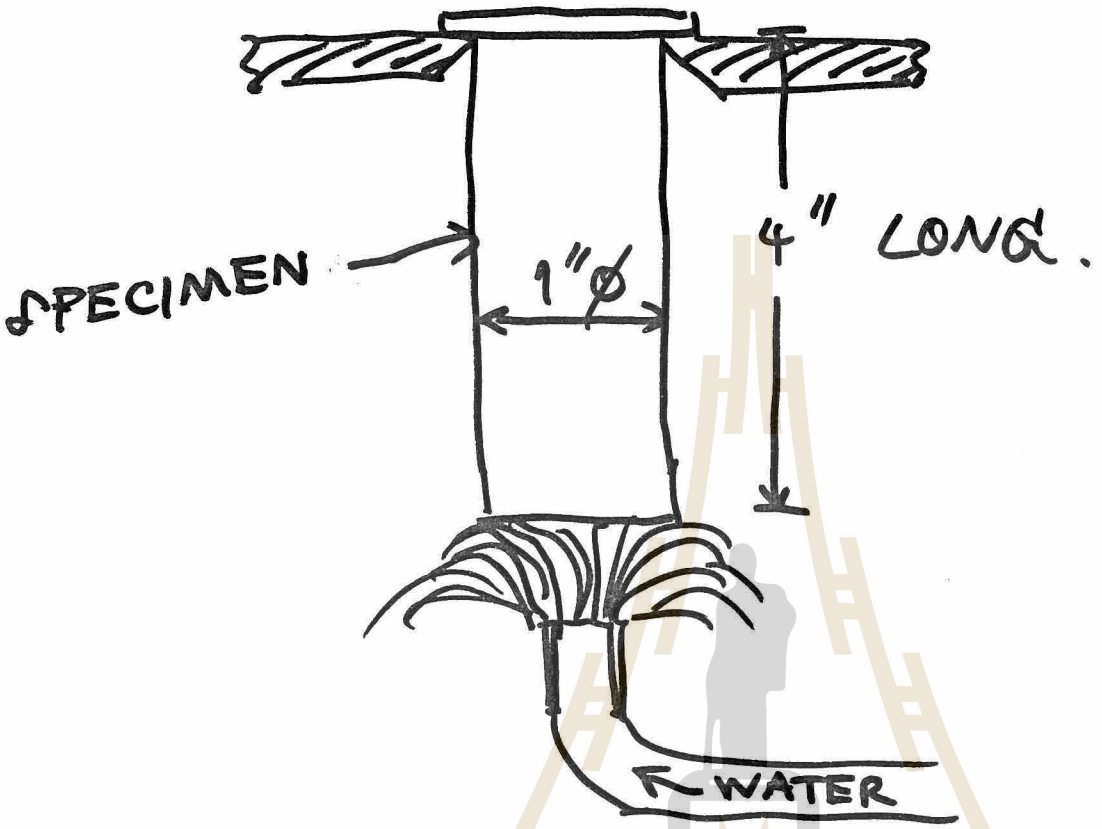


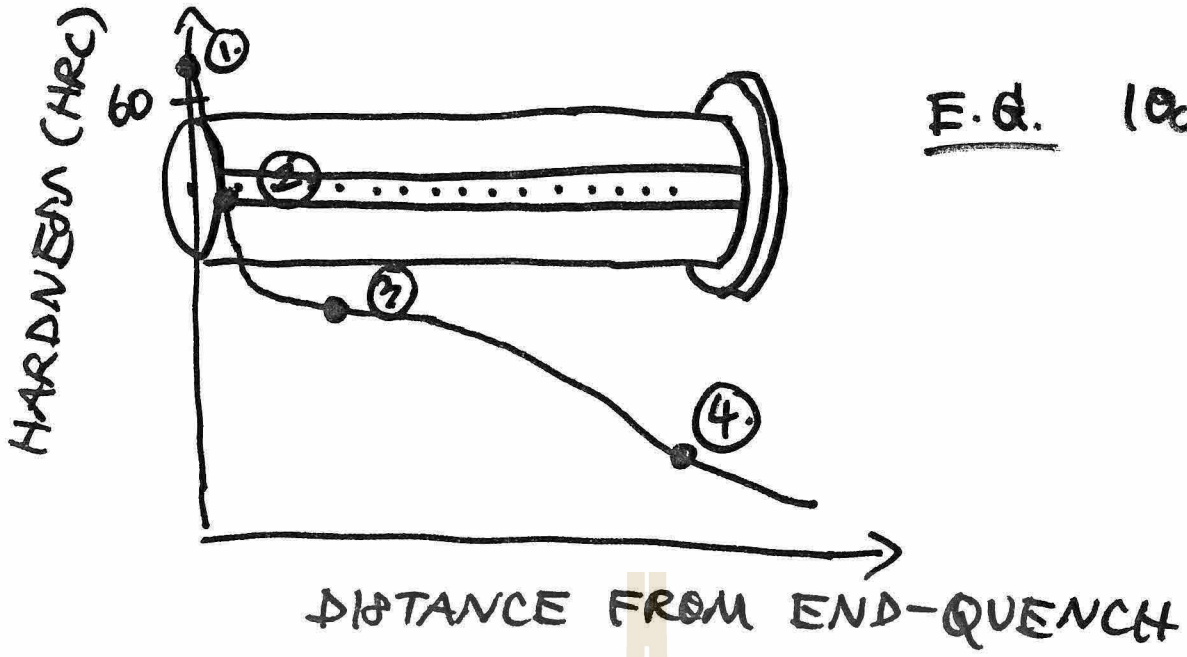


HARDNESS (RESISTANCE TO INDENTATION.)

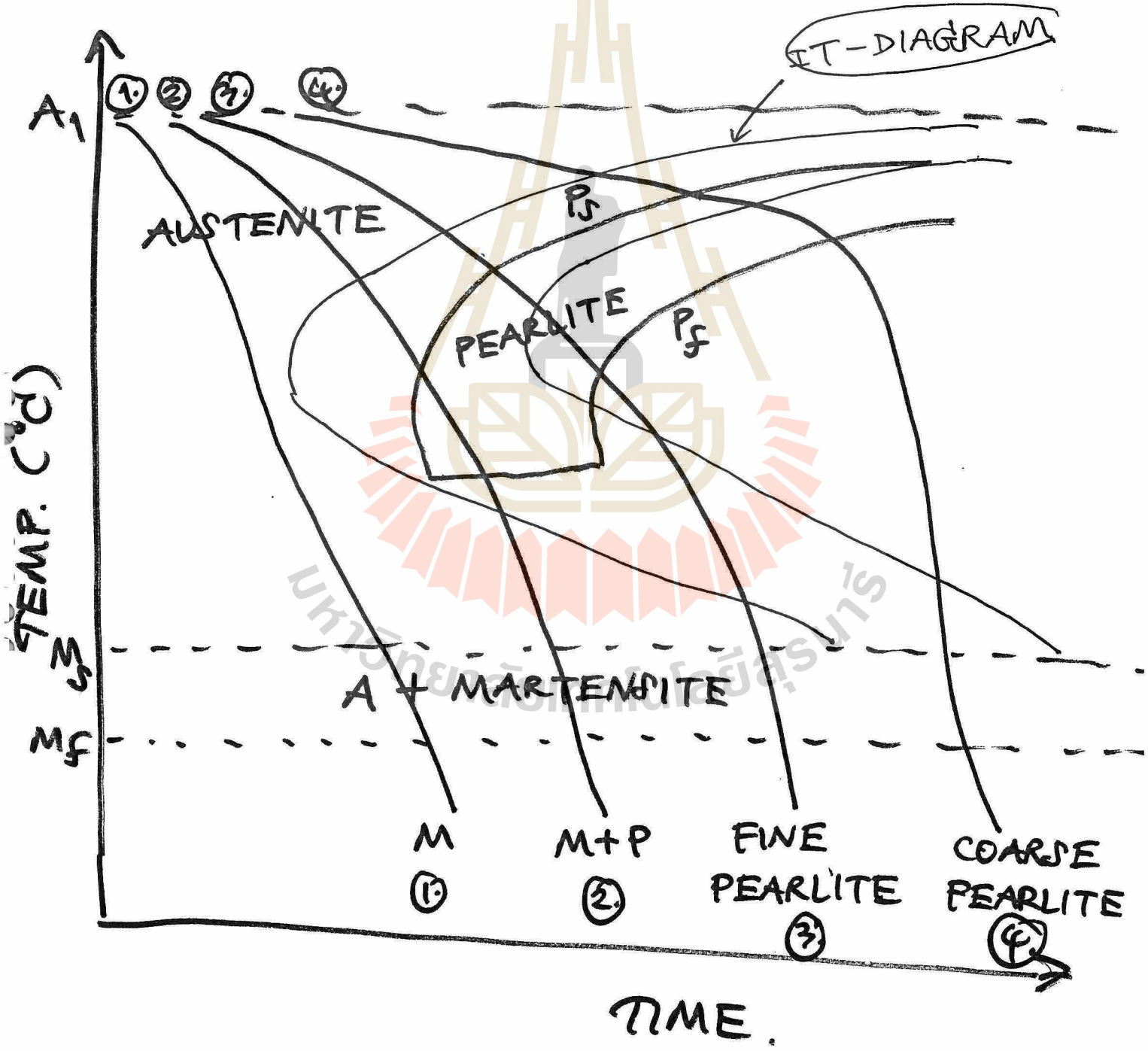
DETERMINATION OF HARDENABILITY

" BY JOMINY END-QUENCH METHOD "





E.G. 1080-STEEL



CCT-CURVE.

HARDENABILITY DEPEND ON :—

→ CHEMICAL COMPOSITION

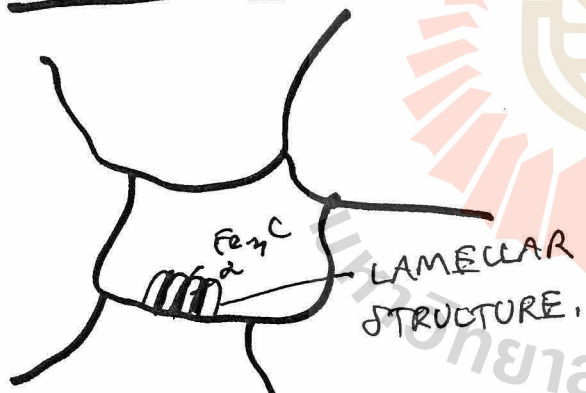
→ AUSTENITE GRAIN SIZE

→ STRUCTURE OF STEEL BEFORE QUENCHING

(1.) AUSTENITE GRAIN SIZE.

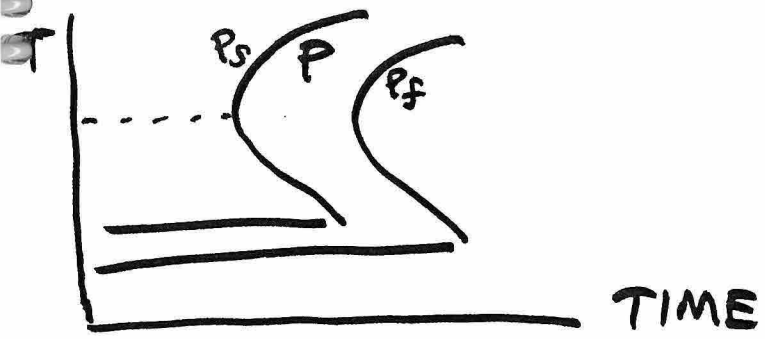
EXPLAIN BY EFFECT OF HETEROGENEOUS NUCLEATION OF PEARLITE AT GRAIN BOUNDARY OF AUSTENITE

LARGE GRAIN



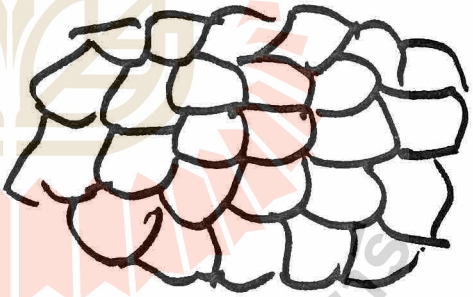
LESS BOUNDARY

↓ RATE OF TRANSFORM.



"HIGHER HARDENABILITY"

SMALL GRAIN.



LARGE BOUNDARY

↑ RATE OF TRANSFORM (NUCLEATION & GROWTH.)

"LOWER HARDENABILITY"

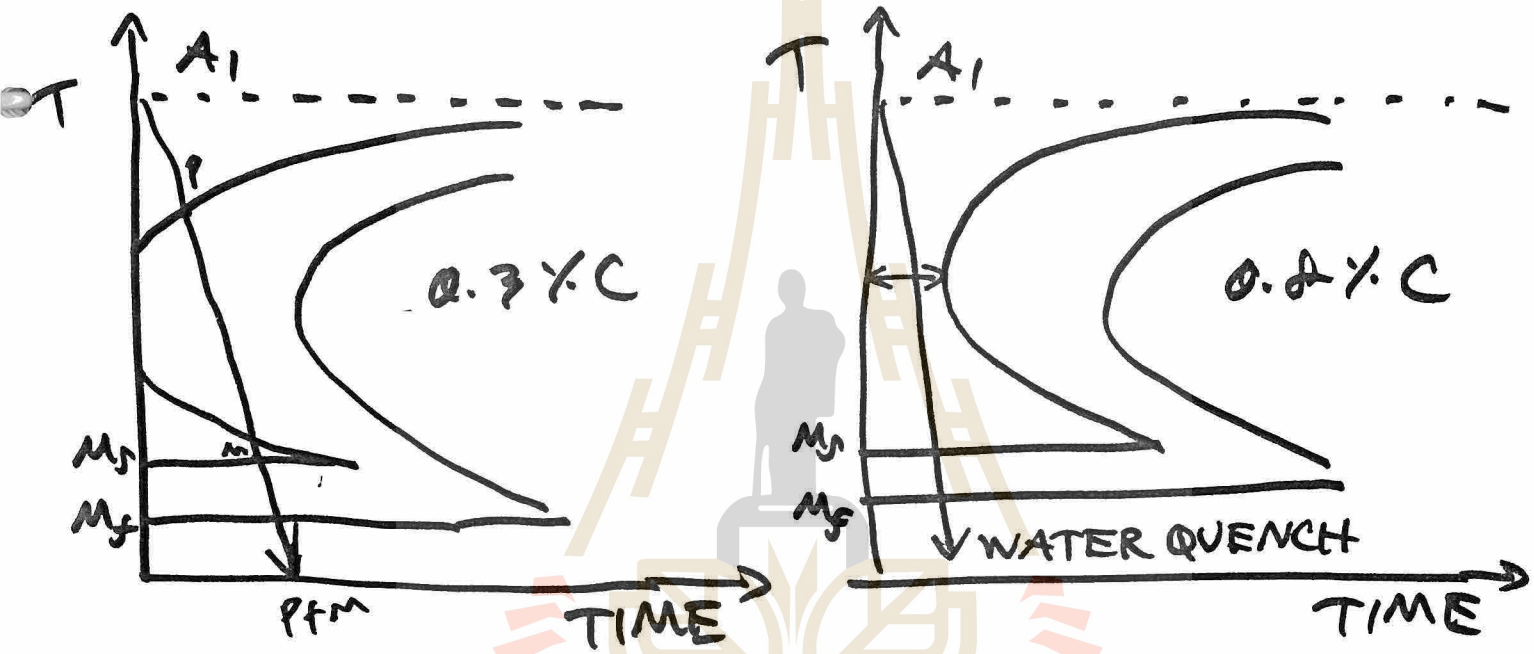
(2.) CHEMICAL COMPOSITION.

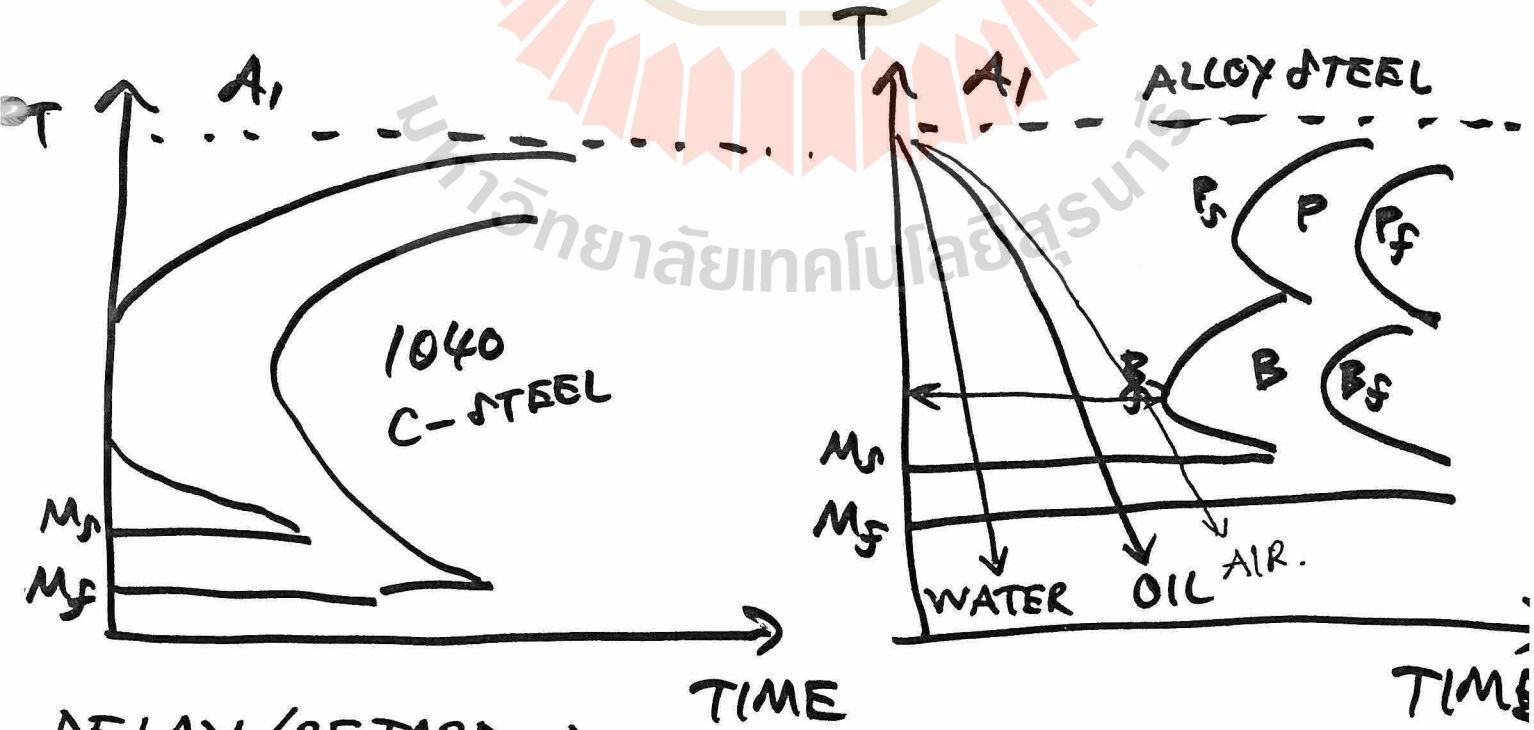
(i) % C ↑ ↑ HARDENABILITY

(ii) ALLOYING ADDED ↑ HARDENABILITY

(EXCEPT Co → INCREASE RATE OF NUCLEATIO

AND GROWTH OF PEARLITE → ↓ HARDENABILITY



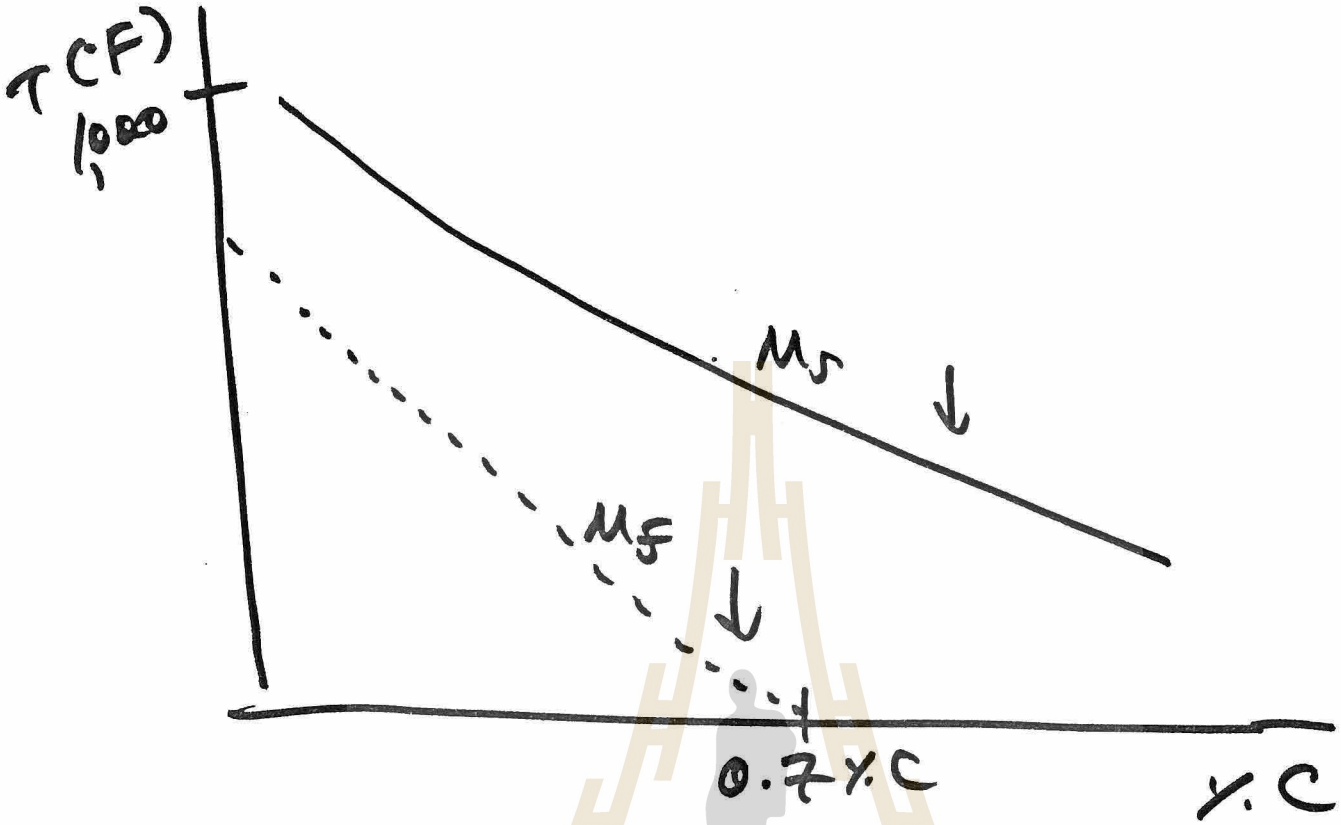


DELAY/RETARD $\gamma \rightarrow P$ TRANSFORMATION

⇓

REDUCE CRITICAL COOLING RATE

ALLOYS & C LOWER M_s & M_f



$$M_s\,(°F) = 1{,}000 - (650 \times \%C) - (70 \times \%Mn) - (35 \times \%Ni) - (70 \times \%Cr) - (50 \times \%Mo)$$

ALLOY STEELS CASTING

① STRONG (STABLE) ② WEAK (NON-STABLE)

AS-CAST: CARBIDES + MATRIX

TIME, TEMP.

HARDENING (AUSTENITIZING)

C, alloy.

DISSOLVED CARBIDE (INTO SOLUTION)
↑ HARDENABILITY
HIGH → RETAINED-γ OCCUR)

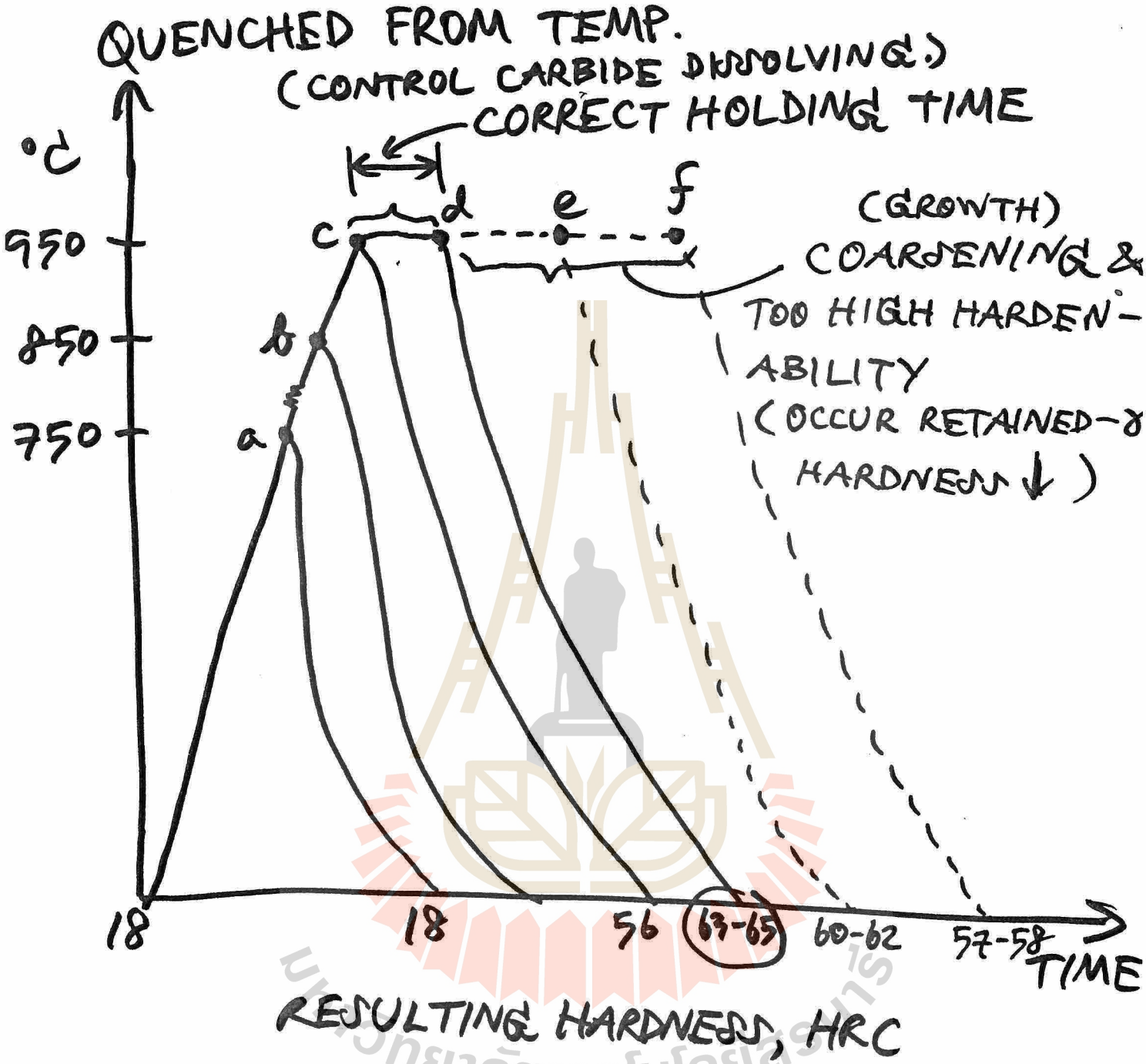
NON-DISSOLVED CARBID
W, V, Mo, ~~Cr~~
- RETARD GRAIN GROWTH
- ↑ WEAR RESISTANCE

QUENCHING TO FORM MARTENSI
(WATER, OIL, AIR)
UP TO HARDENABILITY
(DEPEND ON: COMPOSITION, γ-GRAIN SIZE)

TEMPERING
→ RESIST TO SOFTENING
→ 2nd-HARDENING EFFECT.
Cr, Mo, W, V

No 2nd-HARDENING

OCCUR 2nd-HARDENING
(Mo) → NO TEMPER BRITTLE.
HIGH → Mn, Cr, P, S
TEMPER BRITTLENERS



EFFECT OF HARDENING TEMPERATURE & HOLDING TIME.

EFFECT OF ALLOYING ELEMENT IN ALLOY STEEL

① NICKEL (Ni).

- AUSTENITE STABILIZER
- ไม่รวมตัวกับ C เกิดเป็นคาร์ไบด์
- ลด %C เค: อุณหภูมิยูเทคตอยด์ให้ต่ำลง (เพิ่มปริมาณ Pearlite, เกิดการเปลี่ยนเฟสของ γ ที่อุณหภูมิต่ำ, เกรนละเอียดขึ้น.)
- เพิ่ม Hardenability
  - → เลื่อน IT-CURVE ไปทางขวามือ
  - → ลด M_s ให้ต่ำลง
- เพิ่ม STRENGTH & HARDNESS โดยที่ DUCTILITY ไม่ลดลง
- เพิ่ม Weldability
- เพิ่ม IMPACT STRENGTH (TOUGHNESS) ที่อุณหภูมิต่ำ (ลด TRANSITION TEMPERATURE ให้ต่ำลง)
- ปรับปรุงคุณสมบัติด้านการกัดกร่อน.

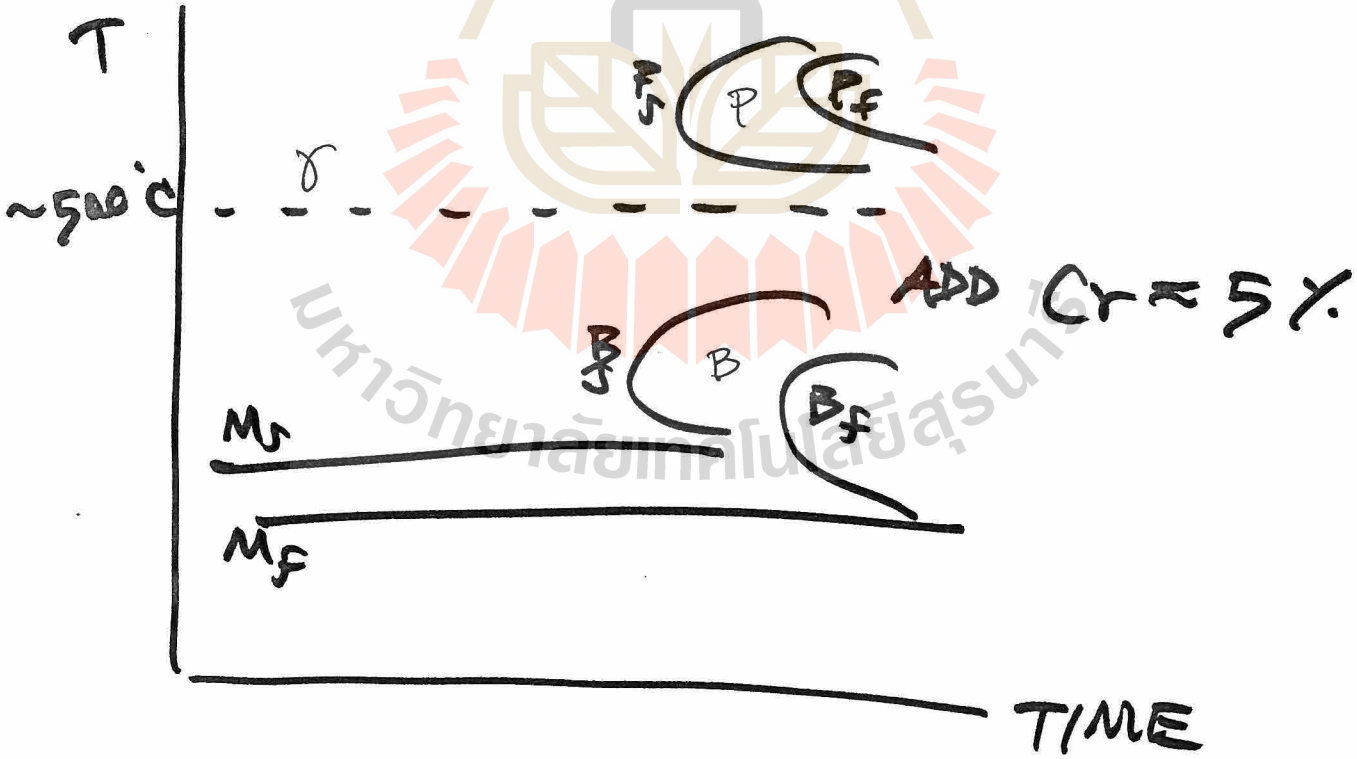
② MANGANESE (Mn).

- γ-STABILIZER
- CARBIDE FORMING ELEMENT
- ลด %C และ T ของยูเทคตอยด์ให้ต่ำ (เพิ่มปริมาณ PEARLITE, ทำให้เกรนละเอียด)
- เพิ่ม HARDENABILITY
- เพิ่ม STRENGTH & HARDNESS

  แต่ DUCTILITY ลดลง เนื่องจาก Mn มีแรงดึงดูดระหว่างอะตอมกับเหล็กสูง
- เกิด TEMPER BRITTLENESS ในช่วง T ≈ 400-600 °C ขณะ TEMPERING. (TOUGHNESS ลดลง, เปราะแตกหักได้ง่าย เนื่องจาก INTERGRANULAR CRACKING)
- CARBIDE มีเสถียรภาพต่ำ เมื่อเผาที่อุณหภูมิสูงจะละลายกลับเข้าไปใน SOLUTION ได้ง่าย ทำให้เกิด GRAIN GROWTH
- ถ้าปริมาณ Mn มาก, γ-STABLE, อาจมี RETAINED-γ เหลือค้างมากหลัง QUENCH ขณะใช้งาน γ → M จะเกิดการขยายตัว/แตกร้าวได้ง่าย

③ CHROMIUM (Cr)

- FERRITE STABILIZER
- CARBIDE FORMING ELEMENT
- ลด %C ที่จุดยูเทคตอยด์
  แต่ เพิ่ม $T_{EUTECTOID}$ ให้สูงขึ้น
- เพิ่ม HARDENABILITY
  (1) SHIFT IT-CURVE ไปทางขวามือ
  (2) แยก IT-CURVE ออกเป็น 2 ส่วน
  ทำให้ γ-STABLE ช่วง T ~ 500 °C



- FORM STABLE CARBIDE, รักษาความแข็ง
  ได้ที่ T สูง
- เกิด SECONDARY HARDENING เช่น มีแรงดึง
  เกิด TEMPER BRITTLENESS เช่นมีธาตุ Mn

④ MOLYBDENUM (Mo)

- FERRITE STABILIZER
- CARBIDE FORMING ELEMENT
- ลด %C ที่จุดยูเทคตอยด์
  แต่ เพิ่ม TEUTECTOID ให้สูงขึ้น
- เพิ่ม HARDENABILITY, ให้ผลรวมแรงกว่า C
  แสดง IT-CURVE ออกเป็น 2 ส่วน
- ฟอร์ม STABLE CARBIDE, ทนความร้อนได้ดี
  ไม่สูญเสียความแข็งแรง
- เกิด SECONDARY HARDENING ขณะ TEMPERI
  แต่ ไม่เกิด TEMPER BRITTLENESS
- เพิ่มคุณสมบัติต้านทานการกัดกร่อน
- ให้โครงสร้าง MARTENSITE ที่ STABLE ถึง
  T ≈ 600 °C (รักษาความแข็งได้ที่ T สูง)

⑤ VANADIUM (V)

- FERRITE STABILIZER
- CARBIDE FORMING ELEMENT (> Mo)

แต่: STABLE กับ T สูง ๆ (ไม่สลายตัวง่าย) ป้องกันการเกิด GRAIN GROWTH, ให้เกรนที่มีขนาดเล็กละเอียด.

V - CARBIDE

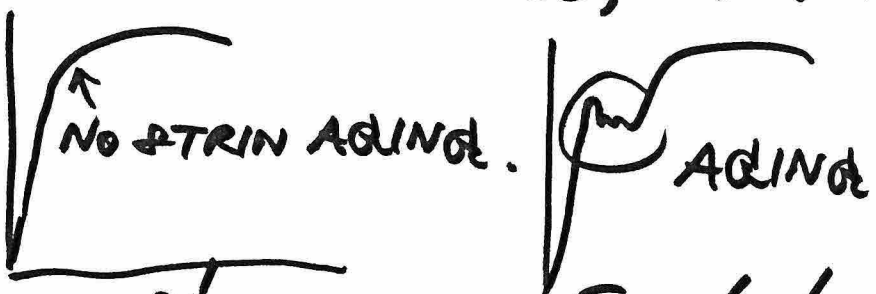
① DISSOLVED

- เพิ่ม HARDENABILITY
- เกิด 2nd HARDENING ได้ผลดีกว่าที่อุณหภูมิ 400-700 °C (ไม่เกิด TEMPER BRITTLE)

② NON-DISSOLVED

- สลายตัวยาก
- ป้องกัน GRAIN GROWTH ได้เกรนละเอียด
- ลด HARDENABILITY, γ → P ได้ง่าย
- ทำให้ความแข็งไม่ได้ที่ T สูง

- ป้องกันการเกิด AGING, ลด N โดยการเกิด VN



- ลด Y.C ที่อุณหภูมิสูงๆ, แต่เพิ่ม TEUTECTOID

⑥ TUNGSTEN (W)

- FERRITE STABILIZER
- CARBIDE FORMING ELEMENT ($\approx Mo$)
- ลด %C ที่จุดยูเทคทอยด์, เพิ่ม $T_{EUTECTOID}$
- เพิ่ม HARDENABILITY ($< Mo$)
- ให้คุณสมบัติ "RED-HARDNESS", คงความแข็งได้ที่ T สูง, ต้านทานการเกิด SOFTENING ที่ T สูง ด้วยการก่อรูป STABLE CARBIDE.
- เกิด SECONDARY HARDENING ขณะที่ TEMPERING เพราะไม่เกิด TEMPER BRITTLENESS
- นิยมใช้ใน TOOL STEEL, HIGH-SPEED TOOL STEEL (ต้องการสมบัติ "RED-HARDNESS") แทนราคาระแพงกว่า Mo

⑦ TITANIUM (Ti)

- FERRITE STABILIZER
- CARBIDE FORMING ELEMENT
- รวมตัวกับ N เกิดเป็น TiN หรือ TiCN, ป้องกันการเกิด GRAIN GROWTH, ให้การละลายตัวของ C ที่ T สูง แต่ลดการเกิด AGING
- ละลายได้น้อยใน γ, ทำให้ STABLE CARBIDE

↓

CARBIDE ที่ละลายตัวของ C ที่ T สูง
(NON-DISSOLVED CARBIDE มาก)

↓

(เพิ่ม HARDENABILITY ถ้าใส่ < 1 %)
ลด HARDENABILITY ถ้าใส่มาก
(DISSOLVED CARBIDE น้อย)
ให้ผล 2nd - HARDENING น้อย
ไม่เกิด TEMPERED BRITTLENESS

- ให้โครงสร้าง MARTENSITE ที่มีเกรนละเอียด ไม่เปลี่ยนความแข็งตอนทำ TEMPERING.

(8) SILICON (Si)

- FERRITE STABILIZER
- แต่ไม่รวมตัวกับ C ให้ CARBIDE (เป็น GRAPHITIZER)
- SOLID-SOLUTION STRENGTHENING ให้กับ FERRITE, ถ้ามีมากจะเพิ่ม & เปราะ, เพิ่ม Y.S.
- ไม่มีผลต่อ HARDENABILITY, SECONDARY HARDENING & TEMPER BRITTLENESS
- Si ลดจะทด WELDABILITY (เกิด SiO_2)

๙. ALUMINIUM (Al).

- FERRITE STABILIZER
- ไม่รวมตัวกับ C ทำให้ CARBIDE
  แต่ รวมตัวกับ N ทำให้ NITRIDE (AlN)
  ป้องกันการเกิด GRAIN GROWTH
  & ป้องกันการเกิด AGING ฯ.
- ช.ช.ช. ให้ตัว FERRITE, เพิ่ม STRENGTH
- ธาตุที่ได้น้อยใน γ, ลดค่า HARDENABILITY ต่ำ
  ไม่มีผลต่อ SECONDARY HARDENING แต่:
  TEMPER BRITTLENESS
- ใช้เป็น DEOXIDIZER (De-O), จาก O_2 gas
  ในน้ำเหล็ก, เหล็กฆ่าเชื้อแล้ว (KILLED-STEEL)
- ทำให้ Al_2O_3 FILM, ป้องกันการเกิดการกัดกร่อน

(10) COBALT (Co)

- γ-STABILIZER
- ไม่รวมตัวกับ C เป็น CARBIDE
- เพิ่ม STRENGTH เนื่องจากการเกิด FERRITE
- * ลด HARDENABILITY, เพิ่ม RATE OF γ→α TRANSFORMATION (เลื่อน IT-CURVE ลงทางขวามือ, เพิ่ม M_s ในที่สุดอีกด้วย)
- ไม่มีผลต่อ 2nd HARDENING เช่น TEMPER BRITTLENESS
- มีคุณสมบัติ "RED-HARDNESS" (HIGH-TEMPERATURE HARDNESS) ซึ่งมีใน HIGH-SPEED TOOL STEELS เช่น ทำแม่เหล็กถาวร (PERMANENT MAGNET)

(11) BORON (B)

- ราคาถูก, เติมในปริมาณน้อยมาก
- FERRITE STABILIZER
- รวมตัวกับ C ให้ STABLE CARBIDE
- รวมตัวกับ N ให้ NITRIDE (BN)

ตัวยับยั้งการเกิด GRAIN GROWTH & ABLING

- เพิ่ม HARDENABILITY

→ เลื่อน IT-CURVE มาทางขวามือ

แต่ ไม่กด M_s ให้ต่ำลง

(12) NIOBIUM (Nb)

- FERRITE STABILIZER
- CARBIDE FORMER → NbC

& ให้ NbCN

↓

ตัวยับยั้งการเกิด GRAIN GROWTH ใน HSLAs

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* Al, Ti, V, Nb, B ⇒ ALLOYS ที่มีความสำคัญเกี่ยวเติมในปริมาณเล็กน้อยใน HSLAs. เพื่อป้องกันการเกิด GRAIN GROWTH เพราะเพิ่ม T_{nr} ให้สูงขึ้น.

LOW-ALLOY STEELS.

TABLE 4-1
Principal types of standard low alloy steels

13xx	Manganese 1.75
40xx	Molybdenum 0.20 or 0.25; or molybdenum 0.25 and sulfur 0.042
41xx	Chromium 0.50, 0.80, or 0.95, molybdenum 0.12, 0.20, or 0.30
43xx	Nickel 1.83, chromium 0.50 or 0.80, molybdenum 0.25
44xx	Molybdenum 0.53
46xx	Nickel 0.85 or 1.83, molybdenum 0.20 or 0.25
47xx	Nickel 1.05, chromium 0.45, molybdenum 0.20 or 0.35
48xx	Nickel 3.50, molybdenum 0.25
50xx	Chromium 0.40
51xx	Chromium 0.80, 0.88, 0.93, 0.95, or 1.00
51xxx	Chromium 1.03
52xxx	Chromium1.45
61xx	Chromium 0.60 or 0.95, vanadium 0.13 or min 0.15
86xx	Nickel 0.55, chromium 0.50, molybdenum 0.20
87xx	Nickel 0.55, chromium 0.50, molybdenum 0.25
88xx	Nickel 0.55, chromium 0.50, molybdenum 0.35
92xx	Silicon 2.00; or silicon 1.40 and chromium 0.70
50Bxx	Chromium 0.28 or 0.50
51Bxx	Chromium 0.80
81Bxx	Nickel 0.30, chromium 0.45, molybdenum 0.12
94Bxx	Nickel 0.45, chromium 0.40, molybdenum 0.12

Note: B denotes boron steel.

TABLE 4-2
Nominal compositions and typical applications of selected standard alloy steels

AISI-SAE No.	% C	% Mn	% Cr	% Mo	% Ni	% Si†	Typical applications
Manganese steels							
1330	0.30	1.75					High-strength bolts
1340	0.40	1.75					
Chromium steels							
5120	0.20	0.80	0.80				Carburizing steel
5130	0.30	0.80	0.95				Steering parts
5140	0.40	0.80	0.80				
5160	0.60	0.88	0.80				Spring steels
E52100	1.04	0.35	1.45				Ball and roller bearings
Molybdenum steels							
4023	0.23	0.80		0.25			Carburizing steel
4037	0.37	0.80		0.25			
4047	0.47	0.80	0.25				
Chromium-molybdenum steels							
4118	0.18	0.80	0.50	0.13			
4130	0.30	0.50	0.95	0.20			Pressure vessels, aircraft structural parts, auto axles, steering knuckles
4140	0.40	0.88	0.95	0.20			
Chromium-vanadium steels							
6150	0.50	0.80	0.95				0.15V; valves and springs
Nickel-molybdenum steels							
4620	0.20	0.55		0.25	1.83		Transmission gears, chain pins, shafts, roller bearings
4820	0.20	0.60		0.25	3.50		
Nickel (1.83%)-chromium-molybdenum steels							
4320	0.20	0.55	0.50	0.25	1.83		Carburizing steel
4340 (E)	0.40	0.70	0.80	0.25	1.83		Heavy sections, landing gears, truck parts
Nickel (0.55%)-chromium-molybdenum steels							
8620	0.20	0.80	0.50	0.20	0.55		Carburizing steel
8640	0.40	0.88	0.50	0.20	0.55		Auto springs, small machine axles, shafts
8660	0.60	0.88	0.50	0.20	0.55		
Silicon steels							
9260	0.60	0.88				2.0	Leaf springs

† All steels contain 0.28% min Si except 9260; all steels contain 0.035% max P and 0.040% max S except electric furnace steels (E), which have 0.025% max P and 0.025% max S.

Table 9.3 Typical mechanical properties and applications of plain-carbon steels

Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
1010	0.10 C, 0.40 Mn	Hot-rolled	40–60	276–414	26–45	179–310	28–47	Sheet and strip for drawing; wire, rod, and nails and screws; concrete reinforcement bar
		Cold-rolled	42–58	290–400	23–38	159–262	30–45	
1020	0.20 C, 0.45 Mn	As rolled	65	448	48	331	36	Steel plate and structural sections; shafts, gears
		Annealed	57	393	43	297	36	
1040	0.40 C, 0.45 Mn	As rolled	90	621	60	414	25	Shafts, studs, high-tensile tubing, gears
		Annealed	75	517	51	352	30	
		Tempered*	116	800	86	593	20	
1060	0.60 C, 0.65 Mn	As rolled	118	814	70	483	17	Spring wire, forging dies, railroad wheels
		Annealed	91	628	54	483	22	
		Tempered*	160	110	113	780	13	
1080	0.80 C, 0.80 Mn	As rolled	140	967	85	586	12	Music wire, helical springs, cold chisels, forging die blocks
		Annealed	89	614	54	373	25	
		Tempered*	189	1304	142	980	12	
1095	0.95 C, 0.40 Mn	As rolled	140	966	83	573	9	Dies, punches, taps, milling cutters, shear blades, high-tensile wire
		Annealed	95	655	55	379	13	
		Tempered*	183	1263	118	814	10	

Table 9.6 Typical mechanical properties and applications of low-alloy steels

Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
			Manganese steels					
1340	0.40 C, 1.75 Mn	Annealed	102	704	63	435	20	High-strength bolts
		Tempered*	230	1587	206	1421	12	
			Chromium steels					
5140	0.40 C, 0.80 Cr, 0.80 Mn	Annealed	83	573	43	297	29	Automobile transmission gears
		Tempered*	229	1580	210	1449	10	
5160	0.60 C, 0.80 Cr, 0.90 Mn	Annealed	105	725	40	276	17	Automobile coil and leaf springs
		Tempered*	290	2000	257	1773	9	
			Chromium-molybdenum steels					
4140	0.40 C, 1.0 Cr, 0.9 Mn, 0.20 Mo	Annealed	95	655	61	421	26	Gears for aircraft gas turbine engines, transmissions
		Tempered*	225	1550	208	1433	9	
			Nickel-molybdenum steels					
4620	0.20 C, 1.83 Ni, 0.55 Mn, 0.25 Mo	Annealed	75	517	54	373	31	Transmission gears, chain pins, shafts, roller bearings
		Normalized	83	573	53	366	29	
4820	0.20 C, 3.50 Ni, 0.60 Mn, 0.25 Mo	Annealed	99	683	67	462	22	Gears for steel mill equipment, paper machinery, mining machinery, earth-moving equipment
		Normalized	100	690	70	483	60	
			Nickel (1.83%)-chromium-molybdenum steels					
4340 (E)	0.40 C, 1.83 Ni, 0.90 Mn, 0.80 Cr, 0.20 Mo	Annealed	108	745	68	469	22	Heavy sections, landing gears, truck parts
		Tempered*	250	1725	230	1587	10	
			Nickel (0.55%)-chromium-molybdenum steels					
8620	0.20 C, 0.55 Ni, 0.50 Cr, 0.80 Mn, 0.20 Mo	Annealed	77	531	59	407	31	Transmission gears
		Normalized	92	635	52	359	26	
8650	0.50 C, 0.55 Ni, 0.50 Cr, 0.80 Mn, 0.20 Mo	Annealed	103	710	56	386	22	Small machine axles, shafts
		Tempered*	250	1725	225	1552	10	

*Tempered at 600°F (315°C).

Mn-STEELS. (AISI 13XX)

COMERCIAL STEELS ⇒ Mn ≈ 0.25–1.00 %

↓

ADDED FOR De-O & De-S

↓ MnO ↓ MnS

AISI 13XX ⇒ 0.3–0.9 %C

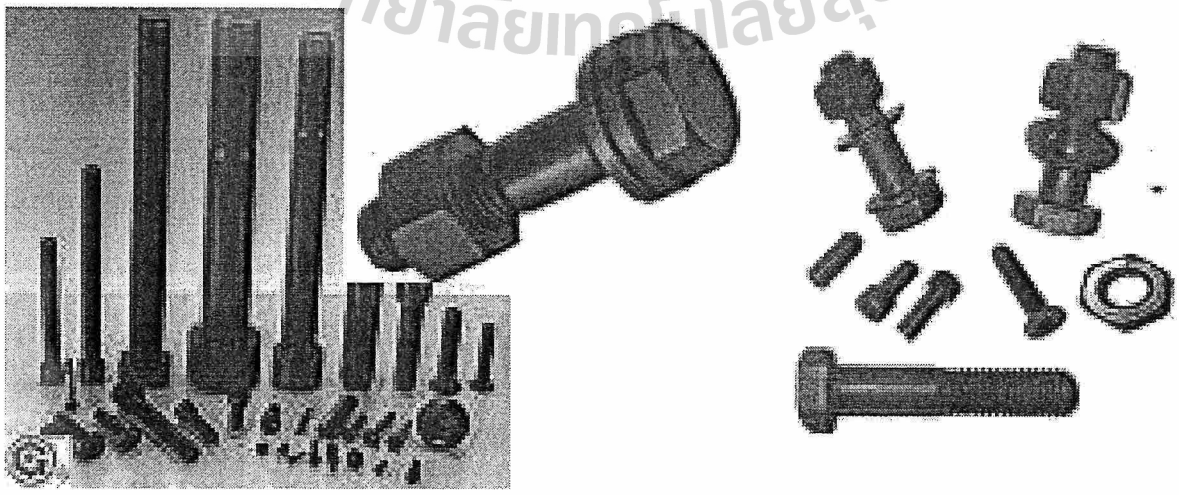
Mn ≈ 1.75%

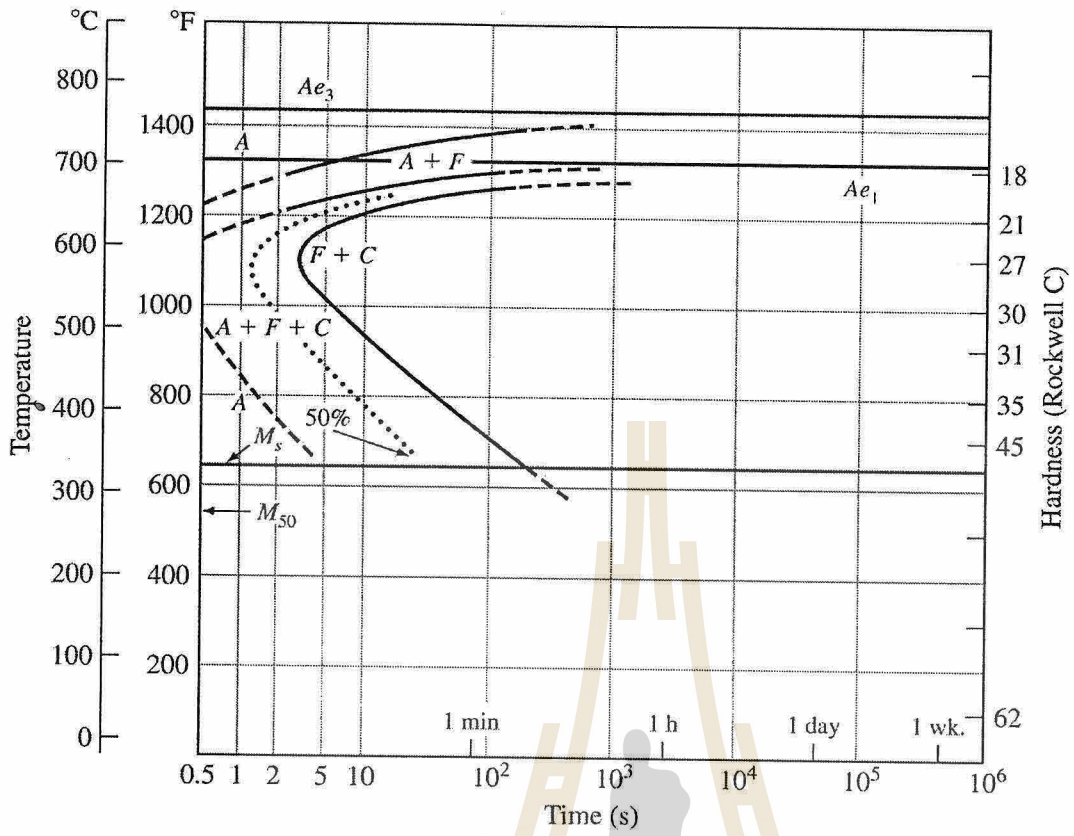
ADD Mn ≈ 1.6–1.9 %

(INCREASE STRENGTH & WELDABILITY) AND HARDENABILITY.

USED FOR : HIGH-STRENGTH BOLTS, AXLES (แกนล้อ/เพลา), SHAFTS (เพลา), GEARS, TIE RODS (ก้านชี้) FOR AUTOMOBILES

Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
		Manganese steels						
1340	0.40 C, 1.75 Mn	Annealed	102	704	63	435	20	High-strength bolts
		Tempered*	230	1587	206	1421	12	

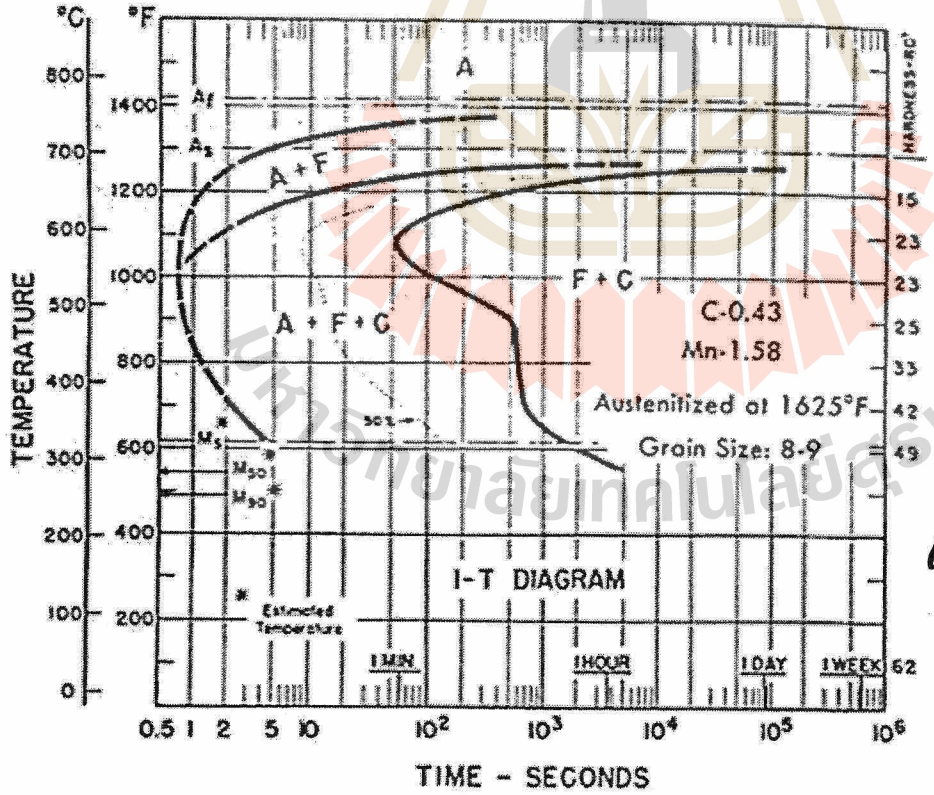




1050

0.47% C

0.57% M



1340

0.40 % C

1.75 % Mn

HIGHER HARDENABILITY

FIGURE 4-10
Isothermal-transformation diagram of AISI 1340 steel. (*After "Isothermal Transformation Diagrams," United States Corporation, 1963, p. 26.*)

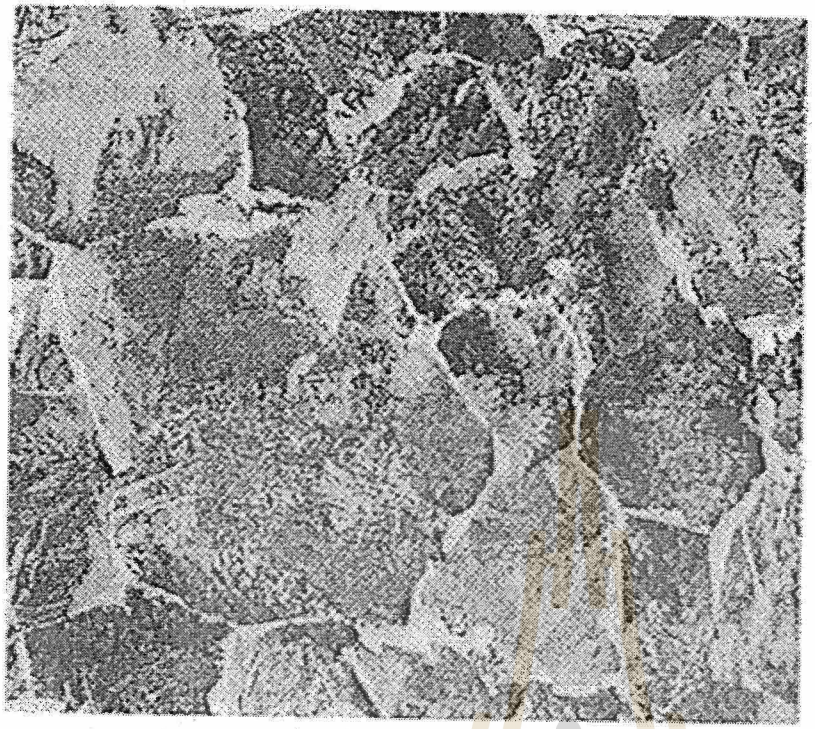


FIGURE 4-11
Microstructure of AISI 1340 steel, containing 1.74% Mn and 0.40% C. Air-cooled from 828°C. Structure shows fine pearlite with some ferrite outlining prior austenite boundaries. (Etch: picral; 500 × .) (*Courtesy of R. M. Fisher, U. S. Steel Research Laboratories.*)

NORMALIZING AISI 1340

0.40 % C, 1.74 % Mn

AUSTENITIZING : 828 °C

&

AIR-COOLED.

STRUCTURE.

FINE PEALITE WITH SOME FERRITE OUTLINING PRIOR γ-BOUNDARY.

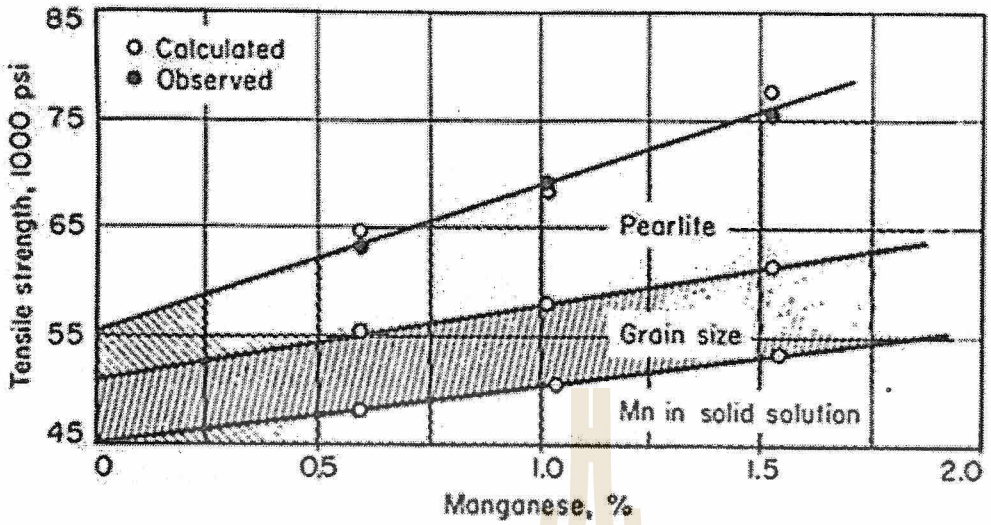


FIGURE 4-12
Factors contributing to the effect of manganese on the tensile strength of annealed 0.15% C steels. [*After K. J. Irving and F. B. Pickering, JISI, 201(1963):944, as presented in E. C. Bain and H. W. Paxton, "Alloying Elements in Steel," 2d ed., American Society of Metals, 1966, p. 270.*]

Mn เพิ่มความแข็งแรงให้กับ C-STEEL ได้ 3 ช่องทาง คือ.

1. SOLID SOLUTION STRENGTHENING
2. GRAIN-SIZE REFINEMENT
3. INCREASE IN PROPORTION OF PEARLITE

Mn → RIFINE PEARLITE

Mn > 2% ⇒ EMBRITTLED.

เพิ่ม Mn = 12-14%, C = 1.0-1.4%

⇓

HIGH-Mn STEEL (HADFIELD'S STEEL)

⇓

RESISTANCE TO ABRASION.

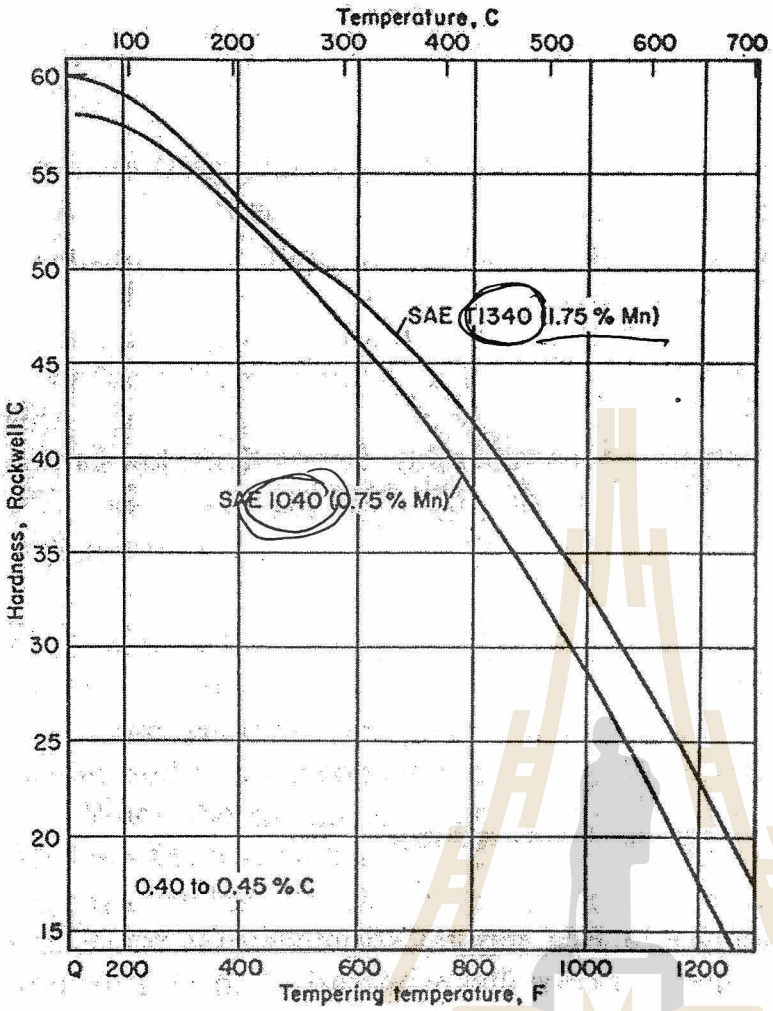


FIGURE 4-13
Softening, with increasing tempering temperature, of quenched 0.40 to 0.45% C steels as influenced by an increase of manganese from about 0.75 to 1.75%. (*After E. C. Bain and H. W. Paxton, "Alloying Elements in Steel," 2d ed., American Society for Metals, 1966, p. 194.*)

1340 RESIST TO SOFTENING THAN 1040.

↓

เพิ่ม TEMPERING TEMPERATURE.

LOW-ALLOY Cr-STEELS. (AISI 51XX)

AISI.	%C	%Mn	%Cr	
5120	0.2	0.80	0.80	→ CARBURIZING GRAD
5130	0.3	0.80	0.95	STEERING PARTS
5140	0.4	0.80	0.80	
5160	0.6	0.88	0.80	→ SPRING STEELS
52100	1.04	0.35	1.45	→ BALL & ROLLER BEARIN

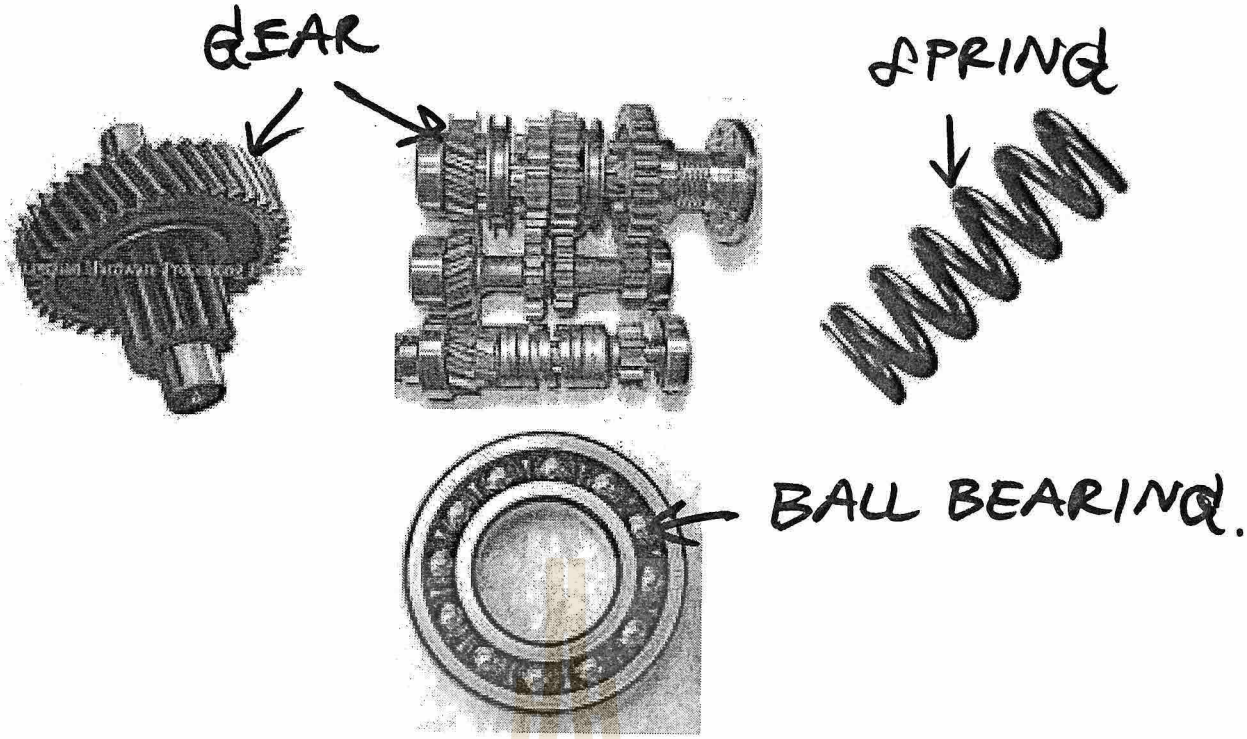
Cr ⇒ ↑ HARDENABILITY, STRENGTH & WEAR RESISTANCE

Cr + C ⇒ FORM CARBIDES

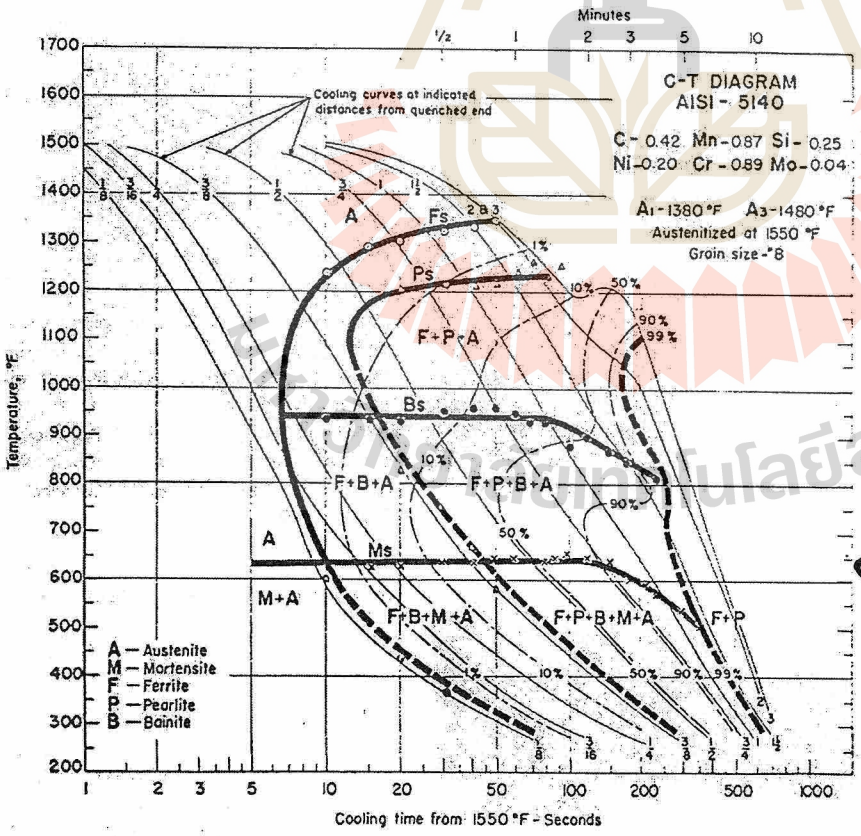
(Cr < 2% ⇒ FORM $(Fe,Cr)_3C$ แทน Fe_3C)

USED FOR: TRANSMISSION GEAR, SPRING STEEL, BALL & ROLLER BEARING (HIGH STRENGTH & WEAR RESIST.

BUT. Cr ⇒ เพิ่มต่อการเกิด TEMPER EMBRITTLEMENT.



Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
			Chromium steels					
5140	0.40 C, 0.80 Cr, 0.80 Mn	Annealed	83	573	43	297	29	Automobile transmission gears
		Tempered*	229	1580	210	1449	10	
5160	0.60 C, 0.80 Cr, 0.90 Mn	Annealed	105	725	40	276	17	Automobile coil and leaf springs
		Tempered*	290	2000	257	1773	9	



AISI 5140

0.4 % C

0.9 % Cr.

เมื่อ $\gamma \rightarrow P$

$\gamma \rightarrow F$

ไปทางขวามือ.

FIGURE 4-14
Continuous-cooling diagram for AISI 5140 alloy steel. (*After Met. Prog.*, Dec. *1965*, *p. 84.*)

ตัวอย่าง 5160 ⇒ SPRING STEEL (AS-ROLLED)

(1.)

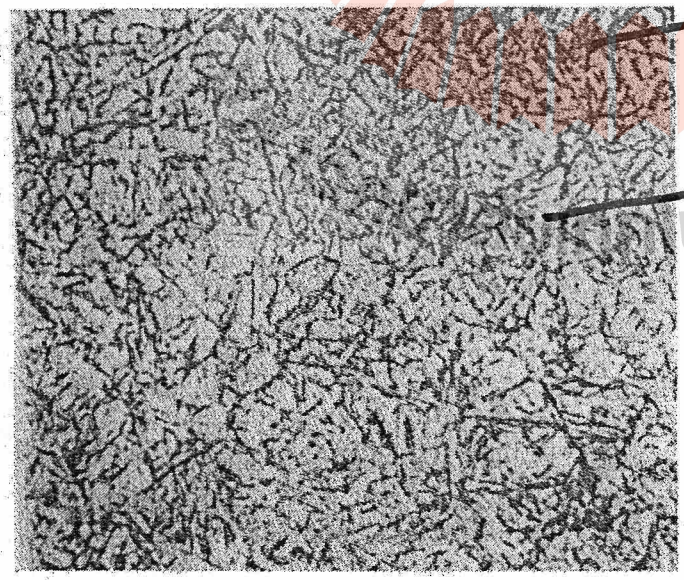
2% nital 550×

FIGURE 4-15
Alloy 5160 hot-rolled 0.635-in diameter, air-cooled from finish-rolling temperature at 982°C; structure consists of unresolved pearlite (dark) and ferrite (light). (*After Metals Handbook, 8th ed., vol. 7, American Society for Metals, 1972, p. 49.*)

5160 HOT-ROLLING AT 982 °C & AIR-COOLED.

ตัวอย่าง (1.) → AUSTENITIZED @ 871°C, 30 MIN.
&
OIL-QUENCHED.

(2.)



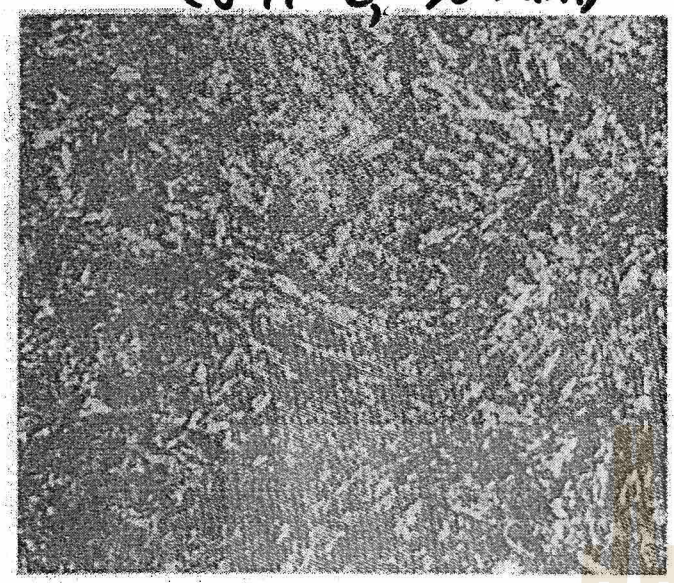
1% picral with 0.05% HCl 500×

FIGURE 4-16
Alloy 5160 hot-rolled coil-spring steel, austenitized at 871°C for 30 min and oil-quenched; structure consists of untempered martensite (dark constituent) and retained austenite (light constituent). (*After Metals Handbook, 8th ed., vol. 7, American Society for Metals, 1972, p. 49.*)

5160 HEAT-TREATMENT & OIL-QUENCHED
(UNTEMPERERED MARTENSITE & RETAINED-γ)

5160 : AUSTENITIZED + OIL-QUENCH + TEMPERED.
(871 °C, 30 MIN.) (204 °C, 1 HR.)

3.



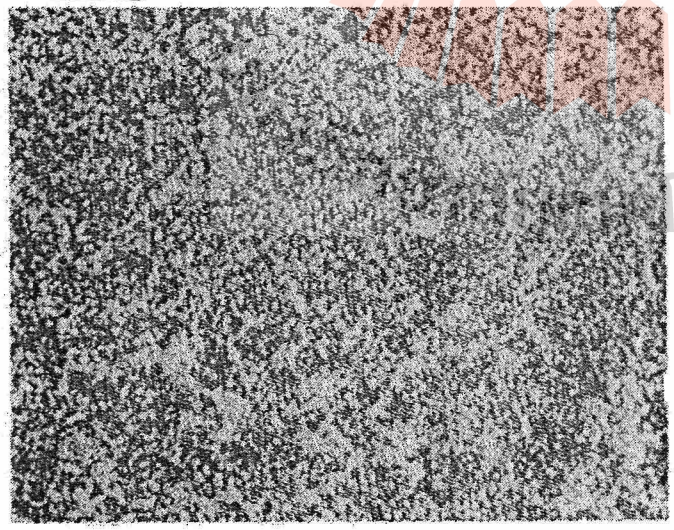
4% nital, 4% picral, mixed 1 to 1 1000×

FIGURE 4-17
Alloy 5160 hot-rolled coil-spring steel, austenitized at 871°C for 30 min, oil-quenched, and tempered 1 h at 204°C; structure consists of tempered martensite. (*After Metals Handbook, 8th ed., vol. 7, American Society for Metals, 1972, p. 49.*)

STRUCTURE : TEMPERED MARTENSITE

52100 : AUSTENITIZED + OIL-QUENCH + TEMPERED
(843 °C, 30 MIN.) (399 °C, 1 HR.)

STRUCTURE : TEMPERED-MARTENSITE WITH DISPERSION OF UNDISSOLVE CARBIDES



4% nital, 4% picral, mixed 1 to 1 500×

FIGURE 4-18
Alloy 52100 steel bar first spheroidized and then austenitized at 843°C for 0.5 h, oil-quenched and tempered 1 h at 399°C; structure consists of tempered martensite and a dispersion of carbide particles not dissolved during austenitizing. (*After Metals Handbook, 8th ed., vol. 7, American Society for Metals, 1972, p. 51.*)

"BALL BEARING"

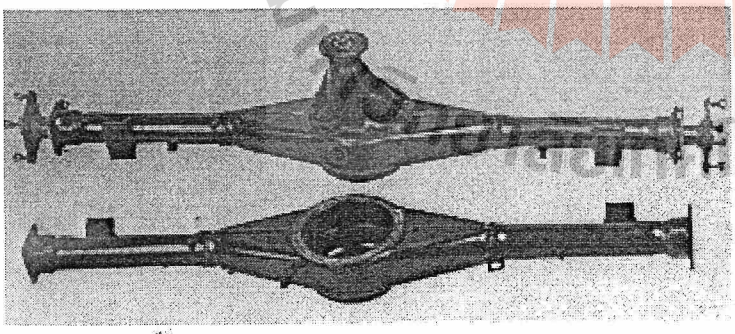
Mo-STEELS (AISI 40XX)

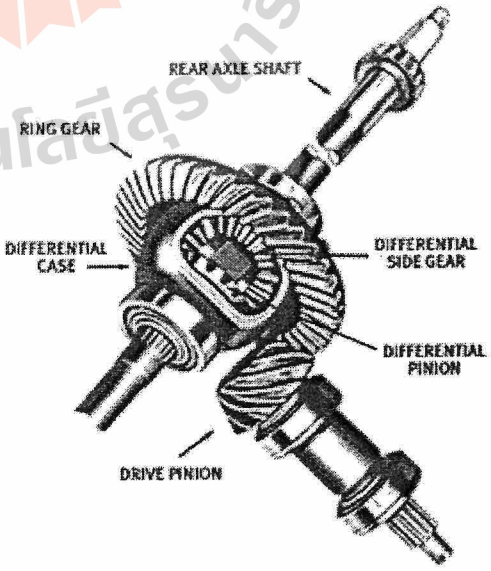
C = 0.2-0.5%, 0.80% Mn, 0.25% Mo

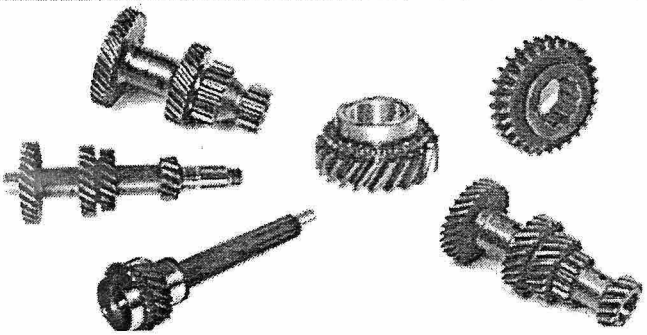
ADDED Mo = 0.25% ⇒ เพิ่ม STRENGTH
เพิ่ม HARDENABILITY

0.25% Mo ⇒ OPTIMUM TO INCREASE TOUGHNESS
HARDENABILITY & STRENGTH.

USED FOR: CARBURIZING GRADES IN AUTO-PART
REAR-AXLE GEARS & TRANSMISSION
COMPONENTS.







AISI 4047. ⇒ REAR-AXLE GEAR.

0.47 % C
0.25 % Mo

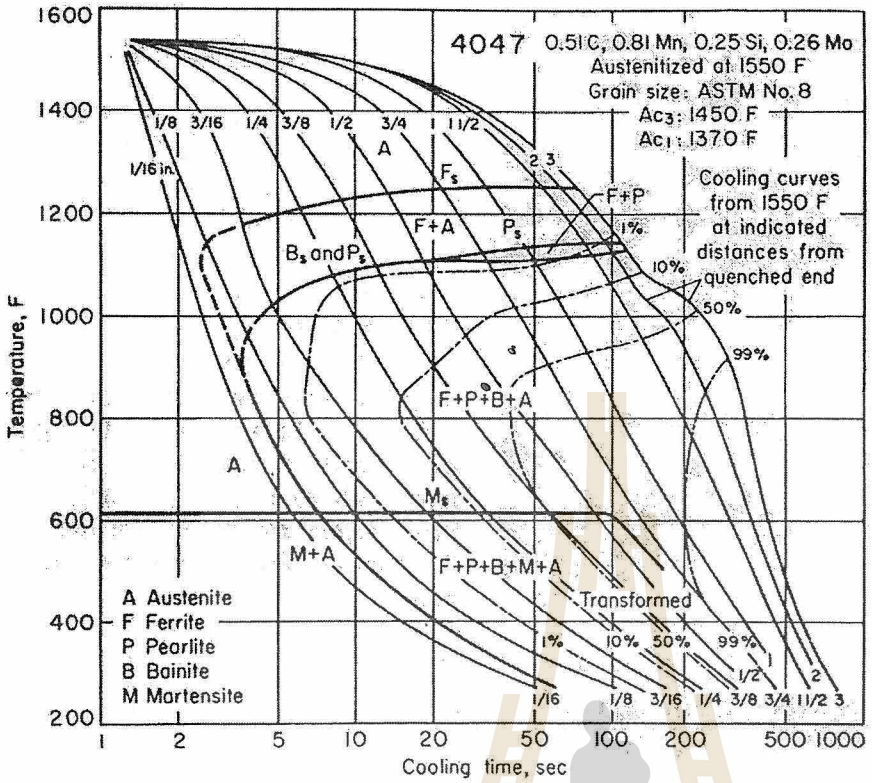


FIGURE 4-19
Continuous-cooling diagram for AISI 4047 alloy steel. (*After Met. Prog.*, Dec. *1963, p. 114.*)

1040 ⇒ COOLED FROM γ → F + P

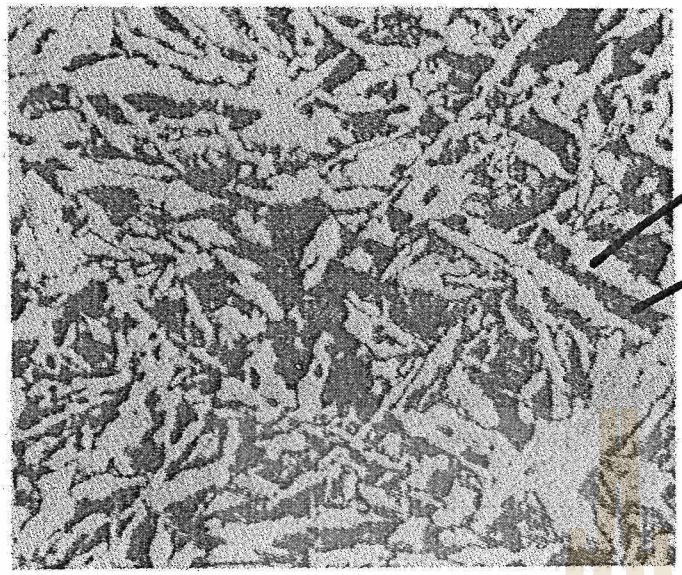
RAPID COOLED γ → BAINITE

4047 ⇒ เนื่องจากเปลี่ยนเฟสของ γ → F+P ไม่ทันตามมือ

⇒ เพิ่มปริมาณการเกิด BAINITE จากการเปลี่ยนเฟสของ γ

4047 : FORGING & AIR-COOLED FROM 1204°C

(1.)



2% nital 550 ×

PLATE-α (สาง)

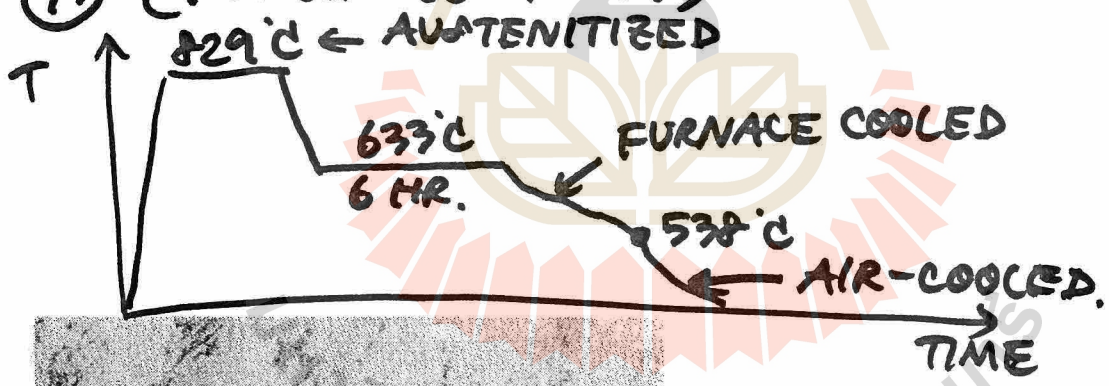
PEARLITE (ดำ)

FIGURE 4-20
Alloy 4047 steel forging ($\frac{1}{2}$-in section thickness) air-cooled from forging temperature of 1204°C; longitudinal section; structure consists of plates of ferrite (white) and fine pearlite (dark). (*After Metals Handbook, 8th ed., vol. 7, American Society for Metals, 1972, p. 370.*)

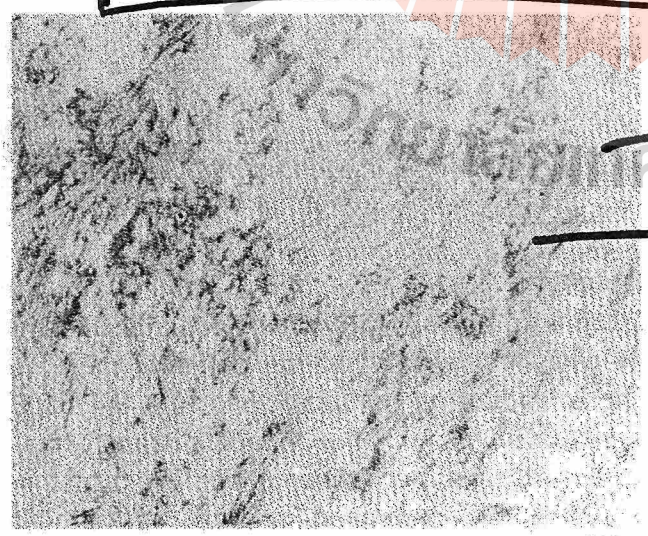
STRUCTURE :

PRO-EUTECTOID-α กับ FINE PEARLITE.

สาง (1.) (FORGING 4047)



(2.)



2% nital 500 ×

FERRITE (สาง)

LAMELLAR PEARLITE (ดำ)

FIGURE 4-21
Alloy 4047 steel forging ($\frac{5}{8}$-in thick, longitudinal section) austenitized at 829°C, cooled to 663°C and held 6 h, furnace-cooled to 538°C, air-cooled. Ferrite (white) and lamellar pearlite (dark). (*After Metals Handbook, 8th ed., vol. 7, American Society for Metals, 1972, p. 37.*)

STRUCTURE : PRO-EUTECTOID-α AND COARSE PEARLITE

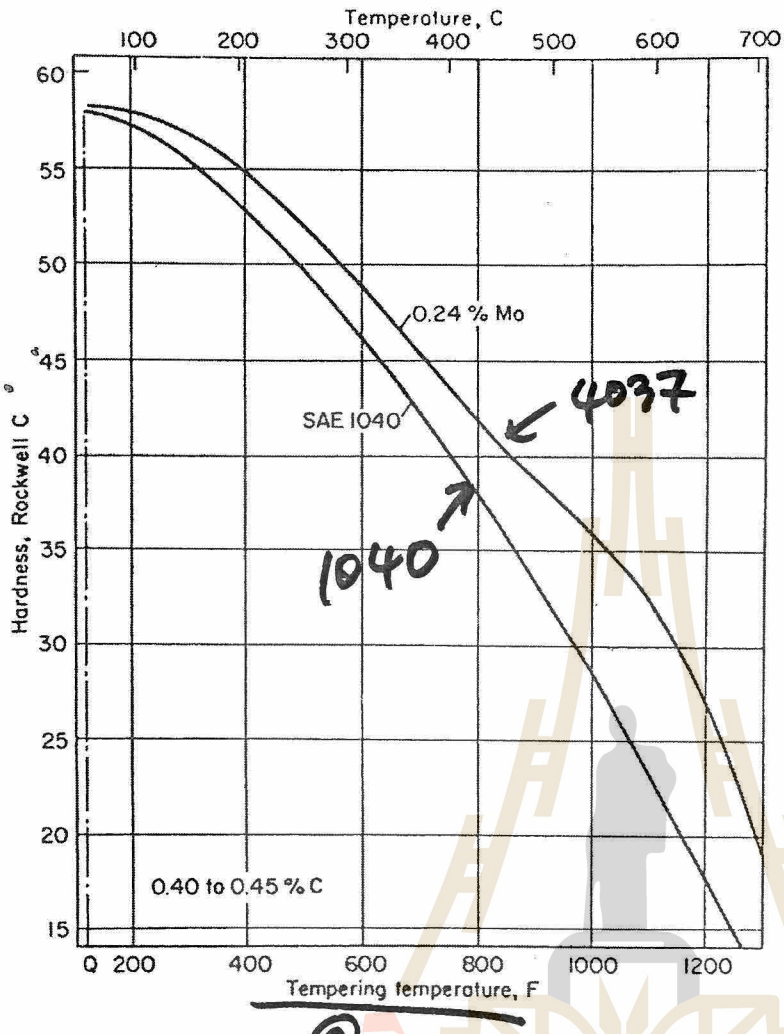


FIGURE 4-22
Comparison of the softening with increasing tempering temperature of alloy 1040 with the same alloy with 0.25% Mo. (*After E. C. Bain and H. W. Paxton, "Alloying Elements in Steel," 2d ed., American Society for Metals, 1966, p. 198.*)

เทียบ 0.25% Mo ใน 1040 (4037)

→ ช่วงอุณหภูมิการเกิด SOFTENING เมื่อ T สูงขึ้น (เพิ่ม TEMPERING TEMPERATURE)

⇒ LARGE Mo-ATOM ENTER THE Fe_3C,

⇓

INHIBITING DIFFUSION

⇓

SLOW DOWN THE RATE OF COALESCENCE OF Fe_3C

Cr-Mo STEELS (AISI 41XX)

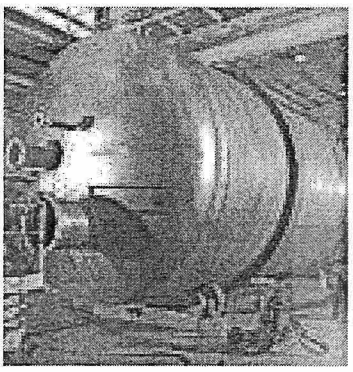
41XX ⇒ 0.5 - 0.95 % Cr
0.13 - 0.20 % Mo

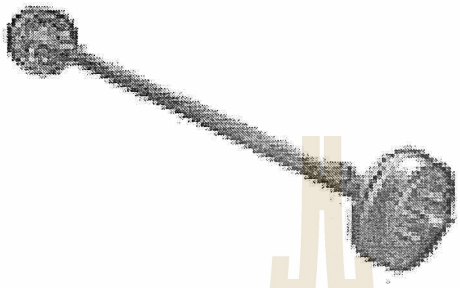
AISI.	% C	% Mn	% Cr	% Mo	USED.
4118	0.18	0.8	0.50	0.13	PRESSURE VESSE
4130	0.30	0.5	0.55	0.20	AIR CRAFT STRUCTURAL PART
4140	0.40	0.88	0.95	0.20	
4150	0.50	0.88	0.95	0.20	AUTO AXLES

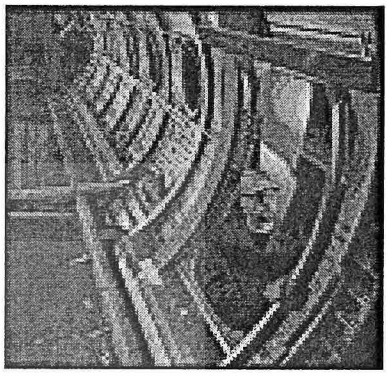
Cr ⇒ เพิ่ม HARDENABILITY, STRENGTH และ WEAR RESISTANCE ดีกว่า C-STEELS.
แต่ เสี่ยงต่อการเกิด TEMPER BRITTLENESS.

41XX ⇒ OIL-QUENCHED TO FORM MARTENSITE
แต่ข้อดี: ต้องทำการ QUENCH ด้วย H_2O
REDUCE TEMPERATURE GRADIENTS AND INTERNAL STRESS DUE TO VOLUME CHANGE DURING QUENCHE
⇓
MINIMIZED TENDENCY OF DISTORTION & CRACKING

Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
		Chromium-molybdenum steels						
4140	0.40 C, 1.0 Cr, 0.9 Mn, 0.20 Mo	Annealed	95	655	61	421	26	Gears for aircraft gas turbine engines, transmissions
		Tempered*	225	1550	208	1433	9	





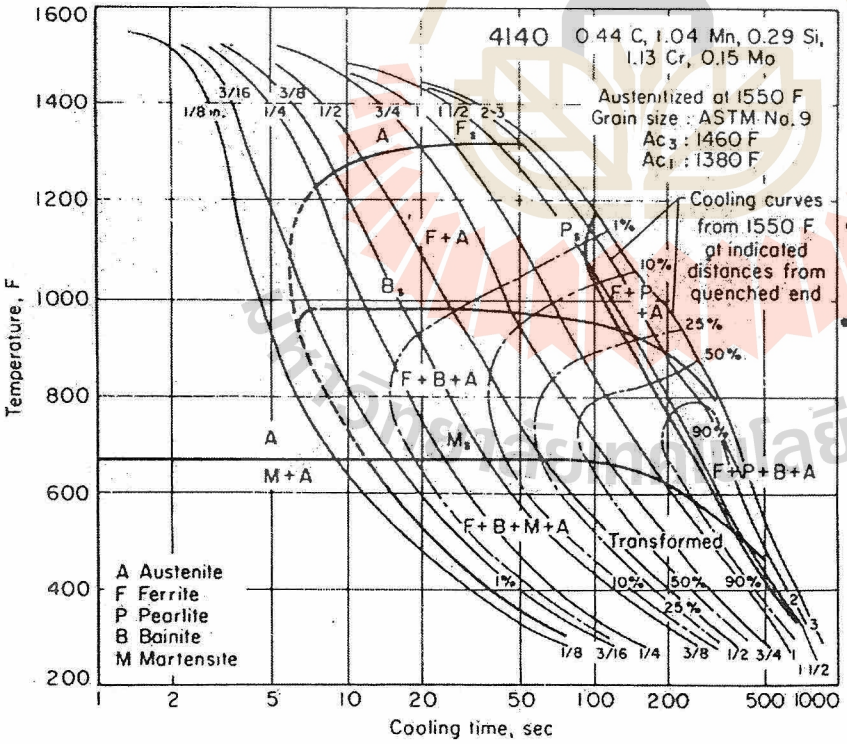


4140 ⇒ 0.95% Cr & 0.20 % Mo

MODIFYING PHASE TRANSFORMATION.

ทำให้ช้าลง & ความสามารถในการเปลี่ยนเฟสจาก

A → M เช่น: A → B ให้เกิดช้า.



Cr:

→ ลด B_s

→ DELAY

$\gamma \rightarrow P$

FIGURE 4-24
Continuous-cooling-transformation diagram for AISI 4140 alloy steel. (*After Met. Prog., January 1964*, p. 100.)

4140: FULLY ANNEALED AT 691°C, 24 HR.

1.

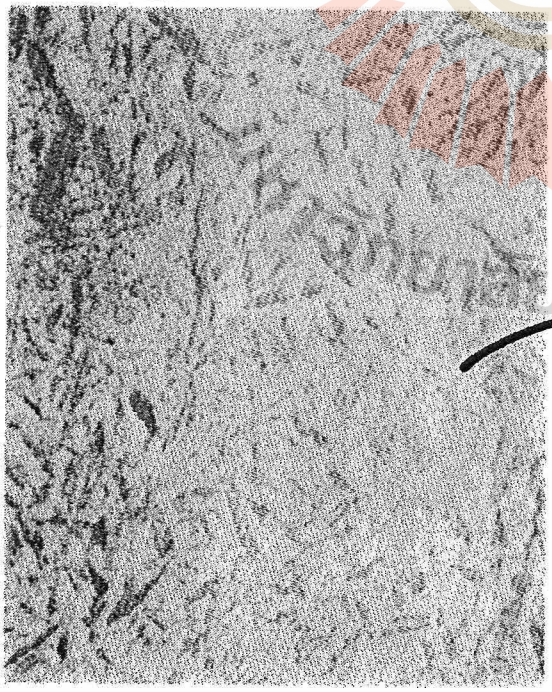
COARSE PEARLITE

FERRITE

FIGURE 4-25
Alloy 4140 steel fully annealed 24 h at 691°C; structure consists of pearlite with ferrite. (Etch: 2% nital; 800 × .) (*Courtesy of Republic Steel Co.*)

4140: FULLY HARDENED, AUSTENITIZED (843°C) & OIL-QUENCHED

2.



MARTENSITE STRUCTURE.

FIGURE 4-26
Alloy 4140 steel fully hardened; sample was austenitized at 843°C and oil-quenched; structure is martensite. (Etch: 2% nital; 800 × .) (*Courtesy of Republic Steel Co.*)

4140 : QUENCH & TEMPER, AUSTENITIZED (843 °C)

↓

OIL-QUENCHED

↓

TEMPERED (315 °C)

3.

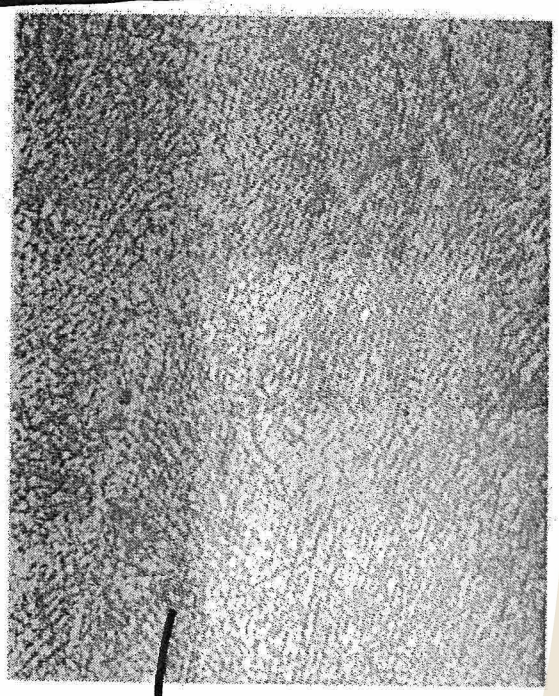


FIGURE 4-27
Alloy 4140 steel fully hardened and tempered; sample was austenitized at 843°C and oil-quenched tempered at 315°C; structure is tempered martensite. (Etch: 2% nital; 800 × .) (*Courtesy of Republic Steel Co.*)

↓

TEMPERED-MARTENSITE STRUCTURE

Ni-Cr-Mo STEELS (AISI 43XX & 86XX)

43XX ⇒ 1.8% Ni, 0.5-0.8% Cr, 0.20% Mo

86XX ⇒ REDUCED Ni TO 0.55% Ni

AISI	%C	%Mn	%Ni	%Cr	%Mo
4320	0.2	0.55	1.83	0.5	0.25
4340	0.4	0.60	1.83	0.8	0.25
8620	0.2	0.80	0.55	0.5	0.20
8640	0.4	0.88	0.55	0.5	0.20
8660	0.6	0.88	0.55	0.5	0.20

Ni + Cr ⇒ HIGHER ELASTIC LIMIT
INCREASE HARDENABILITY
HIGH IMPACT & FATIGUE RESISTANCE

ADDED 0.2% Mo ⇒ INCREASE HARDENABILITY
ลดการเกิด TEMPER BRITTLENESS

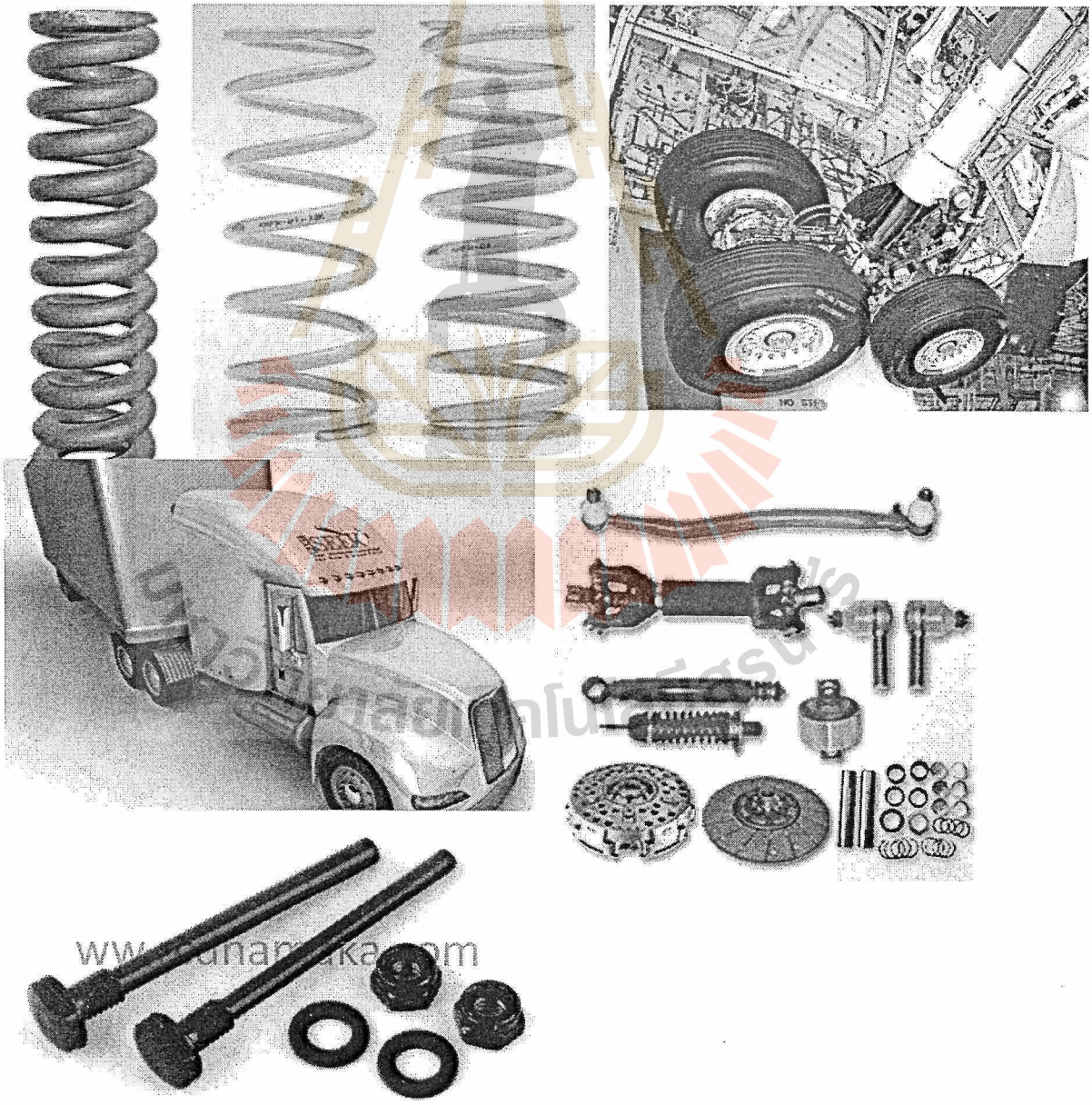
APPLICATIONS.

43XX ⇒ HEAVY-DUTY, HIGH STRENGTH PART
AS LANDING GEAR, AIRCRAFT TUBE

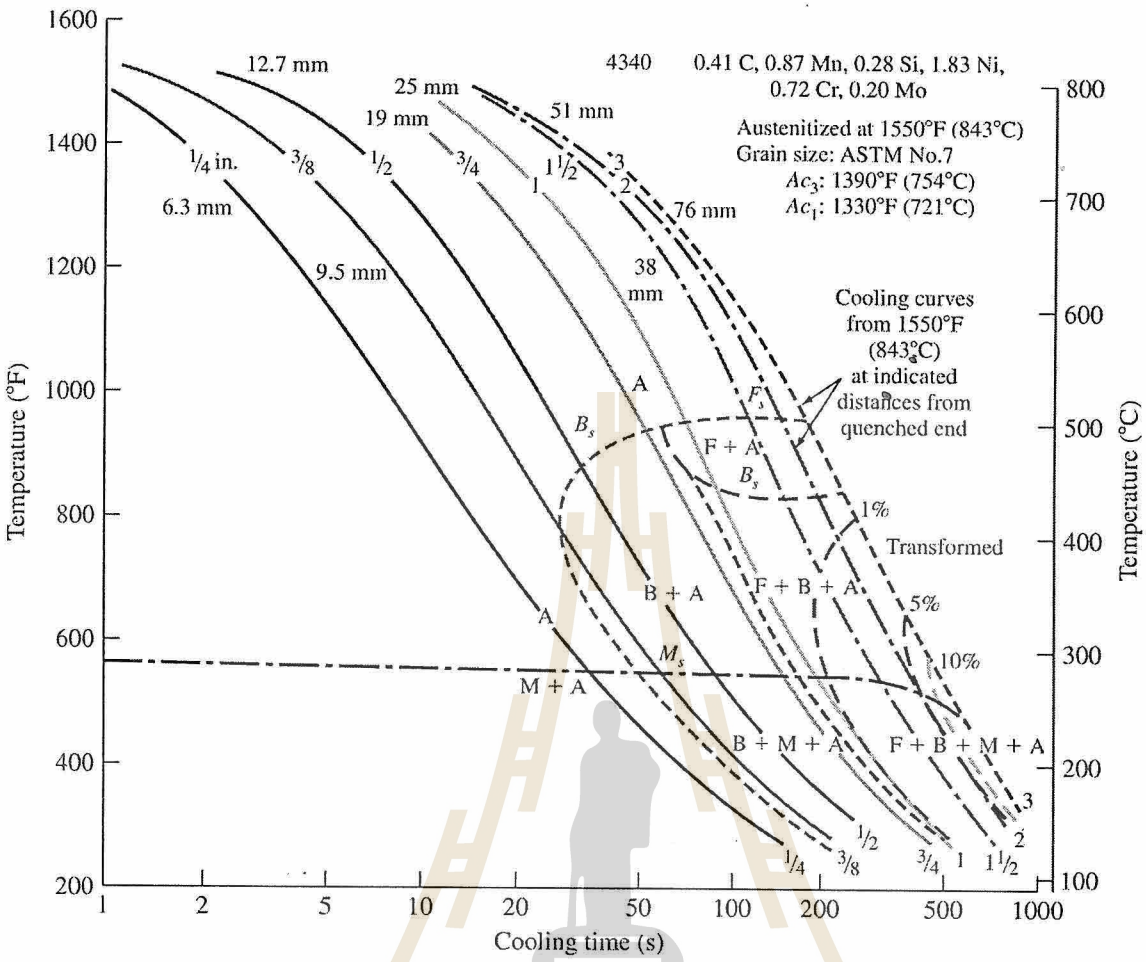
86XX ⇒ USED FOR LOWER STRENGTH REQUIRE
(LOW Ni) THAN 43XX AS SHAFT, FORGING PARTS
THAT REQUIRE HIGH-STRENGTH

Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
Nickel (1.83%)-chromium-molybdenum steels								
4340 (E)	0.40 C, 1.83 Ni, 0.90 Mn, 0.80 Cr, 0.20 Mo	Annealed Tempered*	108 250	745 1725	68 230	469 1587	22 10	Heavy sections, landing gears, truck parts
Nickel (0.55%)-chromium-molybdenum steels								
8620	0.20 C, 0.55 Ni, 0.50 Cr, 0.80 Mn, 0.20 Mo	Annealed Normalized	77 92	531 635	59 52	407 359	31 26	Transmission gears
8650	0.50 C, 0.55 Ni, 0.50 Cr, 0.80 Mn, 0.20 Mo	Annealed Tempered*	103 250	710 1725	56 225	386 1552	22 10	Small machine axles, shafts

*Tempered at 600°F (315°C).



AISI 4340. (CCT-DIAGRAM.)



(i) Ni – Cr – Mo STEEL

⇓

DELAY $\gamma \rightarrow P$ TRANSFORMATION

ให้ช้ำ มากกว่า Cr – Mo STEEL

(ii) ลด M_s ให้ต่ำลง (อยู่ที่ ~ 290 °C)

(Ni DEPRESSES M_s, A_3 & A_1)

(iii) TIME FOR BEGINNING OF $\gamma \rightarrow B$ TRANSFORMATION IS INCREASED BY Ni – Cr – Mo

4340 NORMALIZING.

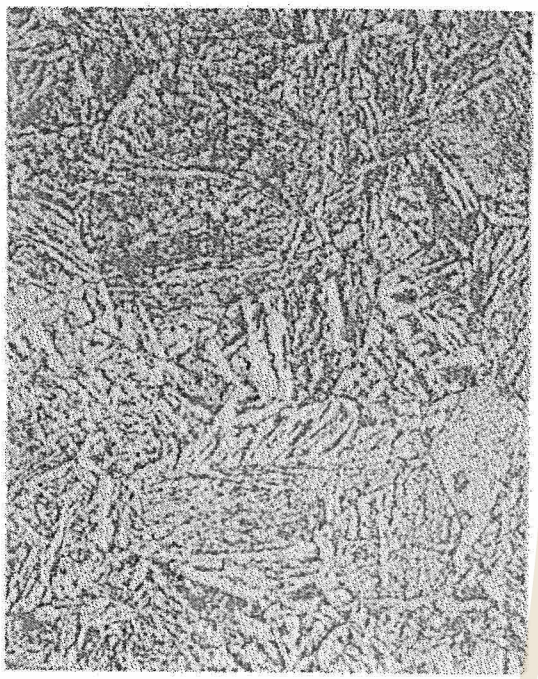


FIGURE 4-30
Alloy 4340 normalized at 871°C for 1 h and air-cooled; structure consists of upper bainite. (Etch: 2% nital; 400 × .) (*Courtesy of Republic Steel Co.*)

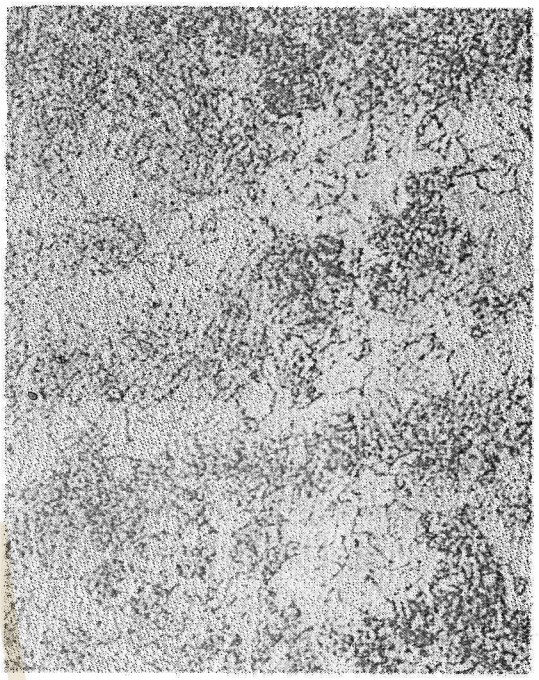


FIGURE 4-31
Alloy 4340 normalized at 871°C for 1 h, air-cooled, and annealed at 691°C for 24 h, tempered structure, tending toward spheroidization. (Etch: 2% nital; 400 × .) (*Courtesy of Republic Steel Co.*)

① NORMALIZING

AUSTENITIZED
(871 °C, 1 HR)
⇓
AIR – COOLED

UPPER BAINITE STRUCTURE

② NORMALIZED & ANNEALED

AUSTENITIZED
(871 °C, 1 HR.)
⇓
AIR-COOLED
⇓
ANNEALED
(691 °C, 24 HR)

TEMPERED-STRUCTURE WITH SPHEROID CARBIDES

4340 HARDENING.

FIGURE 4-32
Alloy 4340 austenitized at 843°C for 1 h and oil-quenched; structure consists of martensite with some possible retained austenite. (Etch: 2% nital; 400×.) (*Courtesy of Republic Steel Co.*)

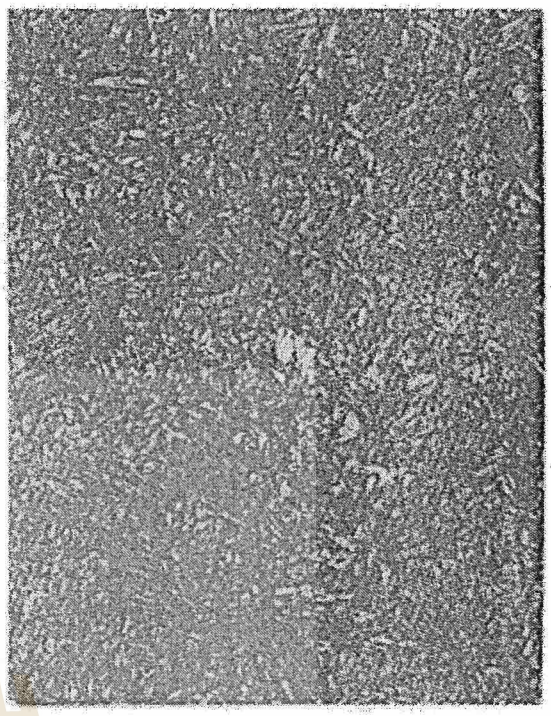


FIGURE 4-33
Alloy 4340 austenitized at 843°C for 1 h, oil-quenched and tempered 4 h at 538°C; structure consists of tempered martensite. (Etch: 2% nital; 400×.) (*Courtesy of Republic Steel Co.*)

1.

HARDENING.

AUSTENITIZED
(843 °C, 1 HR)
⇓
OIL-QUENCHED

MARTENSITE
WITH
SOME RETAINED-γ

2

HARDENING & TEMPERING

AUSTENITIZED
(843 °C, 1 HR)
⇓
OIL-QUENCHED
⇓
TEMPERED
(538 °C, 4 HR.)

TEMPERED MARTENSITE
STRUCTURE

Ni – Si – Cr – Mo STEELS.

(AISI 4340 + 2% Si)

ADDED 2% Si TO 4340 FOR INCREASING STRENGTH & TOUGHNESS.

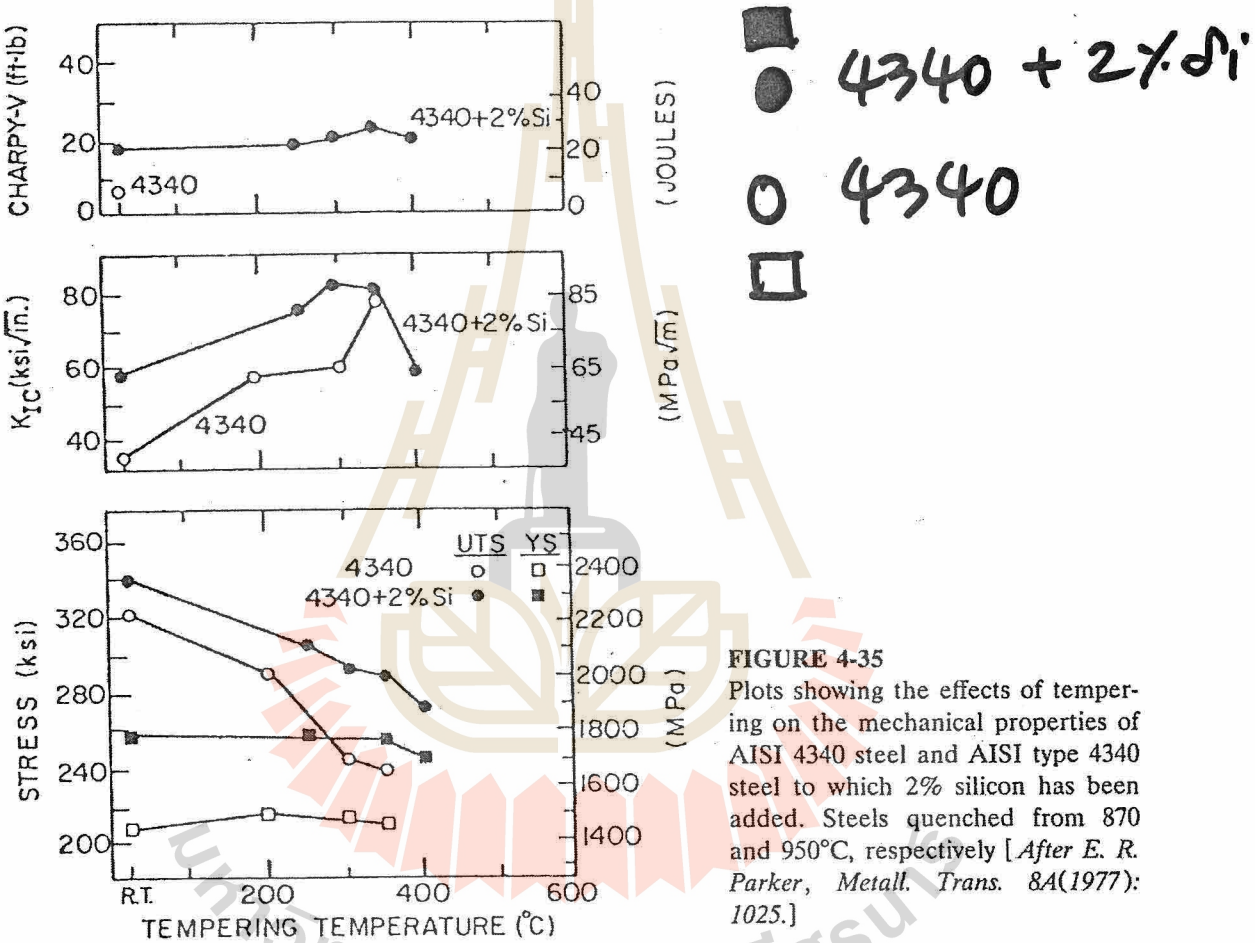


FIGURE 4-35
Plots showing the effects of tempering on the mechanical properties of AISI 4340 steel and AISI type 4340 steel to which 2% silicon has been added. Steels quenched from 870 and 950°C, respectively [*After E. R. Parker, Metall. Trans. 8A(1977): 1025.*]

TOUGHNESS ↑ ⇒ DUE TO Si RETARD THE PRECIPITATION OF Fe_3C FROM γ IN TEMPERED MARTENSITE

(LOW-Si, RETAINED-γ DECOMPOSES UPON TEMPERING IN 200–370°C & Fe_3C FILMS FORM AROUND ITS ⇒ CAUSE TO MARTENSITIC EMBRITTLE

* WITH 2% Si ⇒ STRONGER & TOUGHER IN TEMPERING.

EX. 300M ALLOY STEEL (ULTRA-HIGH STRENGTH

0.4 %C, 0.75 %Mn, 1.6 %Si, 0.8 %Cr, 1.8 %Ni

0.4 %Mo, 0.08 %V, P&S 0.015 % MAX.

(4340 + 1.6 %Si + 0.08 %V WITH LOW P&S)

V ⇒ GRAIN REFINER

LOW P&S ⇒ REDUCE TEMPER BRITTLENESS

(INCREASE TOUGHNESS & DUCTILITY)

APPLY VACUUM-ARC-REMELTED TO LOW H&O

FOR MINIMIZE OXIDE INCLUSIONS AND INCREASE

TOUGHNESS

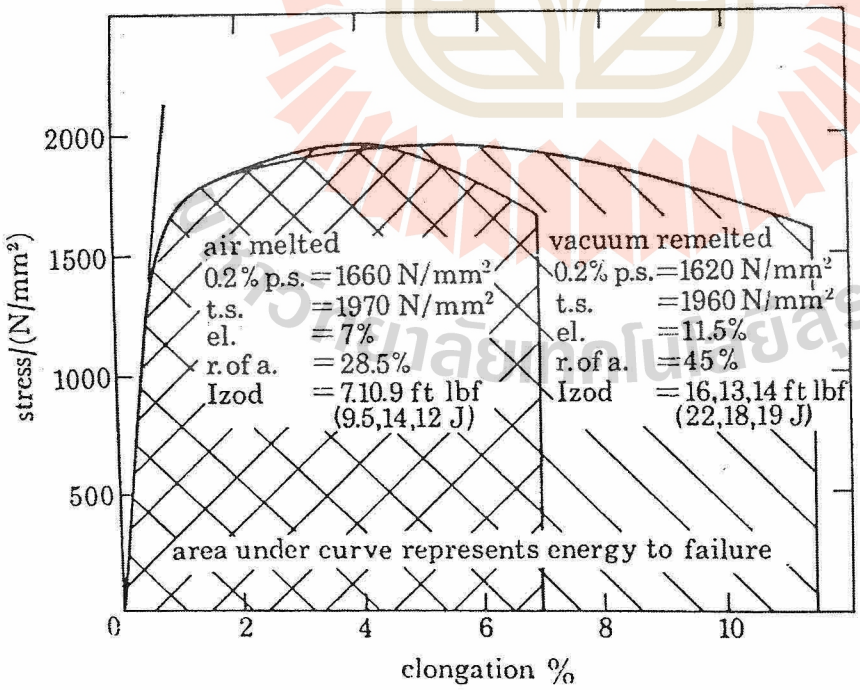


FIGURE 4-36
Energy absorbed in fracturing air and vacuum remelted 300M alloy steel (transverse properties)
[*After W. M. Imrie, Royal Soc. London Phil. Trans. A282(1976):91.*]

TOOL STEELS.

USED FOR WORKING & SHAPING BASIC MAT. e.g. METALS, PLASTICS & WOOD INTO SHAPES.

TOOL STEEL → HIGH C-STEEL & ALLOY STEELS

⇓

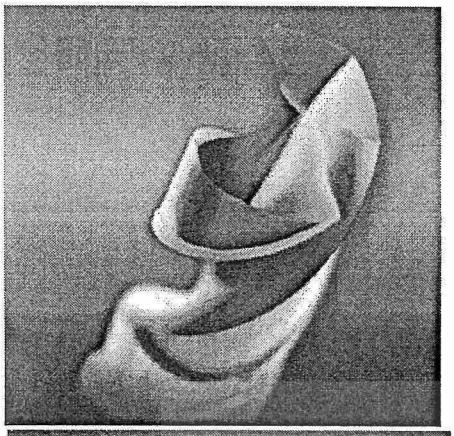
" CAPABLE TO HARDENING & TEMPERING

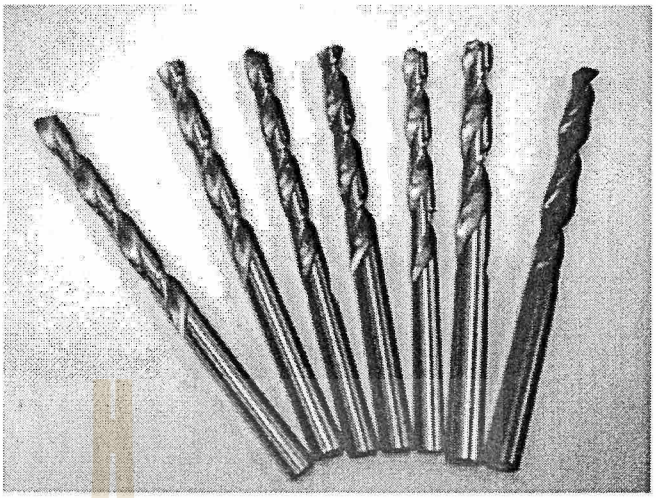
REQUIRE PROPERTIES:

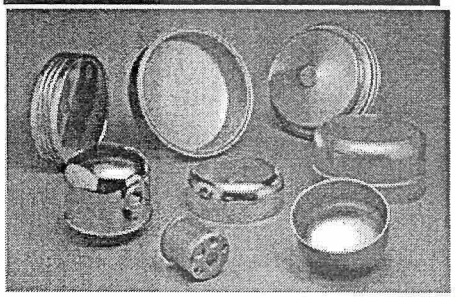
- HIGH HARDNESS & WEAR RESISTANCE
- HEAT RESISTANCE & SUFFICIENT STRENGTH TO WORK (RESIST TO SOFTENING)
- DIMENSION STABILITY

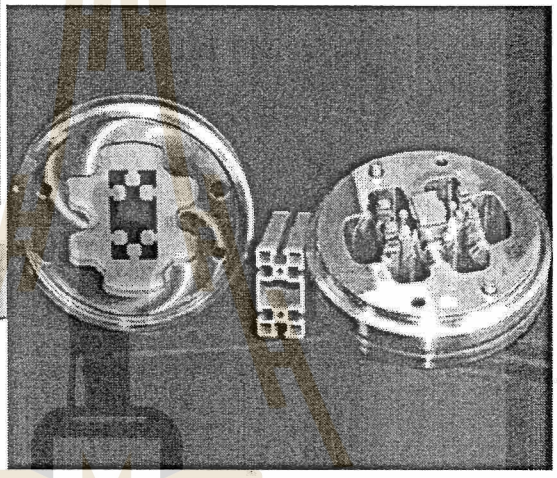
APPLICATONS:

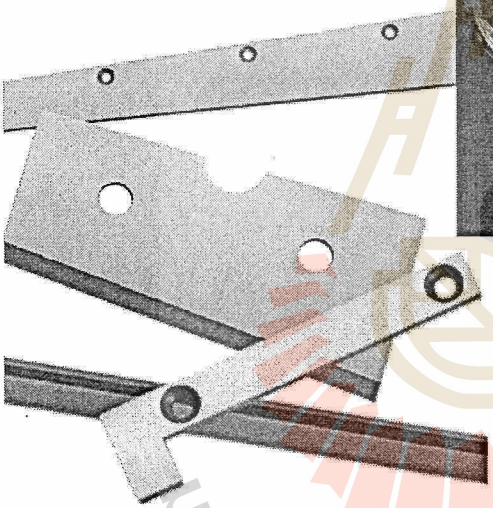
DRILLS, DEEP-DRAWING DIE, SHEAR BLADE PUNCHES, EXTRUSION DIE, CUTTING TOOLS, HIGH-SPEED CUTTING TOOLS.

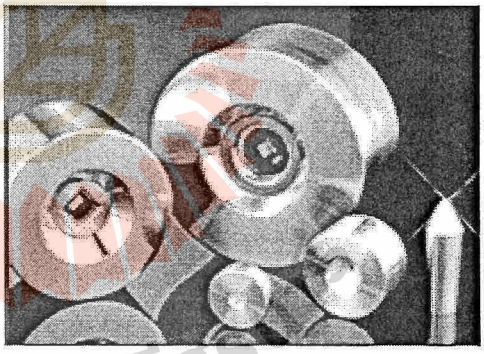


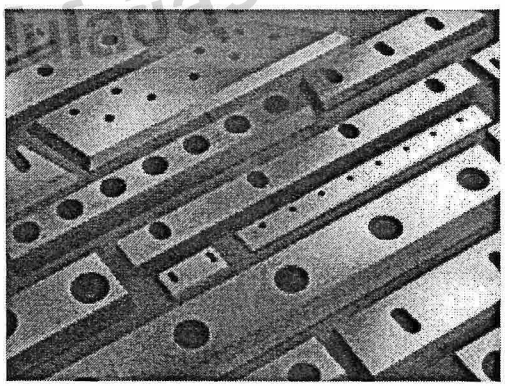












CLASSIFICATION OF TOOL STEELS.

1. WATER-HARDENING (W-TYPE)
2. SHOCK-RESISTANT (S-TYPE)
3. COLD-WORK TOOL STEELS
   - 3.1 OIL-HARDENING (O-TYPE)
   - 3.2 AIR-HARDENING (A-TYPE)
   - 3.3 HIGH-C, HIGH-Cr (D-TYPE)
4. HOT-WORK TOOL STEELS (H-TYPE)
   - 4.1 Cr-TYPE ($H_1 - H_{19}$)
   - 4.2 W-TYPE ($H_{20} - H_{39}$)
   - 4.3 Mo-TYPE ($H_{40} - H_{59}$)
5. HIGH-SPEED TOOL STEELS
   - 5.1 TUNGSTEN TYPE (T-TYPE)
   - 5.2 MOLYBDENUM TYPE (M-TYPE)
6. SPECIAL PURPOSE TOOL STEELS
   - LOW ALLOY (L-TYPE)
8. MOLD TOOL STEELS (P-TYPE)

WATER-HARDENING TOOL STEELS.

(W - TYPE)

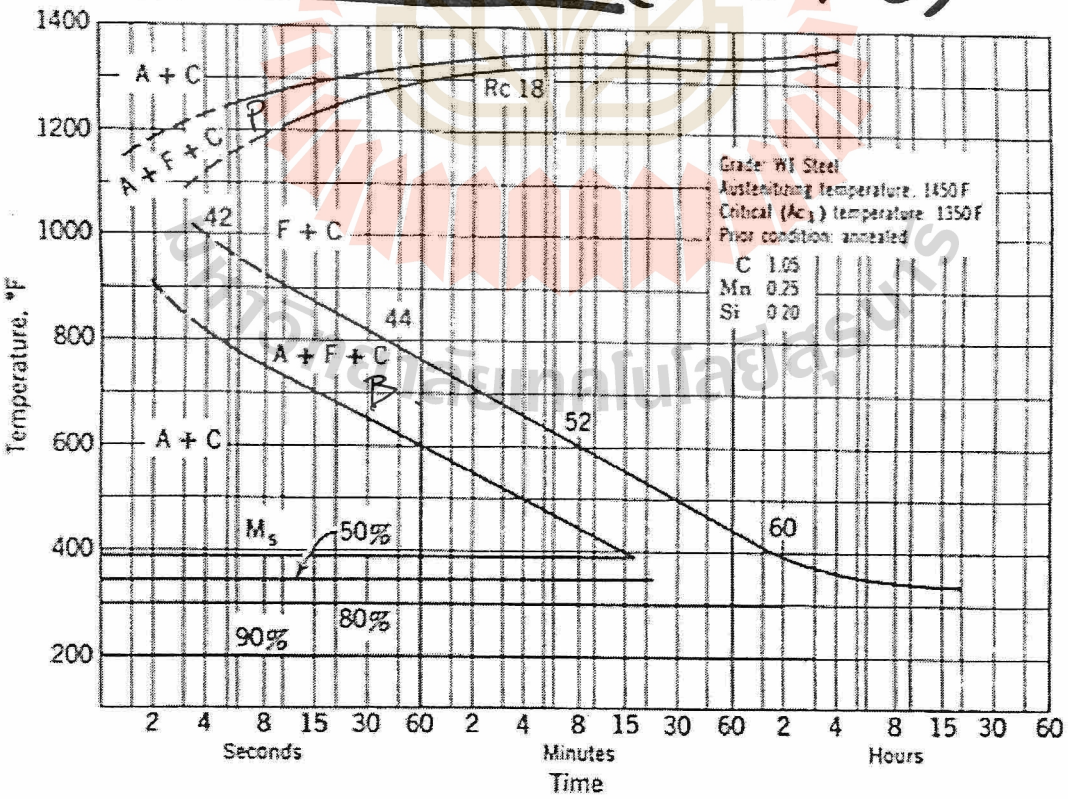
→ LESS EXPENSIVE (เหล็กเครื่องมือชนิดอื่นๆ)

→ LOWEST WEAR-RESIST. (VERY LOW HARDENABILITY.)

TABLE 9-2
Chemical compositions and typical applications of water-hardening (W-type) tool steels†

AISI type	% C	% W	% Mo	% Cr	% V	Typical applications
W1	0.60–1.40	...	...	...	...	Low carbon: blacksmith tools, blanking tools, caulking tools, cold chisels, forging dies, rammers, rivet sets, shear blades, punches, sledges. Medium carbon: arbors, beading tools, blanking dies, reamers, bushings, cold heading dies, chisels, coining dies, countersinks, drills, forming dies, jeweler dies, mandrels, punches, shear blades, woodworking tools. High carbon: glass cutters, jeweler dies, lathe tools, reamers, taps and dies, twist drills, woodworking tools. Vanadium content of W2 imparts finer grain, greater toughness, and shallow hardenability.
W2	0.60–1.40	...	...	...	0.25	
W5	1.10	...	...	0.50	...	Heavy stamping and draw dies, tube-drawing mandrels, large punches, reamers, razor blades, cold-forming rolls and dies, wear plates.

IT-DIAGRAM OF W1. (1.05 % C)



VERY SMALL AMOUNT OF ALLOYING ADDED

⇓

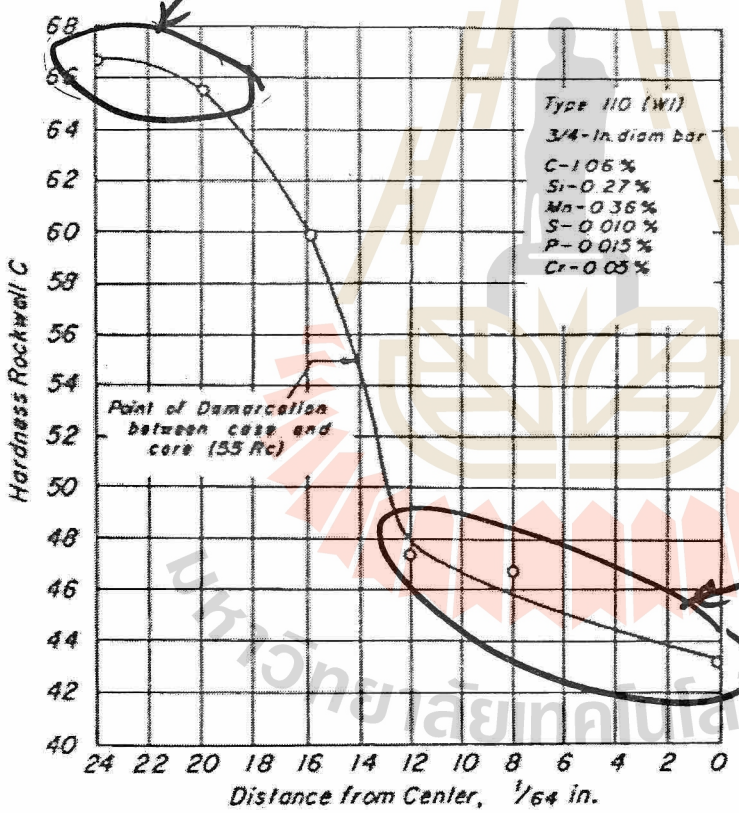
VERY LOW HARDENABILITY.

ONLY WATER-QUENCHED TO HARDENING
(FORM MARTENSITE.)

OUTSIDE (HARDER)
ONLY CASE : $\gamma \longrightarrow$ MARTENSITE

INSIDE
BUT CORE : $\gamma \longrightarrow$ PEARLITE
(SOFTER)

CASE (OUTSIDE)



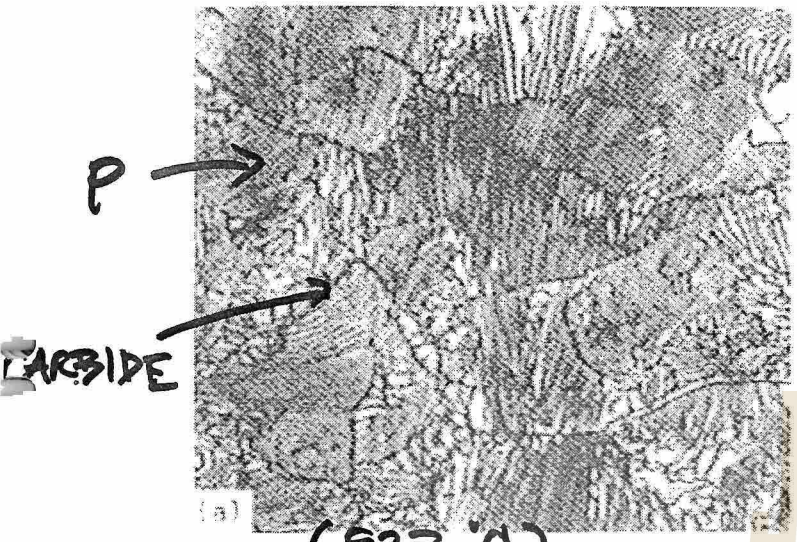
HRC.

W1
1.06 %C

CORE (INSIDE)

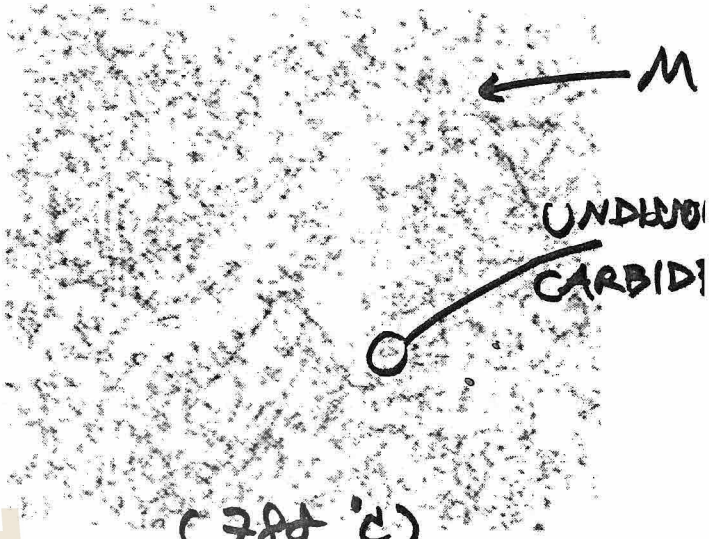
FIGURE 9-1
(Top) Isothermal transformation (IT) diagram from a type W1 water-hardening tool steel. Open part of curve around 1000°F indicates lack of good data for precise position of lines. (*After P. Payson, "Metallurgy of Tool Steels," 1962, p. 63. Reproduced by permission of John Wiley & Sons, Inc.*) (Bottom) Hardness penetration on $\frac{3}{4}$-in bar of W1 tool steel brine quenched from 815°C. Visual measurement of case depth is $\frac{10}{64}$ in from surface. At this point the hardness of R_c55, (*After G. A. Roberts, J. C. Hamaker, and A. R. Johnson, "Tool Steels," 3d ed., American Society for Metals, Metals Park, Ohio, 1962.*)

① W1 (1.10 % C)



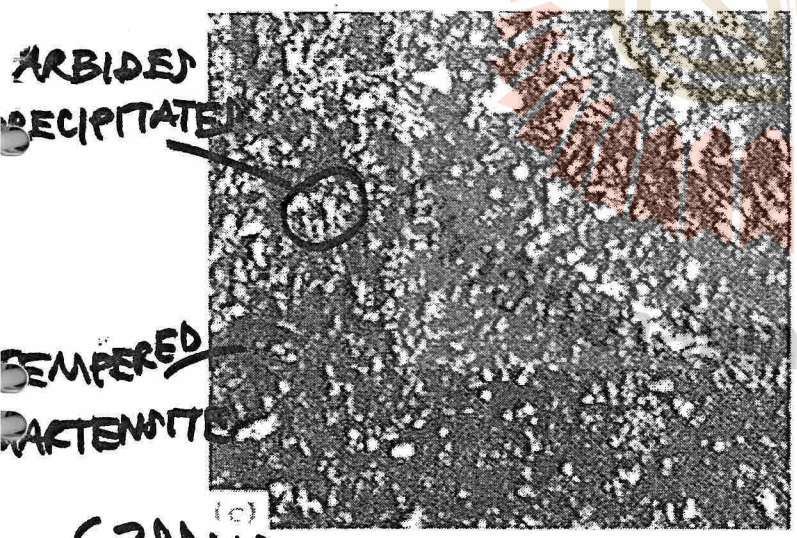
(927 °C)
NORMALIZING
⇓
"PEARLITIC"
227 BHN
(≈ 20 HRC)

② W1 (0.94 % C)



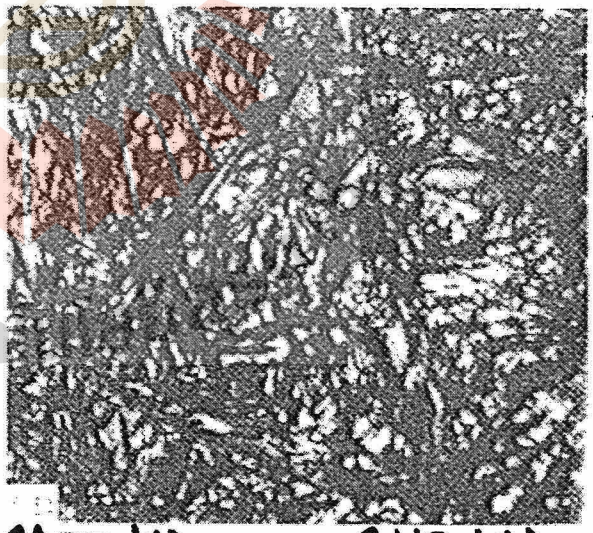
(788 °C)
QUENCHING
⇓
"MARTENSITIC"
65 HRC.

③ W1 (0.94 % C)



(788 °C)
QUENCHED & TEMPERED
⇓
"TEMPERED MARTENSITE"
52 HRC

④ W1 (0.94 % C)



(857 °C) (163 °C)
QUENCHED & TEMPERED
⇓
"COARSE TEMPERED MARTENSITE
+
RETAINED – γ"
OVERHEATING

W2 ⇒ 0.25 % V ADDED

⇓

INHIBIT GRAIN GROWTH DURING AUSTENITIZING

(V DISSOLVED IN Fe_3C, LOWER ITS SOLUBILITY)

↓

MORE STABLE CARBIDE

BUT. CARBIDES ARE NUCLEATING AGENTS FOR PEARLITE → DECREASE HARDENABILITY

W5 ⇒ 0.50 % Cr ADDED

⇓

INCREASE HARDENABILITY

(CARBIDE DISSOLVED DURING AUSTENITIZING) ENRICHED OF Cr IN γ AND INHIBITS THE PEARLITE REACTION.

SHOCK-RESISTANT TOOL STEELS.

(S-TYPE)

TABLE 9-3
Chemical compositions and typical applications of shock-resistant (S-type) tool steels†

LOWER.

AISI type	% C	% W	% Mo	% Cr	% V	% Other	Typical applications
S1	0.50	2.50	...	1.50	...	...	Bolt header dies, chipping and caulking chisels, pipe cutters, concrete drills, expander rolls, forging dies, forming dies, grippers, mandrels, punches, pneumatic tools, scarfing tools, swaging dies, shear blades, track tools, master hobs.
S2	0.50	...	0.50	...	...	1.00 Si	Hand and pneumatic chisels, drift pins, forming tools, knockout pins, mandrels, nail sets, pipe cutters, rivet sets, screw driver bits, shear blades, spindles, stamps, tool shanks, track tools.
S5	0.55	...	0.40	...	...	0.80 Mn, 2.00 Si	Hand and pneumatic chisels, drift pins, forming tools, knockout pins, mandrels, nail sets, pipe cutters, rivet sets and busters, screw driver bits, shear blades, spindles, stamps, tool shanks, track tools, lathe and screw-machine collets, bending dies, punches, rotary shears.
S6	0.45	...	0.40	1.50	...	1.40 Mn, 2.25 Si	Shear blades, aluminum impact extrusion dies and punches, rivet sets, cold-coining dies, cold header punches, knockout punches.
S7	0.50	...	1.40	3.25	...	...	Shear blades, punches, slitters, chisels, forming dies, hot header dies, blanking dies, rivet sets, gripper dies, engraving dies, plastic molds, die-casting dies, master hobs, beading tools, caulking tools, chuck jaws, clutches, pipe cutters, swaging dies.

⇒ REQUIRE TOUGHNESS (USED FOR IMPACT STRESS), WITH HARDNESS INCREASE BY SECONDARY HARDENING

⇒ LOWER C-CONTENT (0.50 %C) THAN OTHER (USED AT LOWER HARDNESS, 56-60 HRC)

⇒ APPLICATIONS: SHEAR BLADES, CHISELS, RIVET SETS.

S5 : 0.55% C, 0.35% Mo, 2.0% Si, 0.8% Mn

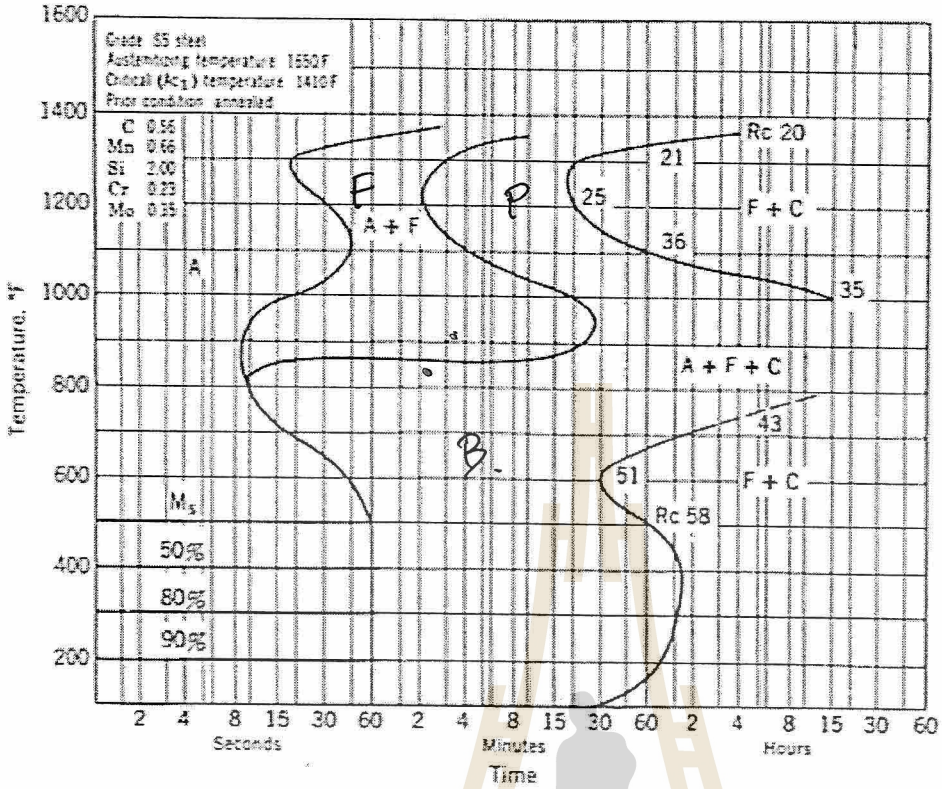


FIGURE 9-3
IT diagram of type S5 shock-resistant tool steel. (*After P. Payson, "Metallurgy of Tool Steels," Wiley, 1962, p. 60. Reproduced by permission of John Wiley & Sons, Inc.*)

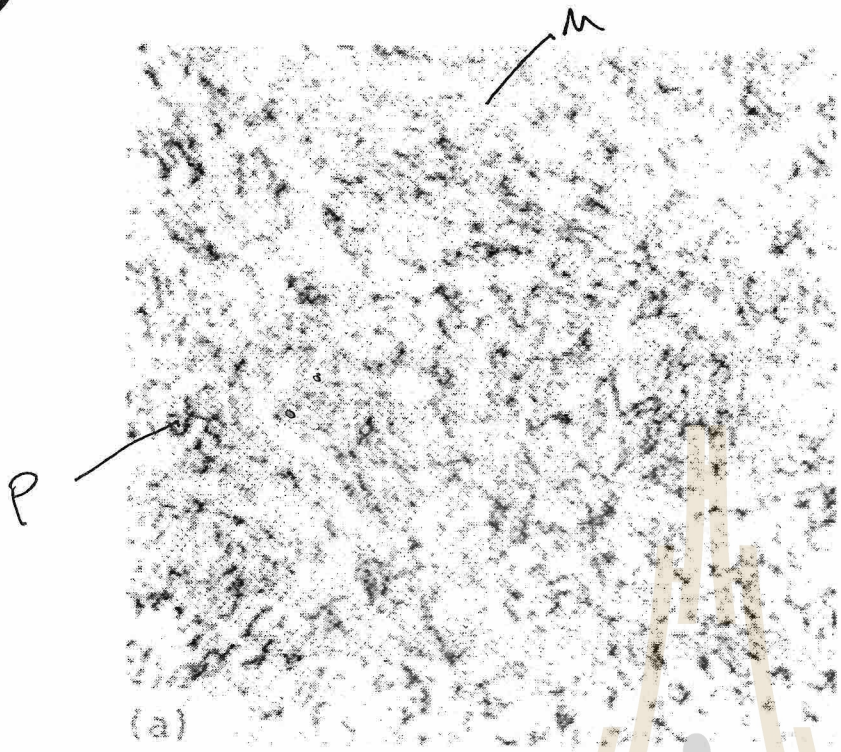
S5 ⇒ LOW-PRICE & MEDIUM HARDENABILITY

AUSTENITIZING COMPLETE AT HIGH ($\alpha \rightarrow \gamma$) TEMPERATURE ≈ 927 °C

S7 (0.5% C, 1.4% Mo & 3.25% Cr)

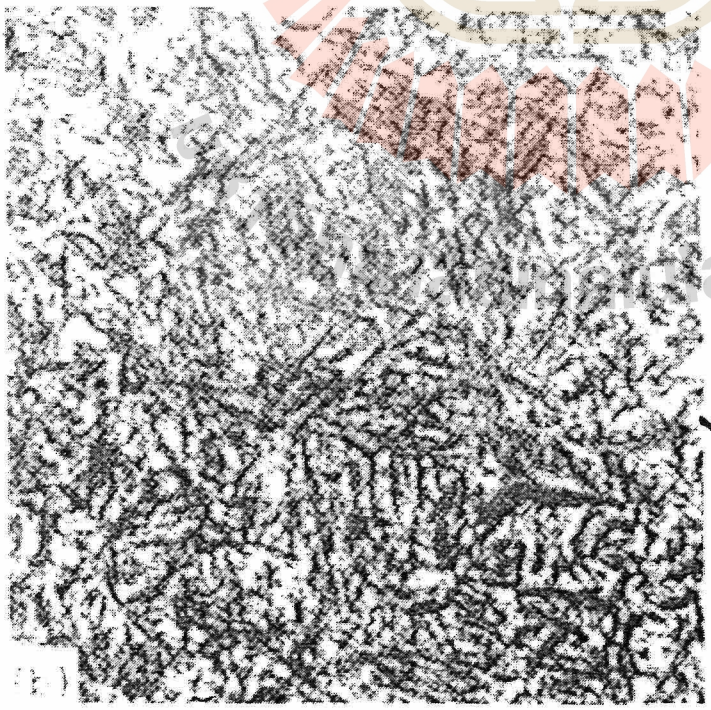
- INCREASED DEPTH OF HARDENING (HIGH Mo & Cr FOR INCREASE HARDENABILITY
- LOW-C FOR HIGH TOUGHNESS

① S5 : NORMALIZING



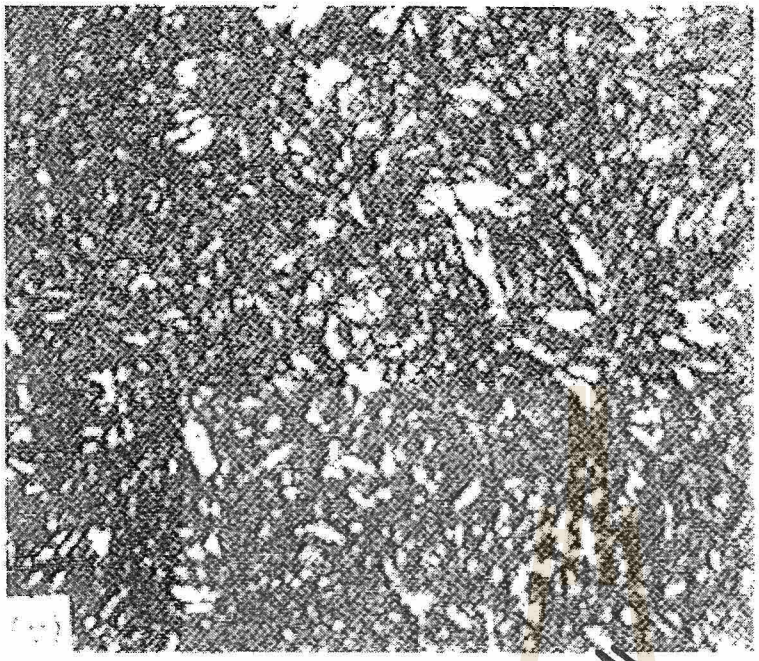
AUSTENITIZED
(927 °C, 1 HR)
⇓
AIR-COOLED
⇓
"MARTENSITE"
+
"COARSE PEARLITE"

② S5 : OIL-QUENCHED



AUSTENITIZED
(899 °C)
⇓
OIL-QUENCHED
⇓
"FINE MARTENSITE"

③ S5 : Q & T.



AUSTENITIZED
(899 °C)
⇓
OIL-QUENCHED
⇓
TEMPERED
(399 °C)
⇓

FINE TEMPERED MARTENSITE

COLD-WORK TOOL STEELS.

USED FOR: COLD-WORK TOOL & DIE APPLICATIONS

(RESISTANCE TO WEAR & REQUIRE TOUGHNESS)

GROUPS OF CW TOOL STEELS.

1. OIL-HARDENING (O-TYPE)
2. AIR-HARDENING (A-TYPE)
3. HIGH-C, HIGH-Cr (D-TYPE)

CW OIL-HARDENING TOOL STEELS.

(O - TYPE)

TABLE 9-4
Chemical compositions and typical applications of cold-work oil-hardening (O-type) tool steels†

AISI type	% C	% W	% Mo	% Cr	% V	% Other	Typical applications
O1	0.90	0.50	...	0.50	...	1.00 Mn	Blanking dies, plastic mold dies, drawing dies, trim dies, paper knives, shear blades, taps, reamers, tools, gauges, bending and forming dies, bushings, punches.
O2	0.90	...	...	...	...	1.60 Mn	Blanking, stamping, trimming, cold-forming dies and punches, cold-forming rolls, threading dies and taps, reamers, gauges, plugs and master tools, broaches, circular cutters and saws, thread roller dies, bushings, plastic-molding dies.
O6	1.45	...	0.25	...	...	0.80 Mn, 1.00 Si	Blanking dies, forming dies, mandrels, punches, cams, brake dies, deep-drawing dies, cold-forming rollers, bushings, gauges, blanking and forming punches, piercing and perforating dies, taps, paper-cutting dies, wear plates, tool shanks, jigs, machine spindles, arbors, guides in grinders and straighteners.
O7	1.20	1.75	...	0.75	...	...	Mandrels, slitters, skiving knives, taps, reamers, drills, blanking and forming dies, gauges, chasers, brass finishing tools, dental burrs, paper knives, roll turning tools, burnishing dies, pipe-threading dies, rubber-cutting knives, woodworking tools, hand reamers, scrapers, spinning tools, broaches, blanking and cold-forming punches.

→ HIGH AS-QUENCHED HARDNESS

→ HIGH HARDENABILITY

→ FREEDOM FROM CRACKING ON QUENCHING

→ MAINTAIN SHARP EDGE FOR CUTTING

(BUT. CAN NOT USED FOR CUTTING AT HIGH SPEED & FOR HOT-WORING)

HIGHER

O1 (0.9% C, 0.5% W, 0.5% Cr, 1.0% Mn)

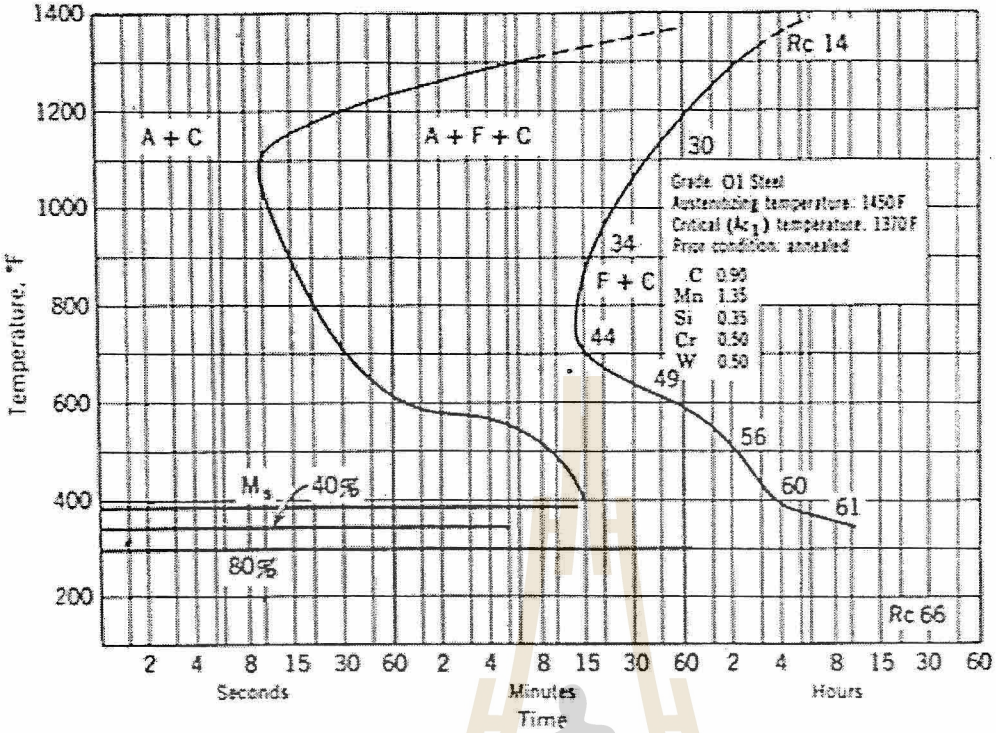


FIGURE 9-5
IT diagram of type O1 oil-hardening tool steel. (*After P. Payson, "Metallurgy of Tool Steels," Wiley, 1962, p. 64. Reproduced by permission of John Wiley & Sons, Inc.*)

→ HIGH-C & Mn WITH W & Cr

⇓

INCREASE HARDENABILITY

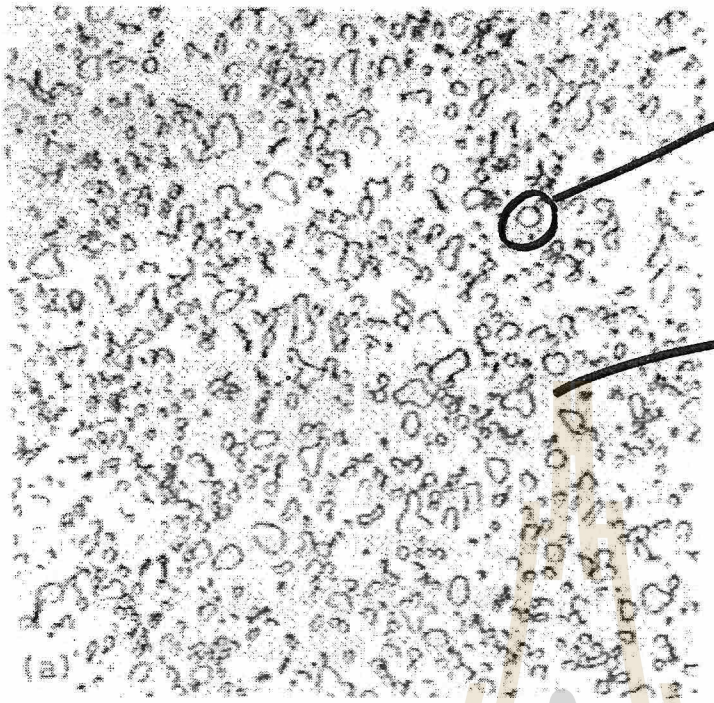
→ SLOWER OIL-QUENCHING RATE CAN BE PRODUCE MARTENSITIC STRUCTURE

⇓

LESS DIMENSION CHANGE, DISTORTION AND CRACKING THAN WATER-QUENCHED.

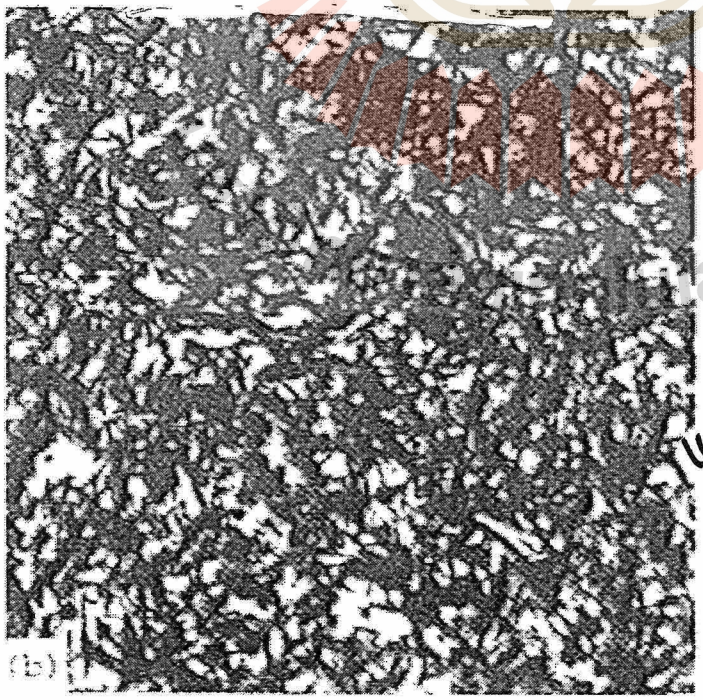
O1 (0.94% C, 1.20% Mn, 0.5% W, 0.5% Cr)

① O1 : FULL-ANNEALED.



SPHEROID CARBIDE IN FERRITE MATRIX

② O1 : NORMAL OIL-QUENCHED



MOST OF CARBIDE DISSOLVE
SMALL AMOUNT OF UNDISSOLVED-C
BIDI

↑

AUSTENITIZED (815 °C)

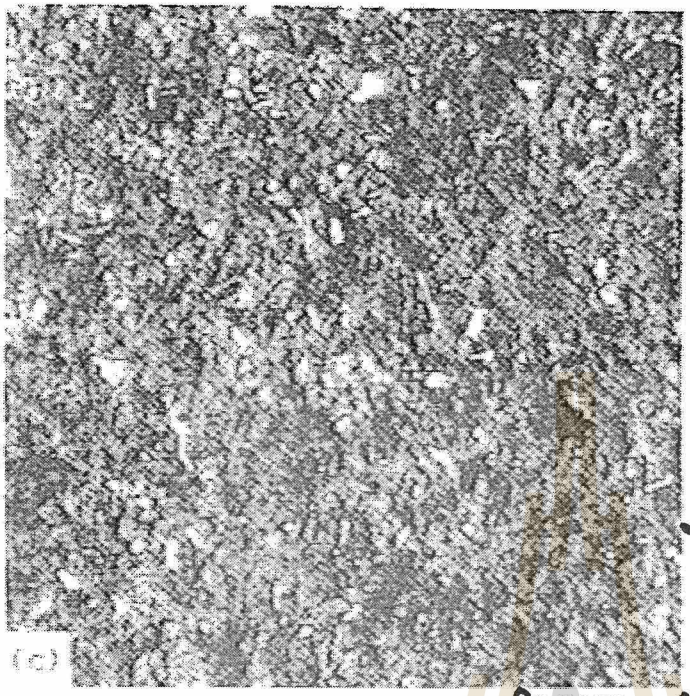
⇓

OIL-QUENCHED

⇓

UNTEMPERED - M
+
SOME UNDISSOLVED-C
+
BAINITE & RETAINED-γ
(WHITE)

③ O1: Q & T



AUSTENITIZED
(815 °C)
⇓
OIL-QUENCHED
⇓
TEMPERED
(150 °C, 2HR.)
⇓
TEMPERED-M MATRIX
+
SOME NON-DISSOLVED CARBIDE

④ O1: OVERHEAT.

AUSTENITIZED
(927 °C)
⇓
OIL-QUENCHED
⇓
TEMPERED
(150 °C, 2HR.)
⇓
COARSE STRUCTURE
RETAINED
+
FEW NON-DISSOLVED CARBIDE

CW AIR-HARDENING TOOL STEELS

(A - TYPE)

TABLE 9-5
Chemical compositions and typical applications of cold-work (medium-alloy) air-hardening (A-type) tool steels†

AISI type	% C	% W	% Mo	% Cr	% V	% Other	Typical applications
A2	1.00	...	1.00	5.00	...	...	Thread-rolling dies, extrusion dies, trimming dies, blanking dies, coining dies, mandrels, shear blades, slitters, spinning rolls, forming rolls, gauges, beading dies, burnishing tools, ceramic tools, embossing dies, plastic molds, stamping dies, bushings, punches, liners for brick molds.
A3	1.25		1.00	5.00	1.00	...	
A4	1.00	...	1.00	1.00	...	2.00 Mn	Blanking dies, forming dies, trimming dies, punches, shear blades, mandrels, bending dies, forming rolls, broaches, knurling tools, gauges, arbors, bushings, slitting cutters, cold-treading rollers, drill bushing, master hobs, cloth-cutting knives, pilot pins, punches, engraver rolls.
A6	0.70	...	1.25	1.00	...	2.00 Mn	Blanking dies, forming dies, coining dies, trimming dies, punches, shear blades, spindles, master hobs, retaining rings, mandrel, plastic dies.
A7	2.25	1.00‡	1.00	5.25	4.75	...	Brick mold liners, drawing dies, briquetting dies, liners for shot-blasting equipment and sand slingers, burnishing tools, gauges, forming dies.
A8	0.55	1.25	1.25	5.00	...	...	Cold slitters, shear blades, hot-pressing dies, blanking dies, beading tools, cold-forming dies, punches, coining dies, trimming dies, master hobs, rolls, forging die inserts, compression molds, notching dies, slitter knives.
A9	0.50	...	1.40	5.00	1.00	1.50 Ni	Solid cold-heading dies, die inserts, heading hammers, coining dies, forming dies and rolls, die casings, gripper dies. Hot-work applications: punches, piercing tools, mandrels, extrusion tooling, forging dies, gripper dies, die casings, heading dies, hammers, coining and forming dies.
A10	1.35	...	1.50	...	...	1.80 Mn, 1.25 Si, 1.80 Ni	Blanking dies, forming dies, gauges, trimming shears, punches, forming rolls, wear plates, spindle arbors, master cams and shafts, stripper plates, retaining rings.

A-TYPE SUITABLE FOR APPLICATIONS :-

- HIGH TOUGHNESS
- GOOD ABRASION RESISTANCE

USED FOR:

BLANKING, FORMING & DRAWING DIES.

WHICH LESS DIMENSION CHANGE AFTER HARDENING & TEMPERING (≈ 1/4 OF O-TYPE)

COMPOSITIONS.

1.0-2.0 % C WITH ADDED Cr, Mn, Mo, V & Ni

TWO IMPORTANT ALLOYS IN A-TYPE :-

- A2 (5% Cr, 1% Mo)
- A4 (1% Cr, 1% Mo, 2-3% Mn)

A2 (1 % C, 5 % Cr, 1 % Mo), V 0.3 %

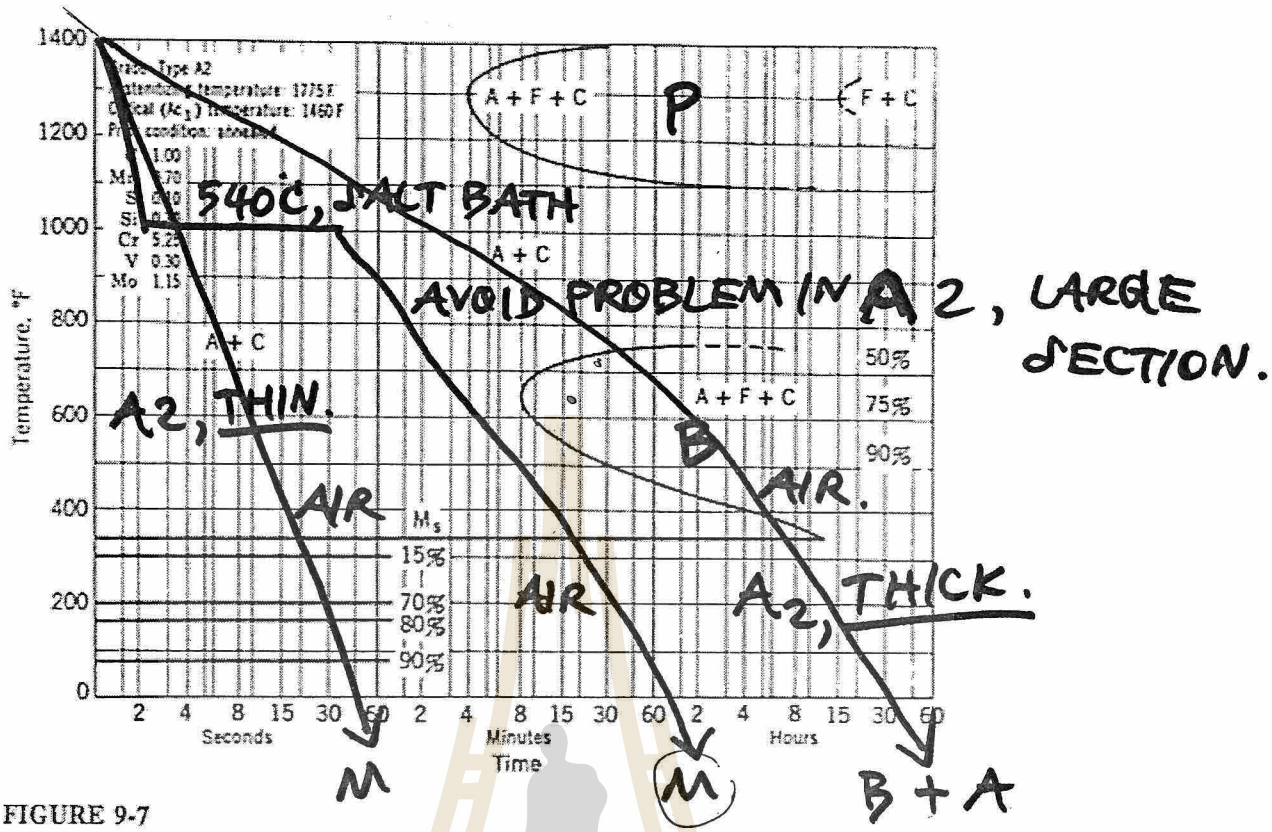


FIGURE 9-7
IT diagram of A2 type cold-work medium-alloy air-hardening tool steel. (*After P. Payson, "Metallurgy of Tool Steels," Wiley, 1962, p. 267. Reproduced by permission of John Wiley & Sons, Inc.*)

A2 ⇒ USE FOR APPLICATIONS OF TOUGHNESS MORE IMPORTANT THAN WEAR-RESISTANCE

⇒ การที่ Cr, Mo, V ทำให้เส้นโค้งของ AUSTENITE ทำให้ A_2 มี HARDENABILITY สูง

⇒ A_2, LARGE SECTION $\xrightarrow{(968°C)}$ AIR-COOLED

⇓

FORMATION OF B & A.

AVOID THE PROBLEM BY :-

AUSTENITIZED (968°C)

↓

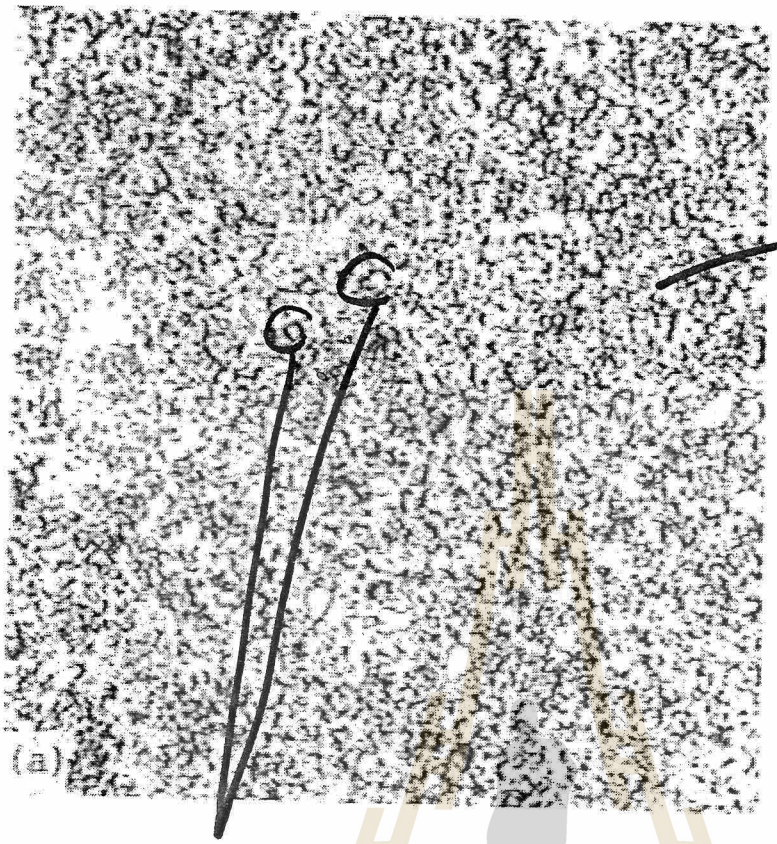
QUENCHED IN SALT BATH (540°C)

↓

AIR-COOLED.

A2 : (1.0 %C, 0.9 %Mn, 5.25 %Cr, 0.25 %V, 1.1 %Mo)

① A2 : ANNEALING.

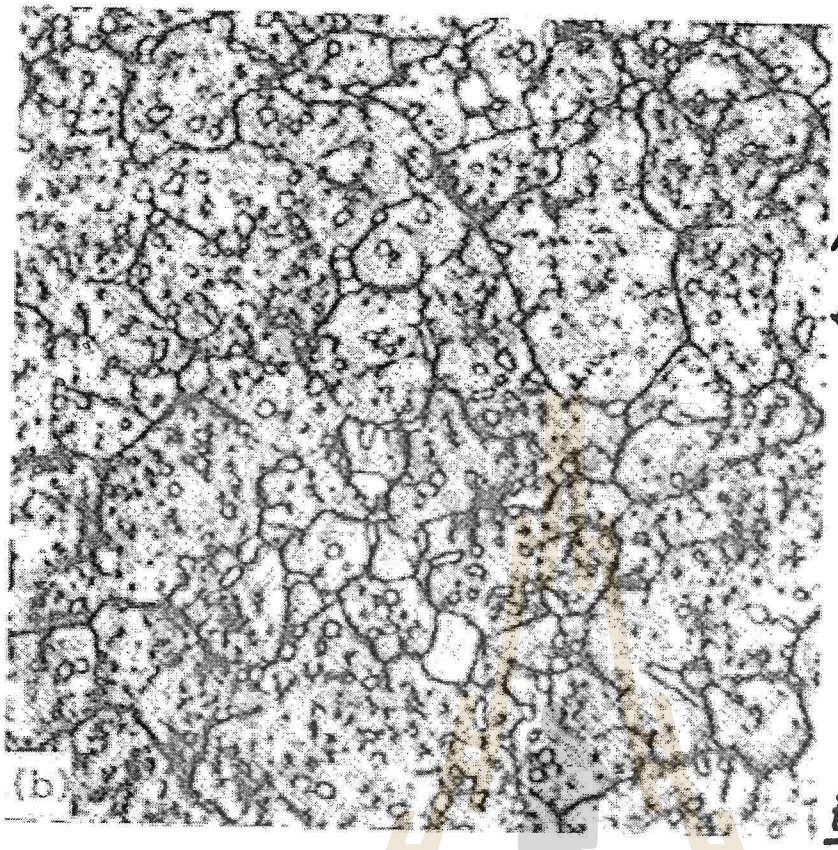


FERRITE MATRIX.

~ 15 % OF SPHEROID CARBIDES (M_7C_3, $M_{23}C_6$)

AUSTENITIZED → AIR-COOLED → DOUBLE-TEMPERED

② A2 : NORMAL HEAT-TREAT CONDITION



AUSTENITIZED
(955 °C)
MOST OF C, Cr, Mo, V
DISSOLVED IN γ

⇓

AIR-COOLED

⇓

DOUBLE-TEMPER
(232 °C, 2 HR)

FOR:

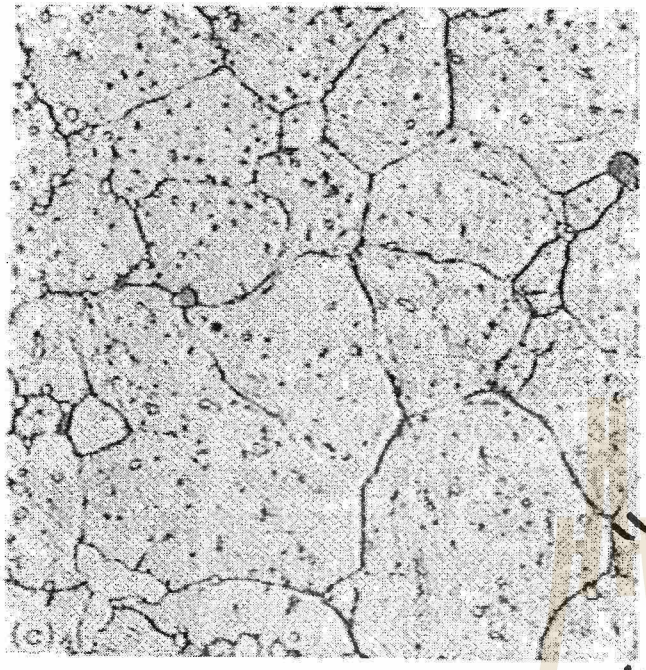
(i) TEMPERED THE M.

(ii) REDUCE RETAINED-γ
TO PREVENT DIMENSION CHA
DUE TO γ → M AT R.

STRUCTURES:

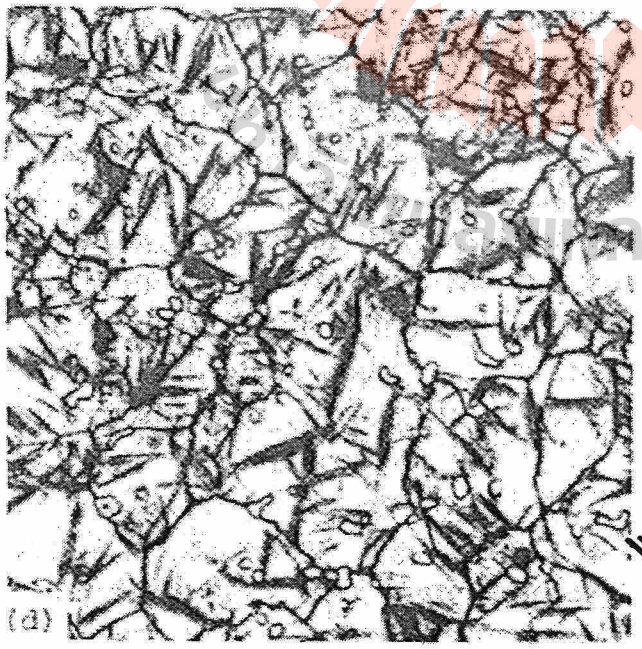
CARBIDE PARTICLES IN TEMPERED-MARTENSITE MATRIX. "

③ A2 : OVERHEAT



AUSTENITIZED
(1,010 °C)
⇓
AIR-COOLED
⇓
NO-TEMPERED
⇓
CARBIDE PARTICLES
+
UNTEMPERED-MARTENSITE
+
RETAINED-γ.

④ A2 : HOT-TEMPERING



AUSTENITIZED
(982 °C)
⇓
AIR-COOLED
(TO 204 °C)
⇓
DOUBLE-TEMPERED
(510 °C, 2 HR. EACH)
⇓
CARBIDE PARTICLES
+
TEMPERED & UNTEMPERED-M
+
RETAINED-γ

CW (HIGH-C, HIGH-Cr) TOOL STEELS.

(D-TYPE)

TABLE 9-6
Chemical compositions and typical applications of cold-work, high-carbon, high-chromium (D-type) tool steels†

AISI type	HIGH % C	% W	% Mo	HIGH % Cr	% V	% Other	Typical applications
D2	1.50	...	1.00	12.00	1.00	...	Blanking dies, cold-forming dies, drawing dies, lamination dies, thread-rolling dies, shear blades, slitter knives, forming rolls, burnishing tools, punches, gauges, knurling tools, lathe centers, broaches, cold-extrusion dies, mandrels, swaging dies, cutlery.
D3	2.25	...	...	12.00	...	...	Blanking dies, cold-forming dies, drawing dies, lamination dies, thread-rolling dies, shear blades, slitter knives, forming rolls, seaming rolls, burnishing tools, punches, gauges, crimping dies, swaging dies.
D4	2.25	...	1.00	12.00	...	...	Blanking dies, brick molds, burnishing tools, thread-rolling dies, *hot-swaging dies, wiredrawing dies, forming tools and rolls, gauges, punches, trimmer dies, dies for deep drawing.
D5	1.50	...	1.00	12.00	...	3.00 Co	Cold-forming dies, thread-rolling dies, blanking dies, coining dies, trimming dies, draw dies, shear blades, punches, quality cutlery, rolls.
D7	2.35	...	1.00	12.00	4.00	...	Brick mold liners and die plates, briquetting dies, grinding wheel molds, dies for deep drawing, flattening rolls, shot and sandblasting liners, slitter knives, wear plates, wiredrawing dies, Sendzimir mill rolls, ceramic tools and dies, lamination dies.

D-TYPE. (C, Cr, Mo, SOME V, Co)

→ HIGH WEAR-RESISTANCE ⟹ BY HIGH 12% Cr & HIGH-C (1.5–2.35%)

→ HIGH DIMENSION STABILITY (LESS DIMENSION CHANGE)

⇓

"VERY USEFUL FOR COLD-WORK DIE"

EXCELLENT WEAR-RESISTANCE OF D-TYPE

↓

BY

HIGH-Cr (12 % Cr) | HIGH-C (1.5-2.35 % C)

EX. D2 (1.5 % C, 12 % Cr)

CARBIDES ≈ 30-40 % LESS THAN D_3

D3 (2.25 % C, 12 % Cr)

→ AMOUNT OF CARBIDES DEPEND ON % C

EFFECT OF ALLOYING ADDED:

- HIGH-Cr ⇒ RESISTANCE TO OXIDATION AT HIGH-TEMP.
- ADDED SMALL AMOUNT OF Mo, V, Co, W IN D-TYP
- Mo ⇒ INCREASE HARDENABILITY & TOUGHNESS
- V ⇒ GRAIN REFINEMENT

BUT DECREASE IN HARDENABILITY.

TTT-DIAGRAM OF D2 (C, Cr, V, Mo) 1.55 12 1 1

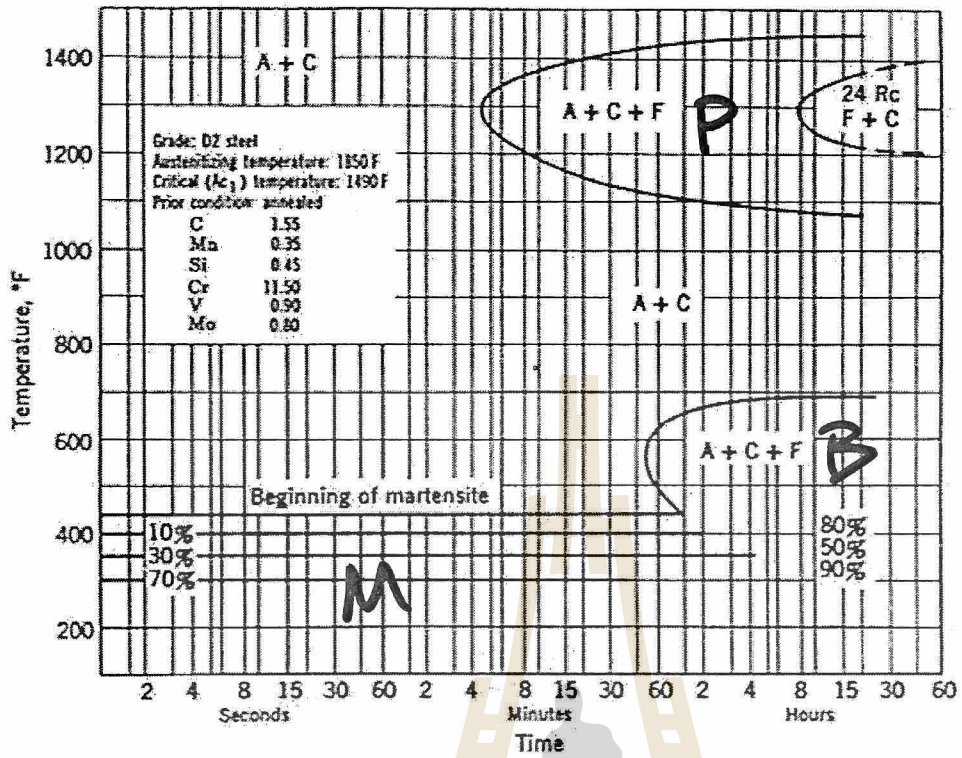
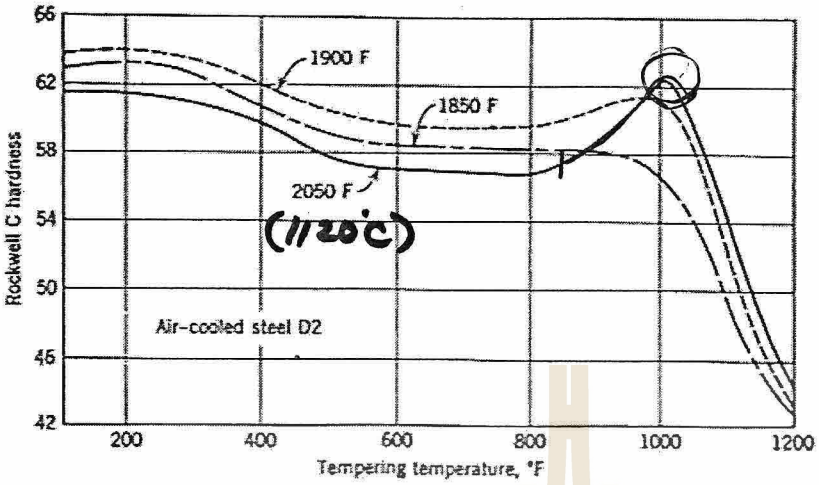


FIGURE 9-10
IT diagram of D2 (high-carbon, high-chromium) tool steel. (*After P. Payson, "Metallurgy of Tool Steels," Wiley, 1962, p. 151. Reproduced by permission of John Wiley & Sons, Inc.*)

- 0.8 % Mo ⇒ INCREASE HARDENABILITY
  ↓
  DELAY $\gamma \rightarrow P$ TRANSFORMATION
  ↓
  FULL-HARDNESS BY AIR-COOLED.
- D_2 USUALLY AIR-COOLED FROM AUTENITIZING TEMP. ≈ 1,010 – 1,038 °C
- TOO HIGH AUSTENITIZING TEMP. (> 1,090 °C)
  ↓
  MORE C & Cr DISSOLVED IN γ
  ↓
  LOWER M_f & MORE RETAINED-γ
  ↓
  LOW HARDNESS IN TEMPERED-CONDITION.

BUT AT > 500 °C ⇒ HARDNESS INCREASE BY 2nd-HARDENING

EFFECT OF AUSTENITIZING TEMP. ON HARDNESS



D2

FIGURE 9-11
Effect of austenitizing temperature on the hardness of type D2 tool steel after tempering. A large amount of retained austenite in the 1120°C (2050°F) sample causes low hardness in the tempered condition. Above about 450°C (842°F) in the 1120°C (2050°F) sample, transformation of the austenite to martensite along with precipitation of chromium carbides causes an increase in hardness. (*After P. Payson, "Metallurgy of Tool Steels," Wiley, 1962, p. 263. Reproduced by permission of John Wiley & Sons, Inc.*)

HIGH AUSTENITIZING TEMP. AT 1,120 °C

⇓

MORE RETAINED-γ

⇓

LOW HARDNESS IN TEMPERED-CONDITION

TEMPERED AT T > 450 °C.

$\gamma \rightarrow M$

WITH Cr-CARBIDE PRECIPITATE

⇓

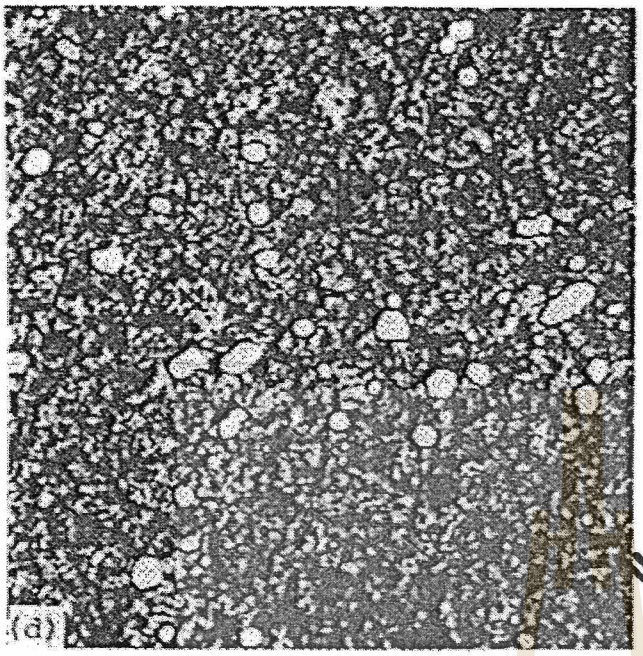
INCREASE HARDNESS

BY SECONDARY HARDENING.

EX. D2 (1.5% C, 0.3% Si, 0.5% Mn, 12% Cr 0.9% V, 0.75% Mo) IN SEVERAL HEAT-TREAT CONDITIONS.

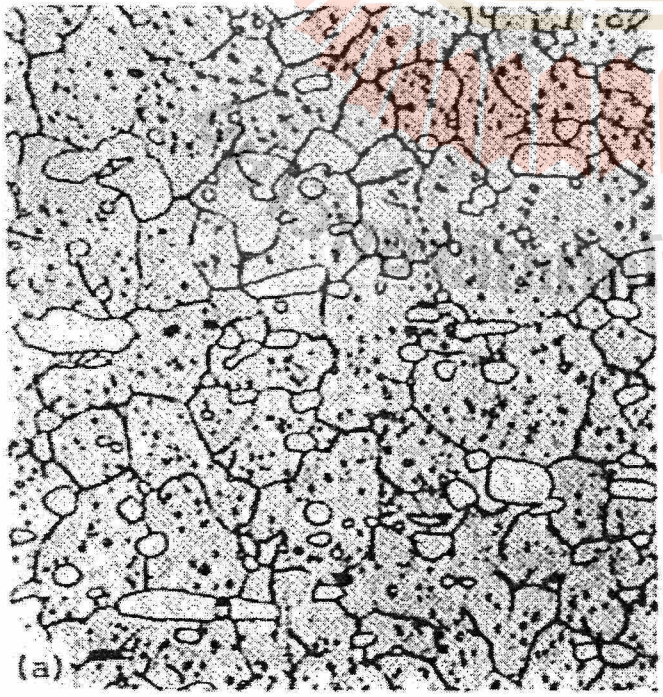
1. NORMAL HEAT-TREATED CONDITION
2. NORMAL HEAT-TREATED BUT LOW-TEMPERING TEMPERATURE
3. OVER-HEATED CONDITION
4. UNDER-HEATED CONDITION.

1) D2 : NORMAL HEAT-TREAT



AUSTENITIZED
(1,023 °C)
⇓
AIR-COOLED TO R.T.
⇓
DOUBLE-TEMPERED
(510 °C, 2 HR EACH.)
⇓
CARBIDE PARTICLES
IN
TEMPERED-M MATRIX."

2) D2: NORMAL HEAT-TREAT BUT LOW-TEMPERING TEMP.

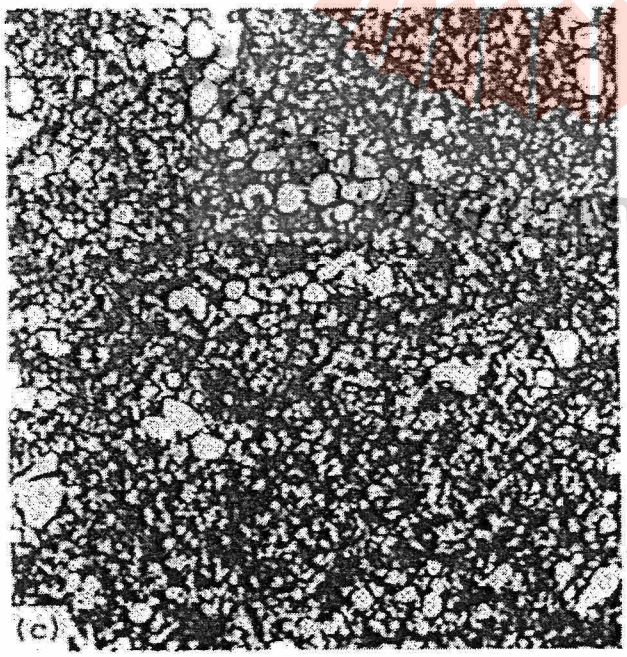


AUSTENITIZED
(1,025 °C)
⇓
AIR-COOLED TO R.T.
⇓
TEMPERED
(288 °C, 2 HR)
⇓
CARBIDE PARTICLES
IN
60-70% OF TEMPERED-M (MATRIX)
+
30-40% OF RETAINED-γ

③ D2 : OVERHEAT-TREATED.

AUSTENITIZED
(1,150 °C)
⇓
AIR-COOLED TO R.T.
⇓
DOUBLE-TEMPERED
(510 °C, 2 HR EACH)
⇓
"CARBIDE PARTICLES
IN
RETAINED-γ MATRIX
WITH
SOME TEMPERED & UNTEMPERED
MARTENSITE."

④ D2 : UNDERHEAT-TREATED



AUSTENITIZED
(982 °C)
⇓
AIR-COOLED TO R.T.
⇓
DOUBLE-TEMPERED
(510 °C, 2 HR EACH.)
⇓
"CARBIDE PARTICLES
IN
TEMPERED-M MATRIX"

HOT-WORK TOOL STEELS.

(H - TYPE)

USED FOR: HOT-WORK APPLICATIONS SUCH AS HOT EXTRUSION DIE, HOT FORGING DIE, DIE-CASTING DIE.

IMPORTANT CHARACTERISTICS.

- HIGH TOUGHNESS (SHOCK RESISTANCE IN BOT THERMAL & MECHANICAL) LOW-C
- RED-HARDNESS (RESIST TO SOFTENING WHE USE AT T = 550 °C)
- RESISTANCE TO EROSION & WEAR AT HIGH-T.
- RESISTANCE TO HEAT-CHECK (DEVELOPE OF FINE SHALLOW CRACK ON SURFACE WHEN APPLY WATER COOLING)

3- TYPE OF H.W. TOOL STEELS:

(1.) Cr- BASE : $H_1 - H_{19}$

(2) W- BASE : $H_{20} - H_{39}$

(3) Mo- BASE : $H_{40} - H_{59}$

TABLE 9-7
Nominal chemical compositions and typical applications of hot-work tool steels (H-type)†

AISI type	% C	% W	% Mo	% Cr	% V	% Other	Typical applications
					Hot work (chromium)		Cr-BASE
H10	0.40	...	2.50	3.25	0.40	...	Mandrels, extrusion and forging dies, die holders, bolsters and dummy blocks, punches, die inserts, gripper and header dies, hot shears, aluminum die-casting dies, inserts for forging dies and upsetters, shell-piercing tools.
H11	0.35	...	1.50	5.00	0.40	...	die-casting dies, punches, piercing tools, mandrels, extrusion tooling, forging dies, high-strength structural components.
H12	0.35	1.50	1.50	5.00	0.40	...	Extrusion dies, dummy blocks, holders, gripper and header dies, forging-die inserts, punches, mandrels, sleeves for cold-heading dies.
H13	0.35	...	1.50	5.00	1.00	...	Die-casting dies and inserts, dummy blocks, cores, ejector pins, plungers, sleeves, slides, extrusion dies, forging dies and inserts.
H14	0.40	5.00	...	5.00	...	...	Backer blocks, die holders, aluminum and brass extrusion dies, press liners, dummy blocks, forging dies and inserts, gripper dies, shell-forging points and mandrels, hot punches, pushout rings, dies and inserts for brass forging.
H19	0.40	4.25	...	4.25	2.00	4.25 Co	Extrusion dies and die inserts, dummy blocks, punches, forging dies and die inserts, mandrels, hot-punch tools.

- 5% Cr ⇒ HIGH HARDENABILITY IN LARGE SECTION
  ↓
  HARDENED BY AIR-COOLED
  (MIN. DIMENSION CHANGE.)
- HIGH-Si OF H13 (1.00% Si)
  ↓
  IMPROVE OXIDATION RESISTANCE AT AUSTENITIZED (1,010 °C)
- 5% Cr, 1.5% Mo ⇒ IN SOLUTION ⇒ เพิ่ม TTT-CURVE
  (LONG TIME TRANSFORMATION)

TABLE 9-7 (*Continued*)

AISI type	% C	% W	% Mo	% Cr	% V	% Other	Typical applications
				Hot work (tungsten)			W – BASE
H21	0.35	9.00	...	3.50	...	...	Mandrels, hot-blanking dies, hot punches, blades for flying shear, hot trimming dies, extrusion and die-casting dies for brass, dummy blocks, piercer points, gripper dies, hot-nut tools (crowners, cutoffs, side dies, piercers), hot headers.
H22	0.35	11.00	...	2.00	...	...	Mandrels, hot-blanking dies, hot punches, blades for flying shear, hot-trim dies, extrusion dies, dummy blocks, piercer points, gripper dies.
H23	0.30	12.00	...	12.00	...	...	Extrusion and die-casting dies for brass, brass and bronze permanent molds.
H24	0.45	15.00	...	3.00	...	...	Punches and shear blades for brass, hot-blanking and drawing dies, trimming dies, dummy blocks, hot-press dies, hot-punches, gripper dies, hot-forming rolls, hot-shear blades, swaging dies, hot-heading dies, extrusion dies.
H25	0.25	15.00	...	4.00	...	...	Hot-forming dies, die-casting and forging dies, die inserts, extrusion dies and liners, shear blades, blanking dies, gripper dies, punches, hot-swaging dies, nut piercers, piercer points, mandrels, high-temperature springs.
H26	0.50	18.00	...	4.00	1.00	...	Mandrels, hot-blanking dies, hot punches, blades for flying shear, hot-trimming dies, extrusion dies, dummy blocks, piercer points, gripper dies, pipe-threadings dies, nut chisels, forging-press inserts, extrusion dies for brass and copper.
				Hot work (molybdenum)			Mo – BASE
H42	0.60	6.00	5.00	4.00	2.00	...	Cold-trimming dies, hot-upsetting dies, dummy blocks, header dies, hot-extrusion dies, cold-header and extrusion dies and die inserts, hot-forming and swaging dies, nut piercers, hot punches, mandrels, chipping chisels.

TTT-CURVE OF H13

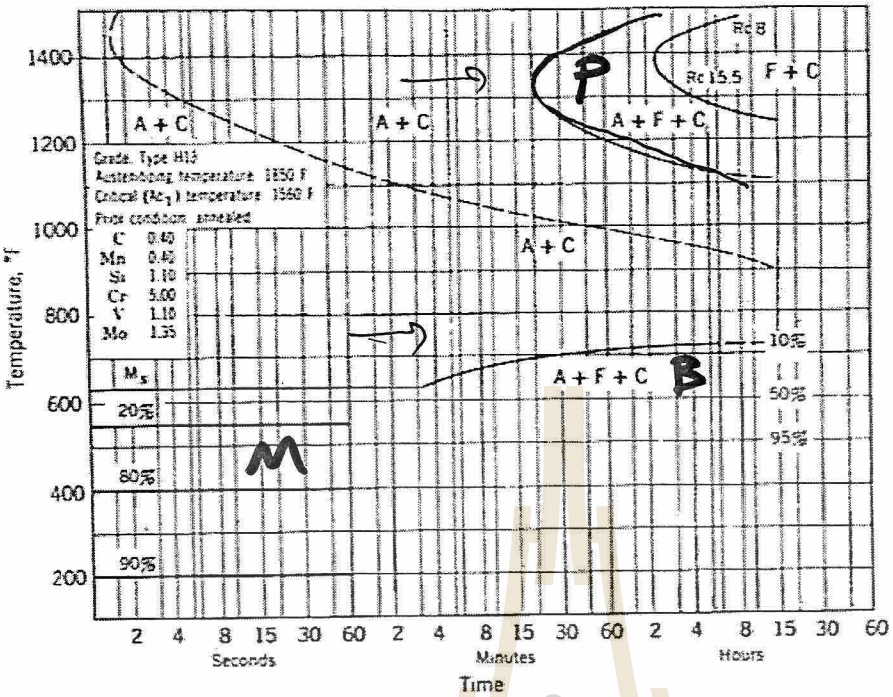


FIGURE 9-13
IT diagram for type H13 hot work tool steel. Since the steel contains residual carbides as austenitized at 1010°C, the constituents, austenite and carbide, are present to the left and below the carbide precipitation line as well as to the right and above. (*After P. Payson, "Metallurgy of Tool Steels," Wiley, 1962, p. 227. Reproduced by permission of John Wiley & Sons, Inc.*)

5% Cr & 1.35% Mo. IN H13

⇓

MAKING LONG-TIME OF TRANSFORMATION.

HEAT-TREATMENT OF H_{13}

① AUSTENITIZED (AT ≈ 1,010 °C), 1 HR.

- Mo & Cr-CARBIDES ARE DISSOLVED IN γ
- ONLY V-CARBIDES REMAINS UNDISSOLVED

② OIL/AIR COOLED TO R.T.

- CONSIST OF MARTENSITE, RETAINED-γ AND SOME BAINITE

③ DOUBLE-TEMPERED (AT. ≈ 578 °C)

- TO OBTAIN MAX. DIMENSION STABILITY

1st-TEMPERING ⇒ RETAINED γ ⟶ MARTENSITE

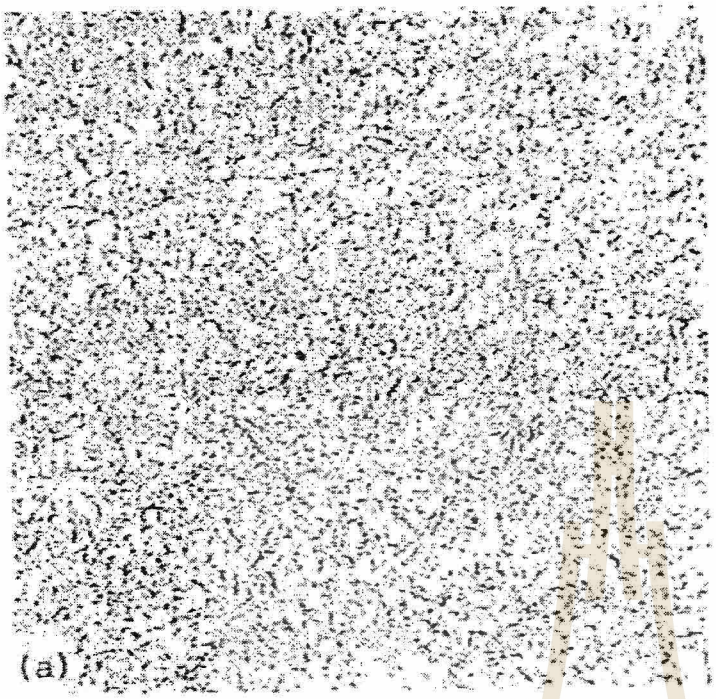
(CALL "CONDITIONING")

2nd-TEMPERING ⇒ MARTENSITE

↓

TEMPERED-MARTENSITE

③ FULL-ANNEALING



~ 3.5% ALLOY CARBI

(Mo_6C, Cr_7C_3, VC)

FINE SPHEROID CARBIDE

+

FERRITE MATRIX.

EFFECT OF TEMPERING TEMP. VS. HARDNESS.

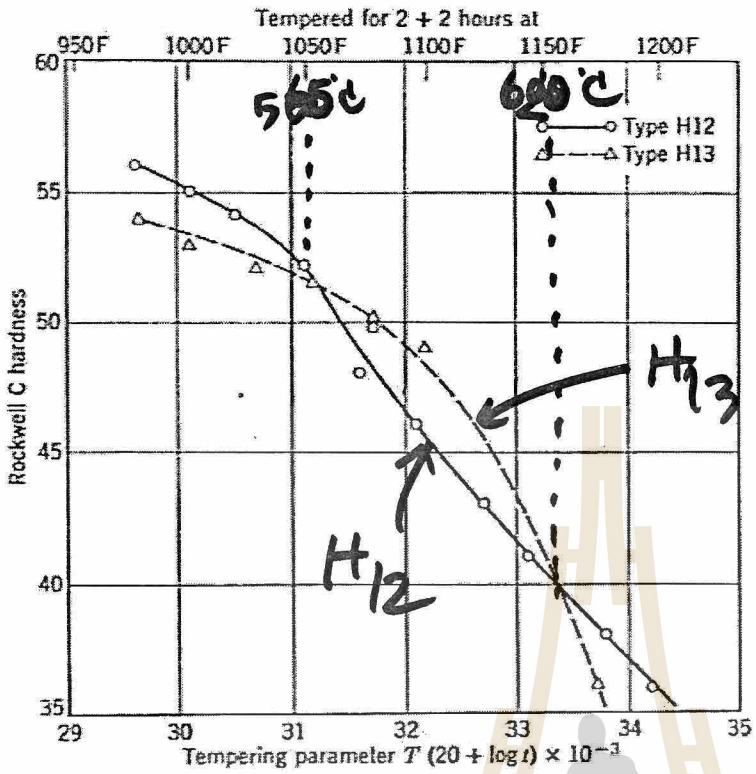


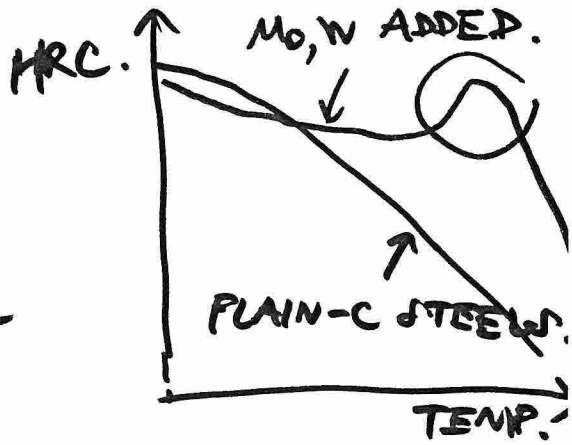
FIGURE 9-14
Tempering curves for H13 and H12 hot-work tool steels. Note that H13 has better resistance to softening in the temperature range of most importance for hot-work steels. (*After P. Payson, "Metallurgy of Tool Steels," Wiley, 1962, p. 229. Reproduced by permission of John Wiley & Sons, Inc.*)

H_{13} BETTER RESIST TO SOFTENING IN HOT-WORK TEMP. RANGE THAN H_{12}

H_{13} ⇒ MAINTAIN 45 HRC AFTER 4 HR. TEMPERING AT ~ 610 °C.

HIGH SPEED TOOL STEEL

SECONDARY HARDENING OF Mo & W-STEELS



PLAIN-C STEELS.

⇓

TEMPERED AT 100 – 700 °C

⇓

STRENGTH WILL DECREASE WITH INCREASING OF DUCTILITY → "SOFTENING"

DUE TO :-

- FORMATION OF Fe_3C
- Fe_3C COARSENING IN α-MATRIX

⇓

CHANGE IN MECHANICAL PROPERTIES.

BY REPLACING Fe_3C WITH MORE STABLE CARBIDE (e.g. WC, Mo_2C) ⇒ REDUCE SOFTENING EFFECT.

⇓

IF ADDED IN SUFFICIENT AMOUNTS

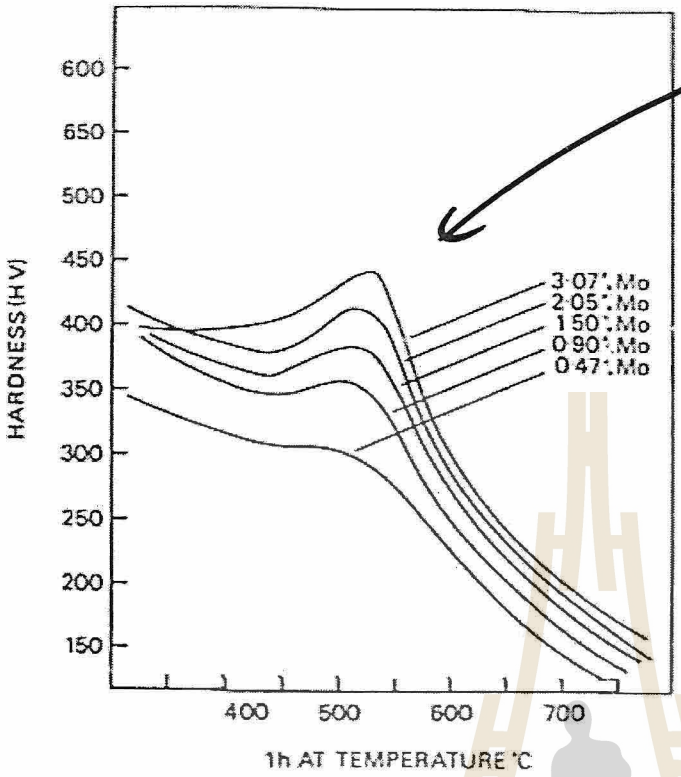
⇓

HARDNESS INCREASING AT 500 – 650 °C

⇓

RE-HARDENING EFFECT ⇒ "SECONDARY HARDENING"

2nd-HARDENING IN Mo-STEEL.



0.5-3.0% Mo

⇓

PRODUCE 2nd-HARDENING IN QUENCHED 0.1% C STEELS.

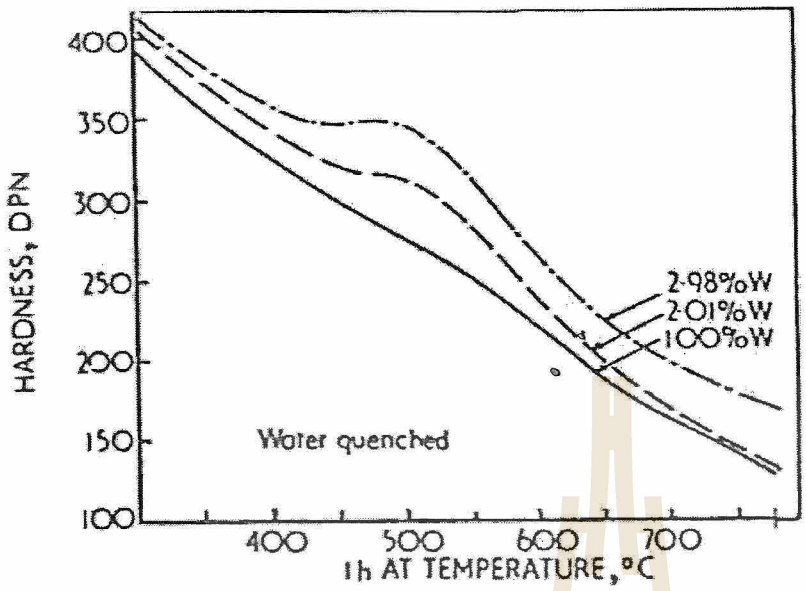
FIGURE 9-16
Effect of molybdenum on the tempering of quenched 0.1% C steels. [*After K. J. Irvine and F. B. Pickering, "The Tempering Characteristics of Low-Carbon Low-Alloy Steels," J. Iron Steel Inst. 194(1960):137.*]

CAUSED BY: VERY FINE PRECIPITATE OF Mo_2C NEEDLES IN DISLOCATION NETWORK FORMED BY QUENCHING TO MARTENSITE

⇓

MAX. 2nd-HARDENING AT 550 °C.

2nd - HARDENING IN W-STEEL.



LESS EFFECT THAN Mo.

FIGURE 9-18
Effect of tungsten on the tempered hardness of quenched 0.1% C steels. [*After K. J. Irvine and F. B. Pickering, "The Tempering Characteristics of Low-Carbon Low-Alloy Steels," J. Iron Steel Inst. 194(1960):137.*]

PRECIPITATION OF W_2C DURING TEMPERING.

<u>BUT.</u> LARGER W_2C-PARTICLES & MORE FAR APART THAN Mo_2C-PARTICLES.

$\Downarrow$

POSSIBLE THAT DISLOCATION NETWORK HAS TIME TO COARSEN BEFORE LOCKING BY W_2C-PARTICLES

HIGH-SPEED TOOL STEELS.

(T AND M-TYPES)

USED FOR: HIGH-CUTTING RATES OF VERY HARD METALS (NAME "HIGH-SPEED"

CUTTING AT HIGH-SPEED.

⇓

CAUSE HIGH-TEMP. AT TOOL TIP INTO RED-RANG

MUST BE RESISTANT TO TEMPERING AT THESE TEMP.

⇓

ABILITY OF STEEL TO RESIST SOFTENING IN RED-HEAT RANGE NAMED "RED-HARDNESS."

IMPORTANT PROPERTY OF HIGH-SPEED TOOL STEE

PROPERTIES OF HIGHSPEED TOOL STEELS:

→ GOOD WEAR RESISTANCE

→ HIGH HARDNESS TO RETAIN A SHARP CUTTING EDGE FOR PROLONGED PERIOD

COMPOSITIONS:

HIGH-SPEED TOOL STEELS.

⇓

ADDED W OR Mo FOR

↙ ↘

CARBIDE FORMATION & RED HARDNESS.

V ⇒ INCREASE ABRASION RESISTANCE

Cr ⇒ REDUCING OXIDATION & INCREASED HARDNESS

Co ⇒ IMPROVE HIGH-TEMP. HARDENING

HIGH-SPEED TOOL STEELS DIVIDED INTO 2 GROUPS

1. TUNGSTEN (W), T-TYPE
2. MOLYBDENUM (Mo), M-TYPE.

TABLE 9-8

Nominal chemical compositions and typical applications for selected high-speed tool steels†

AISI type	% C	% W	% Mo	% Cr	% V	% Other	Typical applications
				High speed (tungsten)			
T1	0.75	18.00	...	4.00	1.00	...	Drills, taps, reamers, hobs, lathe and planer tools, broaches, crowners, burnishing dies, cold-extrusion dies, cold-heading die inserts, lamination dies, chasers, cutters, taps, end mills, milling cutters.
		(W-Cr-V) 18-4-1 ⇒ T1					
T2	0.80	18.00	...	4.00	2.00	...	Lathe and planer tools, milling cutters, form tools, broaches, reamers, chasers.
T4	0.75	18.00	...	4.00	1.00	5.00 Co	Lathe and planer tools, drills, boring tools, broaches, roll-turning tools, milling cutters, shaper tools, form tools, hobs, single-point cutting tools.
T5	0.80	18.00	...	4.00	2.00	8.00 Co	Lathe and planer tools, form tools, cutoff tools, heavy-duty tools requiring high red hardness.
T6	0.80	20.00	...	4.50	1.50	12.00 Co	Heavy-duty lathe and planer tools, drills, checking tools, cutoff tools, milling cutters, hobs.
T8	0.75	14.00	...	4.00	2.00	5.00 Co	Boring tools, lathe tools, heavy-duty planer tools, tool bits, single-point cutting tools for stainless steel.
T15	1.50	12.00	...	4.00	5.00	5.00 Co	Form tools, lathe and planer tools, broaches, milling cutters, blanking dies, punches, heavy-duty tools requiring good wear resistance.
				High speed (molybdenum)			
M1	0.85	1.50	8.50	4.00	1.00	...	Drills, taps, end mills, reamers, milling cutters, hobs, punches, lathe and planer tools, form tools, saws, chasers, broaches, routers, woodworking tools.
	C	W	Mo	Cr	V		
M2	0.85; 1.00	6.00	5.00	4.00	2.00	...	Drills, taps, end mills, reamers, milling cutters, hobs, form tools, saws, lathe and planer tools, chasers, broaches and boring tools.
M3-1	1.05	6.00	5.00	4.00	2.40	...	Drills, taps, end mills, reamers and counterbores, broaches, hobs, form tools, lathe and planer tools, cheeking tools, milling cutters, slitting saws, punches, drawing dies, routers, woodworking tools.

TABLE 9-8 (*Continued*)

AISI type	% C	% W	% Mo	% Cr	% V	% Other	Typical applications
				High speed (molybdenum)			
M3-2	1.20	6.00	5.00	4.00	3.00	. . .	Drills, taps, end mills, reamers and counterbores, broaches, hobs, form tools, lathe and planer tools, cheeking tools, slitting saws, punches, drawing dies, woodworking tools.
M4	1.30	5.50	4.50	4.00	4.00	. . .	Broaches, reamers, milling cutters, chasers, form tools, lathe and planer tools, cheeking tools, blanking dies and punches for abrasive materials, swaging dies.
M6	0.80	4.00	5.00	4.00	1.50	12.00 Co	Lathe tools, boring tools, planer tools, form tools, milling cutters.
M7	1.00	1.75	8.75	4.00	2.00	. . .	Drills, taps, end mills, reamers, routers, saws, milling cutters, lathe and planer tools, chasers, borers, woodworking tools, hobs, form tools, punches.
M10	0.85; 1.00	. . .	8.00	4.00	2.00	. . .	Drills, taps, reamers, chasers, end mills, lathe and planer tools, woodworking tools, routers, saws, milling cutters, hobs, form tools, punches, broaches.
M30	0.80	2.00	8.00	4.00	1.25	5.00 Co	Lathe tools, form tools, milling cutters, chasers.
M33	0.90	1.50	9.50	4.00	1.15	8.00 Co	Drills, taps, end mills, lathe tools, milling cutters, form tools, chasers.
M34	0.90	2.00	8.00	4.00	2.00	8.00 Co	Drills, taps, end mills, lathe tools, milling cutters, form tools, chasers.
M36	0.80	6.00	5.00	4.00	2.00	8.00 Co	Heavy-duty lathe and planer tools, boring tools, milling cutters, drills, cutoff tools, tool-holder bits.
M41	1.10	6.75	3.75	4.25	2.00	5.00 Co	Drills, end mills, reamers, form cutters, lathe tools, hobs, broaches, milling cutters, twist drills, end mills. Hardenable to Rockwell C67 to C70.
M42	1.10	1.50	9.50	3.75	1.15	8.00 Co	
M43	1.20	2.75	8.00	3.75	1.60	8.25 Co	
M44	1.15	5.25	6.25	4.25	2.00	12.00	
M46	1.25	2.00	8.25	4.00	3.20	8.25 Co	
M47	1.10	1.50	9.50	3.75	1.25	5.00 Co	

† After "ASM Databook," published in *Met. Prog.*, vol. 112, no. 1, mid-June 1977.

DEVELOPMENT OF HIGH-SPEED TOOL STEELS.

1st DEVELOPED ⇒ W-BASED

AT 1904: ADDED 1% V TO 18% W, 4% Cr (IN 0.75%

⇓

DEVELOPED 18-4-1 HIGH-SPEED STEEL
(18% W, 4% Cr, 1% V)
" GRADE → T_1 " → WIDELY USED.
UNTIL TODAY.

AT 1912: IN GERMANY ⇒ ADDED Co TO INCREASE
RED-HARDNESS

SERIES OF W-BASED: 12-20% W WITH.
4% Cr
1-5% V

SOME ALLOY ADDED 5-12% Co

↓

TO IMPROVE HIGH-TEMP. HARDNESS.

AFTER 1930: DISCOVERED LARGE DEPOSIT OF

LOWER PRICE → Mo IN COLORADO, USA.

⇓

M_o-TYPE WAS DEVELOPED.

(REPLACE ALL OR PART OF W ADDED.)

e.g. TYPE-M_1: 9 % Mo, 1.5 % W

→ DEVELOPED FIRST.

TYPE-M_2: 6 % W, 5 % Mo, 2 % V

IN U.S.A ⇒ USED M_o-TYPE ≥ 80 % (MOSTLY M_2

IN ENGLAND ⇒ USED W-TYPE (MOSTLY T_1)

PREFERRED TO

Grade. 18-4-1

W Cr V

* M_o-TYPES LOWER COST THAN W-TYPES.

BUT. MORE SUSCEPTIBLE TO De-C

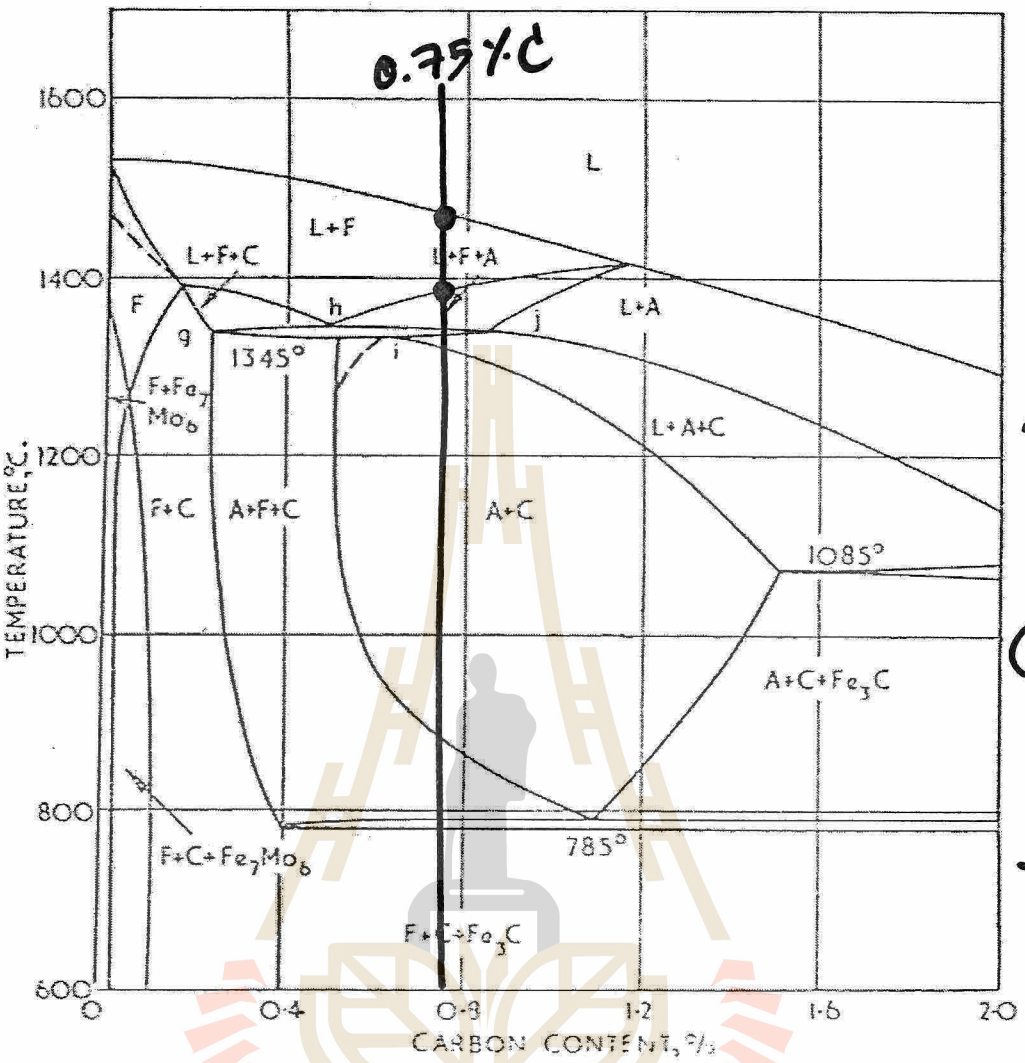
MUST CONTROL IN HEAT-TREATMEN PROCESS.

HIGH-SPEED TOOL STEELS

(TUNGSTEN-TYPES, T-TYPE)

HIGH-SPEED TOOL STEELS.

(TUNGSTEN TYPE, T-TYPE)

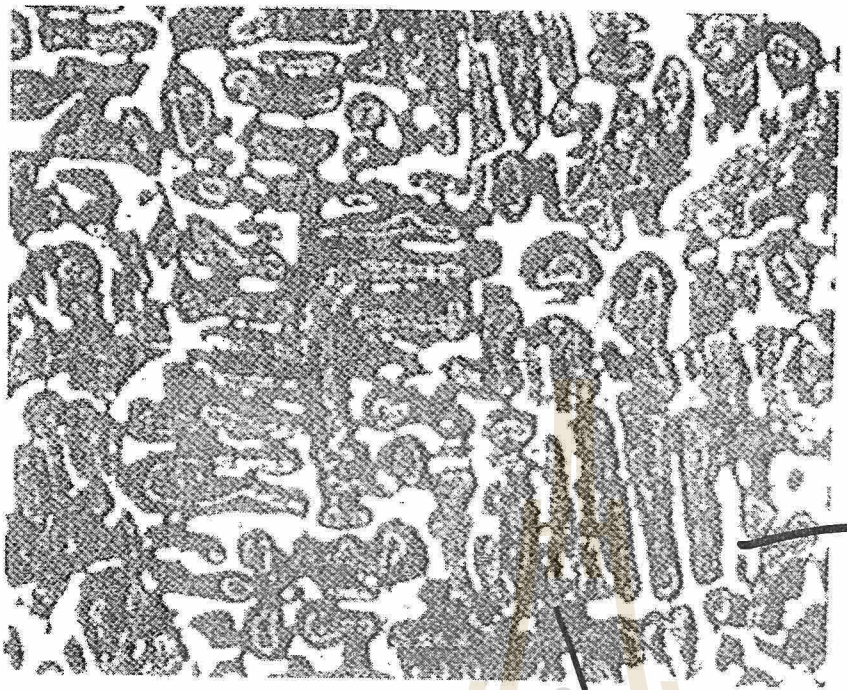


L:liquid; A:austenite; F:ferrite; C:Fe_3W_3C

T1 → 18-4-1 STEEL (W-Cr-V WITH 0.75 %

FIGURE 9-20
Phase diagram of the Fe-W-Cr-C systems. Section is at 18% W and 4% Cr. (After Murakami and Hatta, with alterations indicated by dotted lines.) [*After K. Kuo, J. Iron Steel Inst. 181(1955):128.*]

T_1 AS-CAST STRUCTURE.



18-4-1
%W %Cr %V

0.75 %C.

CARBIDES

MATRIX. (AS-CAST.)

FIGURE 9-21
Microstructure of as-cast T1 high-speed steel showing heavily cored regions. (Etch: 5% nital; ×100.)
(*After G. Hobson and D. S. Tyas, "High Speed Steels," Met. Mater., May 1968, p. 147.*)

UNEVEN COOLING STRUCTURE IN AS-CAST

⇓

HEAVY CORING STRUCTURE.

⇓

NEED TO HOT-WORK TO IMPROVE DISPERSION OF CARBIDES IN MATRIX

T_1 HOT-WORKED.

FIGURE 9-22
Microstructure of T1 high-speed tool steel showing lightly banded carbide regions. Longitudinal direction. Structure after hot working. (Etch: 5% nital; ×100.) (*After G. Hobson and D. S. Tyas, "High Speed Steels," Met. Mater., May 1968, p. 147.*)

H.W. TO ELIMINATE IN-HOMOGENETIES OF AS-CAST STRUCTURE

⇓

RIFINE γ AND CARBIDES

(e.g. HOT FORGING AT HIGH % REDUCTION)

~ 90-95 % R.A.

↓

AT T ≈ 900-1150 °C.

HEAT-TREATMENT OF HIGH-SPEED STEEL.

* MOST IMPORTANT AFFECTING ITS PERFORMANCE

(IF HEAT-TREATMENT IS NOT CORRECTLY, WILL REDUCE ITS PERFORMANCE.)

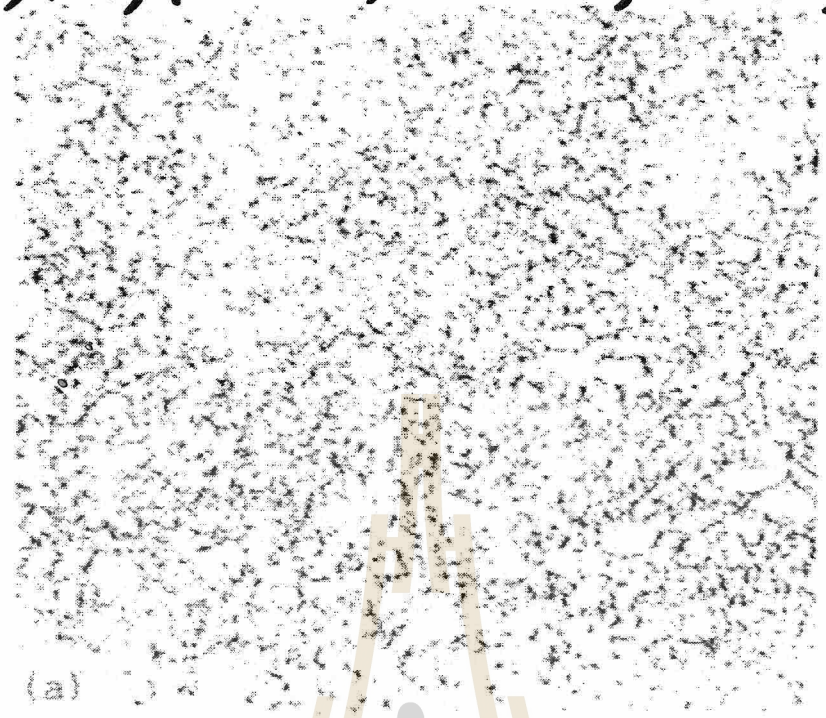
EXAMPLES: STRUCTURES OF T1

1. T_1 : ANNEALING CONDITION

2. T_1 : QUENCHED & TEMPERED CONDITION

ANNEALED-CONDITION OF T1

(T_1 : 0.75% C, 18% W, 4% Cr, 1% V)



(a)

STRUCTURE : LARGE & SMALL SPHEROID CARBIDES
+
FERRITE MATRIX

CARBIDES ≈ 30% OF COMPLEX CARBIDES IN FERRITE MATRIX. DIVIDED IN 3 GROUP

1.> M_6C (Fe_4W_2C, Fe_3W_3C)
→ PRODUCE "RED-HARDNESS"

2.> $M_{23}C_6$ (Cr - CARBIDE)
→ DISSOLVED TO INCREASE HARDENABILITY

3.> MC (V-CARBIDE, VC TO V_4C_3)
→ HIGH-HARDNESS & ABRASION RESISTANCE AND INHIBIT GRAIN GROWTH AT HIGH-T.

QUENCHED & TEMPERED CONDITION OF T1.

① AUSTENITIZING.

→ PREHEAT 1–2 STEPS. TO AUSTENITIZING TEMP. FOR MINIMIZED THERMAL STRESS

→ AUSTENITIZED JUST BELOW SOLIDUS TEMP. ≈ 1,250 – 1,290 °C (FOR CARBIDES DISSOLVED TO γ)

⇓

GIVE MAX. HARDNESS AFTER Q & T.

→ AT AUSTENITIZING TEMP. NOT HOLD TOO LONG TIME FOR PREVENTING GRAIN GROWTH & De-C OCCUR.

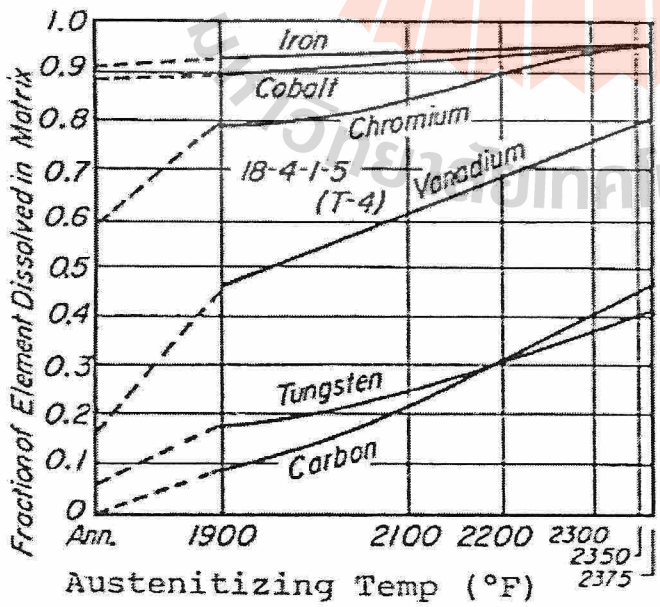


FIGURE 9-24
Partition of elements between carbides and matrix in T4 high tungsten tool steel. (*After F. Kayser and M. Cohen, Met. Prog., June 1952, p. 79.*)

AUSTENITIZING TEMP. & AMOUNT OF CARBIDES DISSOLVED. OF T1

Q & T.

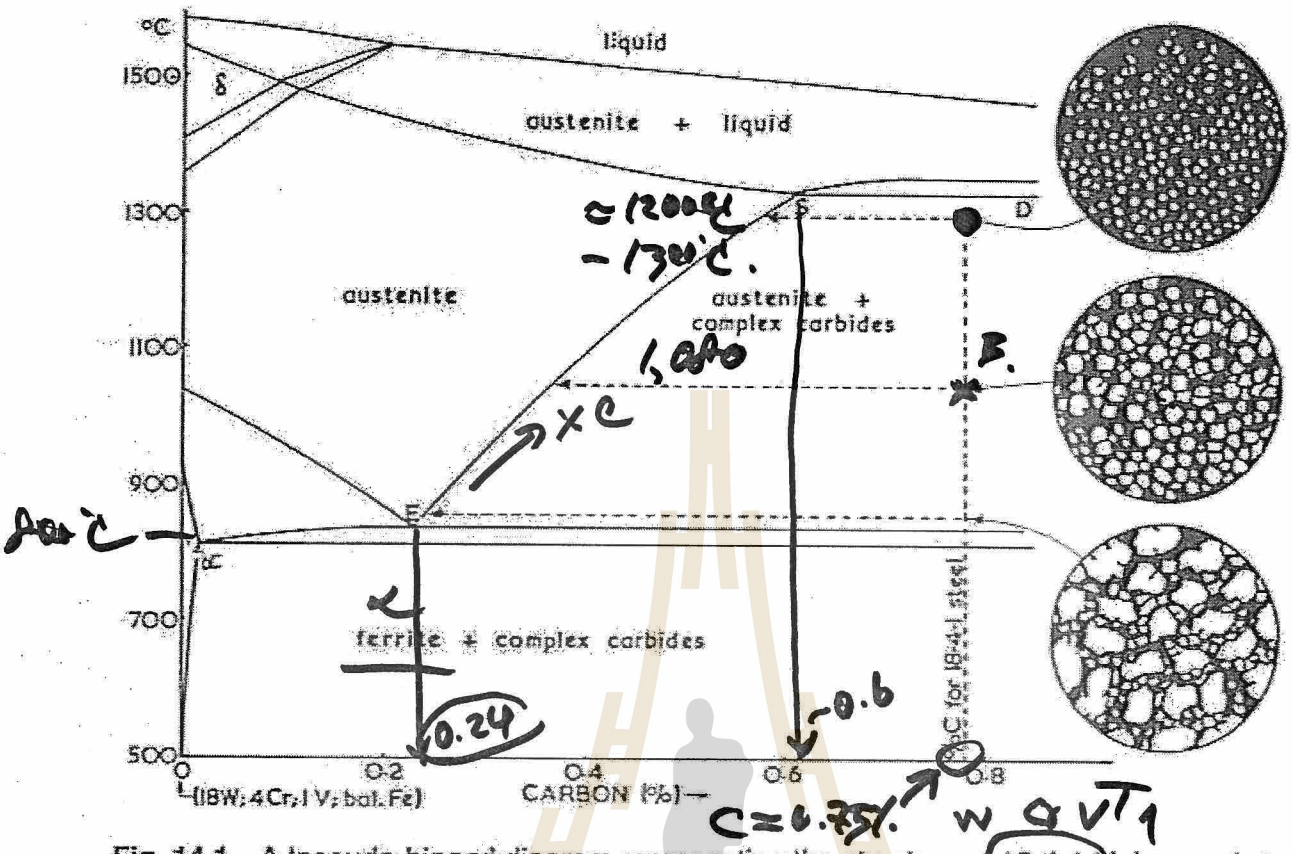


Fig. 14.1 A 'pseudo-binary' diagram representing the structure of 18-4-1 high-speed steel. Here the tungsten–chromium–vanadium content is kept constant but carbon remains variable. The sketches of microstructures show the effects of solution temperature upon the extent of solubility of the complex carbides (light) in the matrix (dark) following quenching. The higher the quenching temperature the greater the solubility of carbides (indicated by the slope of *ES*).

EFFECT OF AUSTENITIZING TEMP. AND AMOUNT OF CARBIDES DISSOLVING INTO γ

DISSOLVED CARBIDES → INCREASE HARDENABILTY AND PRODUCE 2nd HARDENING DURING TEMPERING

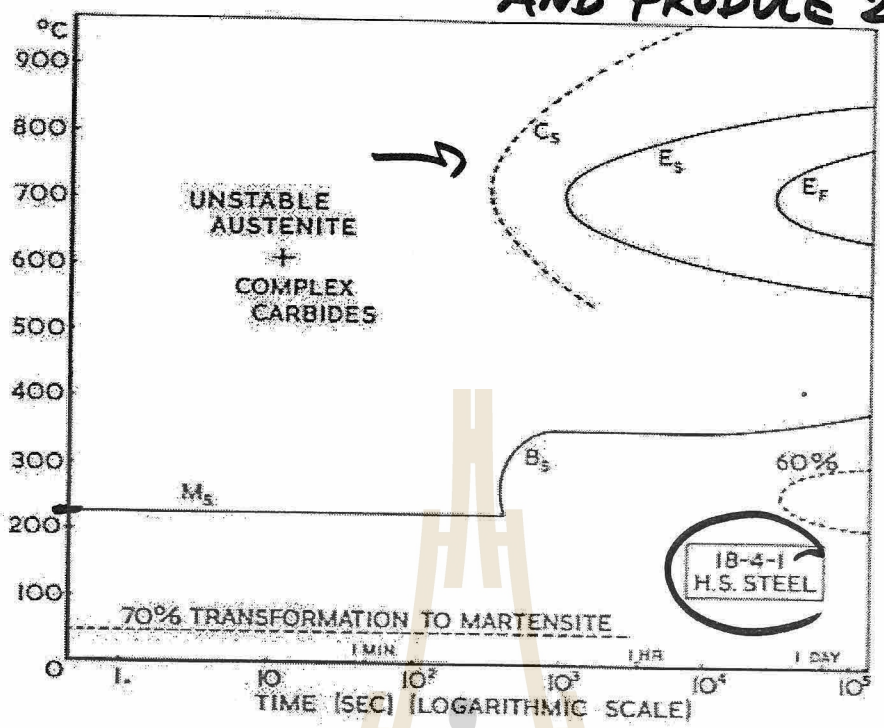


Fig. 14.2 TTT curves for an 18-4-1 high-speed steel.
The initial structure consists of saturated austenite together with some undissolved carbides. The line C_s indicates the commencement of precipitation of primary carbides (since the steel is not of eutectoid composition). E_s and E_F indicate the start and finish of eutectoid ('pearlite') formation. B_s shows the start of bainite formation whilst the associated broken line indicates the time required for 60% transformation to bainite. Note that at room temperature the transformation of austenite to martensite is incomplete (70% at 50°C so that air- or oil quenching will produce a mixture of martensite and retained austenite.

EFFECT ON SECONDARY HARDENING.

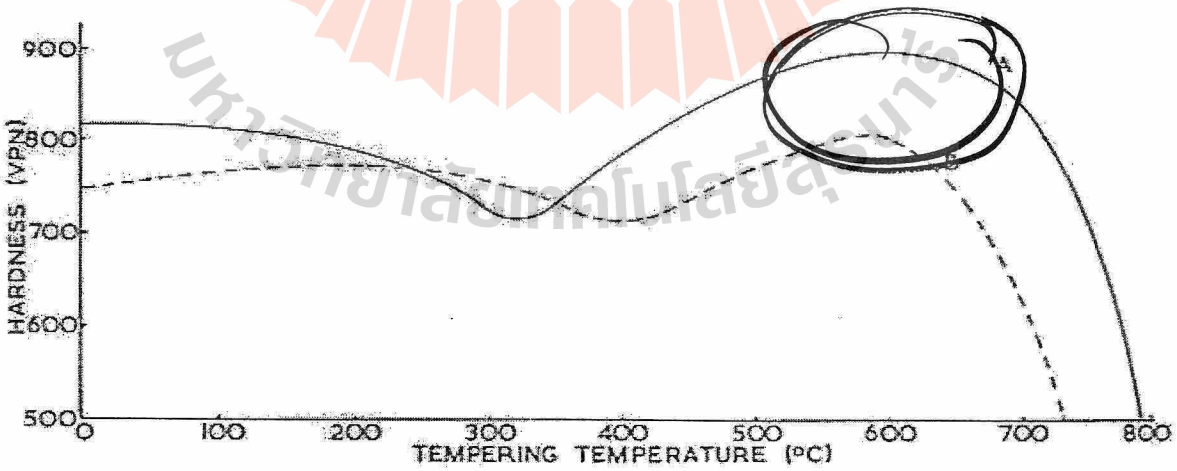
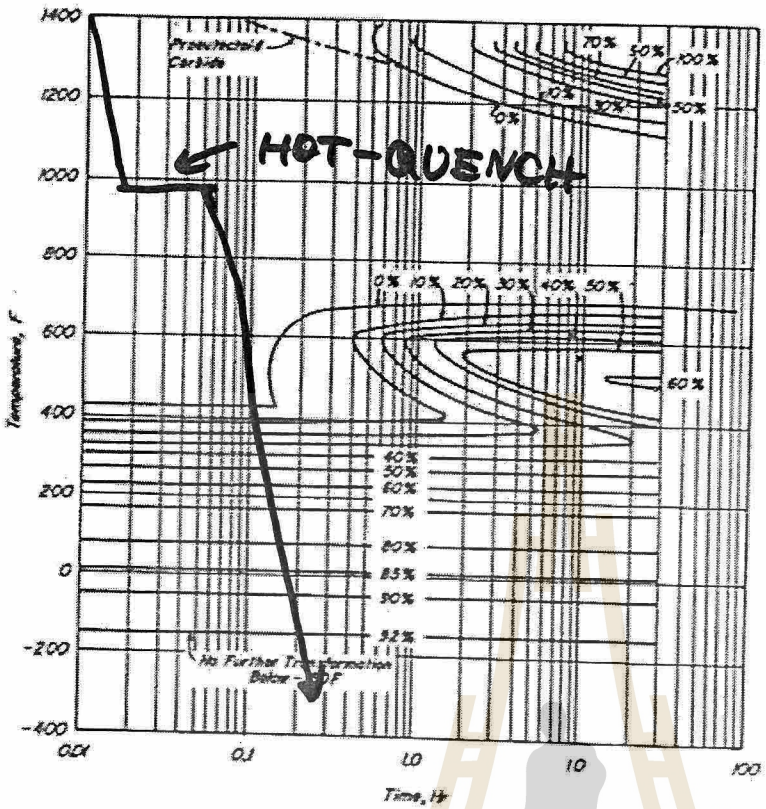


Fig. 14.3 The relationship between hardness and tempering temperature for high-speed steels.
(A) Represents the 12% cobalt type, and (B) the ordinary 18% tungsten type.

② QUENCHING. → TO PRODUCE MARTENSITIC.



AUSTENITIZED AT 1,290 °C -

T1.

FIGURE 9-25
IT diagram for T1 type high-speed tool steel (austenitizing temperature, 1290°C). [*After P. Gordon, M. Cohen, and R. S. Rose, Trans. ASM 31(1943):161.*]

1.> HOT-QUENCH TO 540 – 650 °C

- TO MINIMIZE DISTORTION & CRACK
- TO MINIMIZE GRAIN BOUNDARY PRECIPITATIO & TRANSFORMATION AT HIGH-TEMP.

2.> COOLED TO R.T.

STRUCTURE: HIGHLY ALLOYED MARTENSITE (60–80 %)

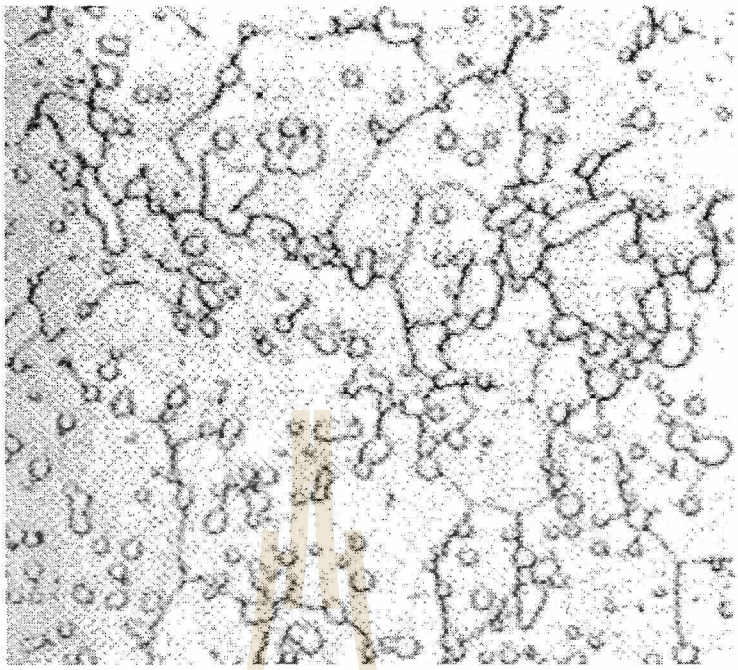
+

RETAINED – γ (15–30 %)

+

NON-DISSOLVED CARBIDES (M_6C, VC) (5–10 %)

AS-QUENCHED STRUCTURE.



AUSTENITIZED
(1,279 °C, 3-4 MIN.)

↓

SALT-QUENCHED TO 607 °C
(HOT-QUENCHED)

↓

AIR-COOLED TO R.T.

③ TEMPERING.

$$°C = \frac{5}{9}(°F - 32)$$

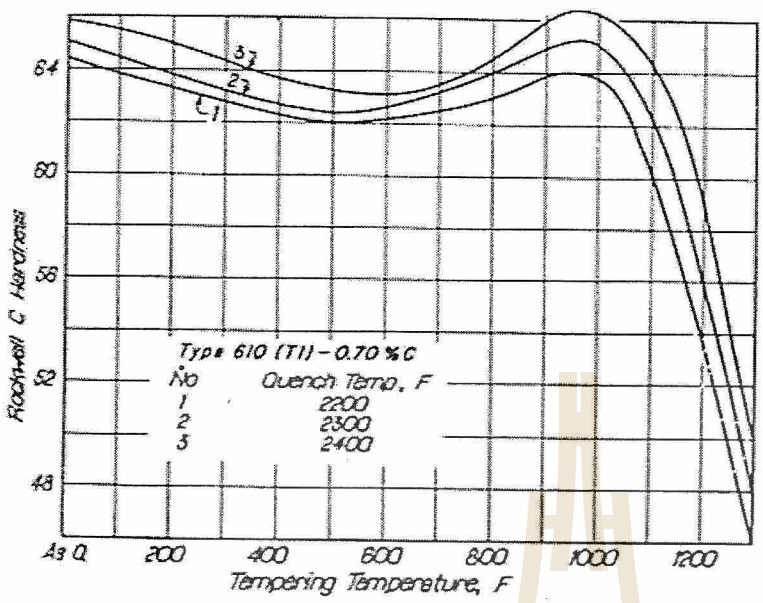


FIGURE 9-26
Effect of tempering temperature on the hardness of a 0.70% C type T1 high-speed tool steel after quenching from 1204°C (2200°F), 1260°C (2300°F) and 1315°C (2400°F). For this steel the normal austenitizing temperature is 1290°C. Tempering time, .5 h. (*After G. A. Roberts, J. C. Hamaker, and A. R. Johnson, "Tool Steels," 3d ed., American Society for Metals, Metals Park, Ohio, 1962, p. 647.*)

CHANGES IN STRUCTURES DURING TEMPERING T1.

<1> 1st STAGE. (R.T. TO 400 °C) ⇒ HARDNESS SLITHLY DECREASE

- MARTENSITE LOSE ITS TETRAGONALITY.
- DECOMPOSE & FORM HEXAGONAL ε-CARBIDE (~270 °C)
- AT 300-400 °C, ε-CARBIDE DISSOLVED AND REPLACE BY Fe_3C

<2> 2nd STAGE. (470 – 570 °C) ⇒ HARDNESS INCREASE

- Fe_3C DISSOLVED AND PRECIPITATES OF M_2C LEAD TO "SECONDARY HARDENING"

<3> 3rd STAGE. (500 – 620 °C)

- TRANSFORMATION OF γ ON COOLING FROM TEMPERED BY PRECIPITATION OF ALLOY CARBIDES FROM RETAINED-γ.

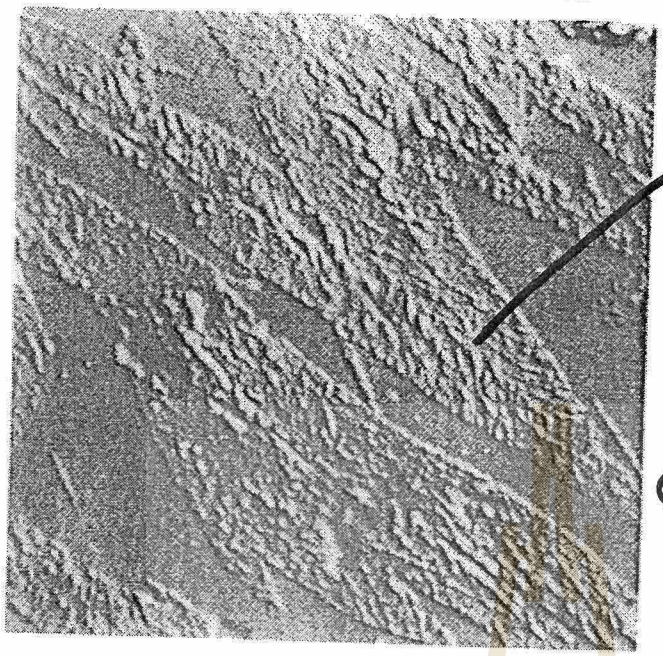
(4.) 4th STAGE. (> 620 °C)

- GROWTH & COALESCE OF CARBIDES.

↓

DECREASING HARDNESS.

2nd STAGE.

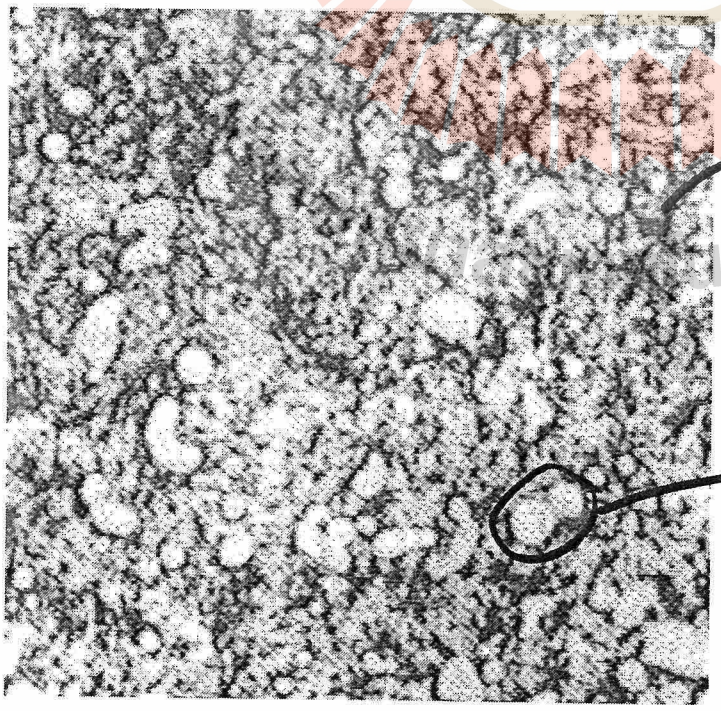


CARBIDES PRECIPITATES IN TEMPERED-M.

FIGURE 9-27
Electron micrograph of T1 high-speed tool steel (18-4-1) quenched to 1130°C and tempered 24 h at 565°C. Structure shows smooth background of untempered martensite contrasted to heavy carbide precipitation within tempered martensite. [*After R. J. Beltz and R. W. Lindsay, Trans. ASM 61(1968):790.*]

PRECIPITATES OF HEAVY CARBIDES IN TEMPERED MARTENSITE → CAUSE TO 2nd-HARDENING.

T_1 : AFTER DOUBLE-TEMPERED AT 538 °C



TEMPERED-M MATRIX.

UN-DISSOLVED CARBIDES

HIGH-SPEED TOOL STEELS.

(MOLYBDENUM TYPE, Mo-TYPE)

- Mo USED TO REPLACE ALL OR PART OF W
- BECAUSE OF Mo LOWER COST
- ABOUT 80% HIGH-SPEED STEEL USED IN U.S.A. IS Mo-TYPE.

	%W	%Mo	%V	%Cr
T_1 :	18	–	1	4
M_1 :	1.5	8.5	1	4
M_2 :	6	5	2	4

BUT. Mo-TYPE MORE SUSCEPTIBLE TO De-C

(NEED TO BETTER HEAT-TREAT CONTROL.)

↓ FURNACE

USE SALT BATH OR ATMOSPHERE CONTROL.

- Mo-TYPE HAVE LOWER AUSTENITIZING-T

M_2 → AUSTENITIZED AT 1190 – 1230 °C

T_1 → " ——— " 1260 – 1300 °C.

TTT-CURVE OF M_2

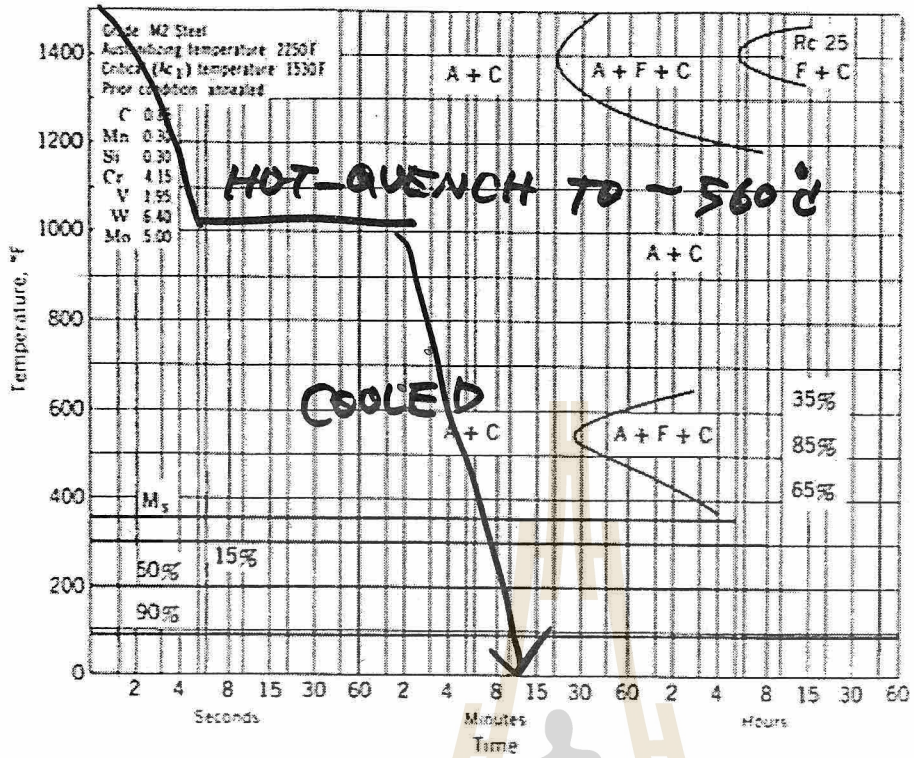


FIGURE 9-28
IT diagram of type M2 high-speed tool steel. (*After P. Payson, "Metallurgy of Tool Steels," Wiley, 1962, p. 66. Reproduced by permission of John Wiley & Sons, Inc.*)

- AVOID TRANSFORMATION AT HIGH-TEMP. AS T_1 ⇒ BY HOT-QUENCH AT 560°C
- MAX. SECONDARY HARDENING AT 550°C
- STRUCTURE OF M_2 CLOSE TO T_1.

EFFECT OF TEMPERING TEMP. ON HARDNESS OF M

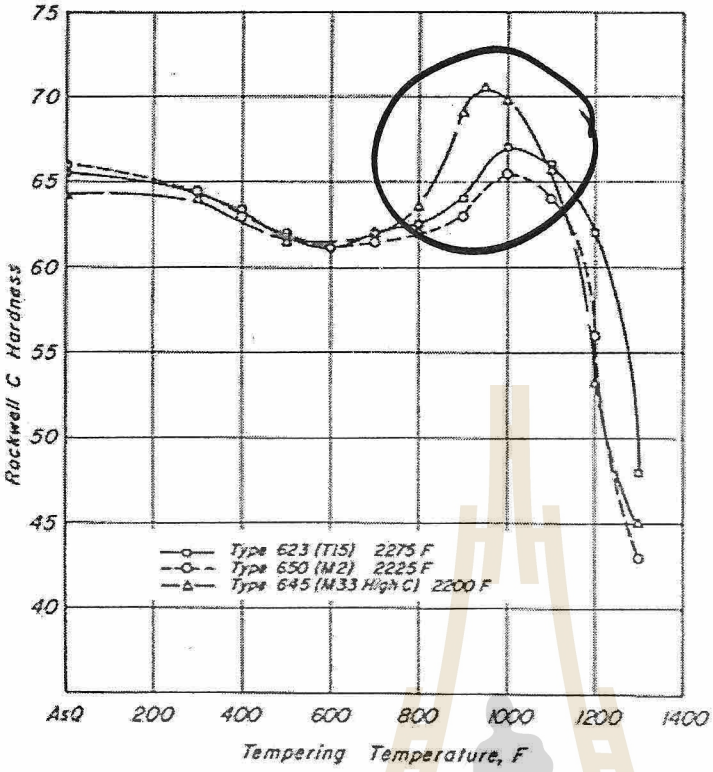
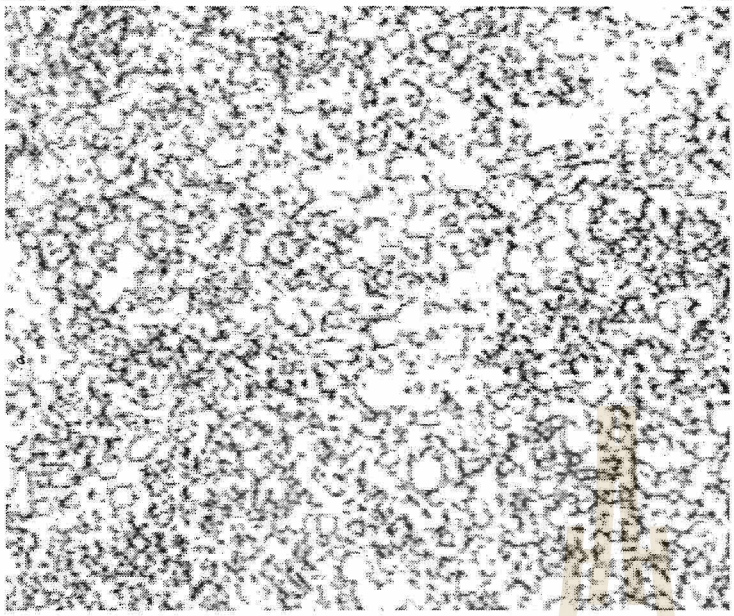


FIGURE 9-29
Effect of tempering temperature on the hardness of M2 high-speed tool steel. (*After G. A. Roberts, J. C. Hamaker, and A. R. Johnson, "Tool Steels," 3d ed., American Society for Metals, Metals Park, Ohio, 1962, p. 648.*)

M2 (0.85 %C, 6.3 %W, 4.15 %Cr, 1.85 %V, 5.05 %Mo

① M2 : FULL ANNEALING.

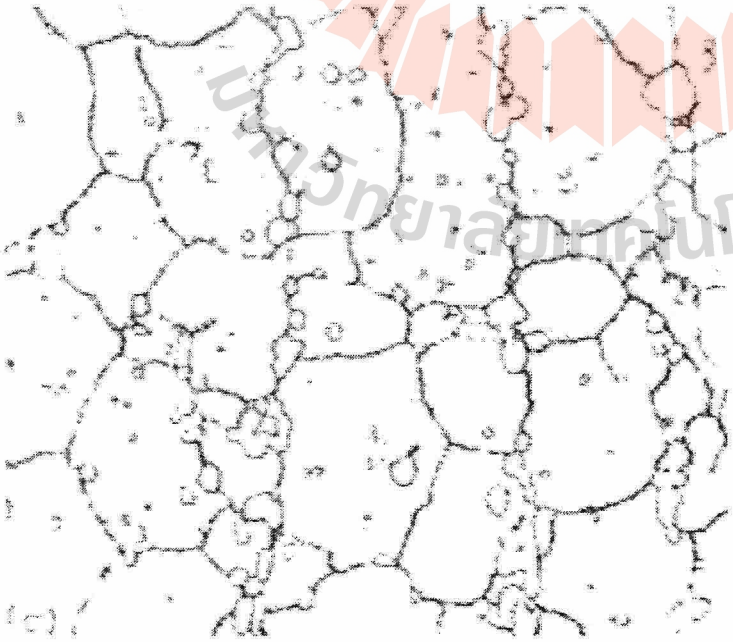


CARBIDES PARTICLE
IN
FERRITE MATRIX

② M2 : ~~NORMAL~~ Q~~&T~~ CONDITION.

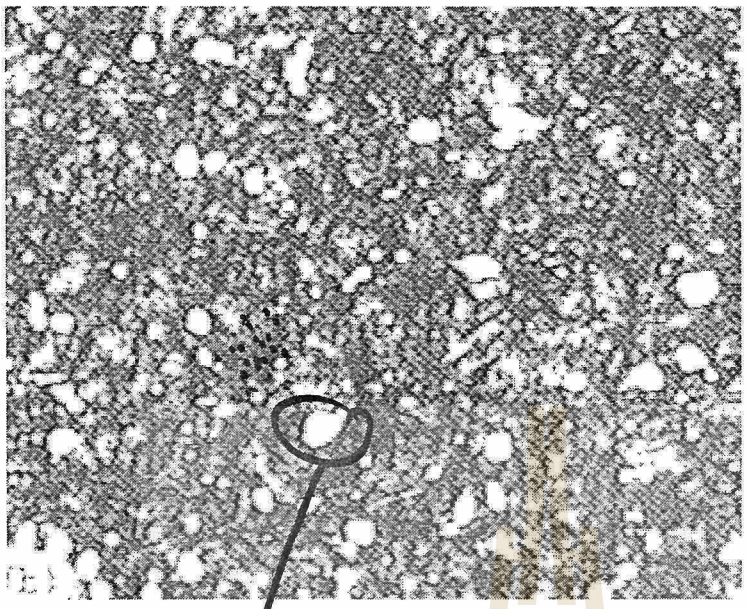
AS-QUENCHED.

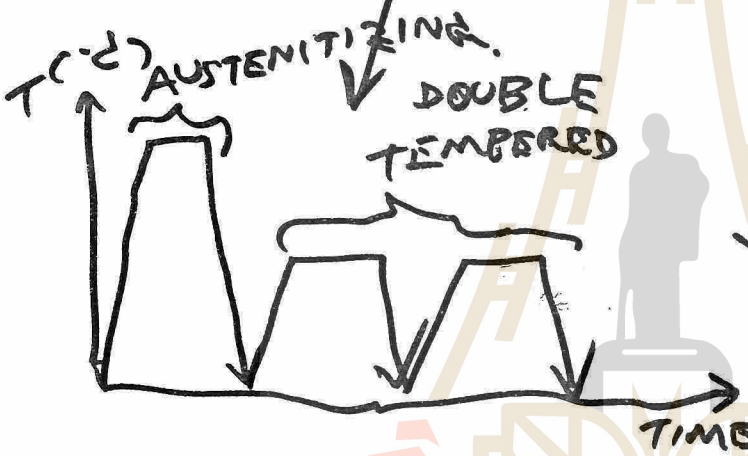
AUSTENITIZED
(1200 °C)
⇓
HOT-QUENCHED TO
565 °C
⇓
AIR-COOLED TO R.T.
⇓
~~NO.~~
~~DOUBLE TEMPERED~~
~~(550 °C, 2 HR. EACH)~~



STRUCTURE : CARBIDE PARTICLES + UNTEMPERED-M
+ RETAINED-γ

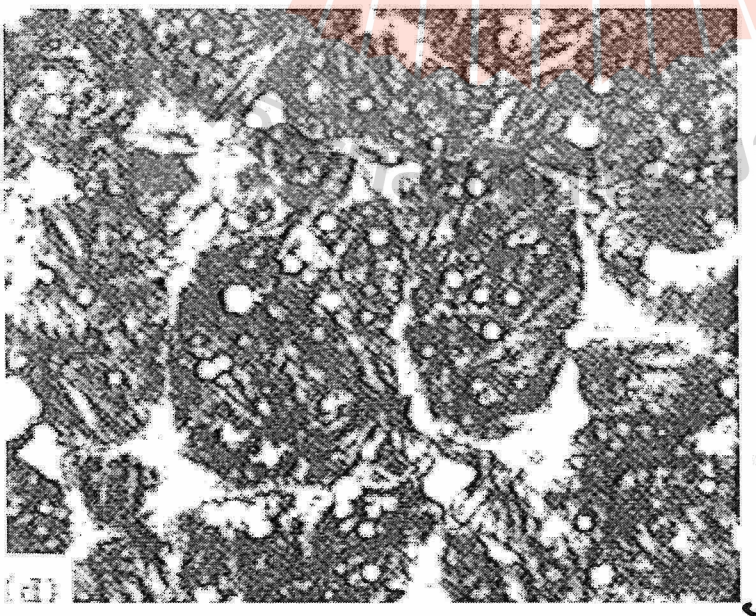
③ M2 : NORMAL Q&T CONDITION.





AUSTENITIZED
(1,200 °C)
⇓
HOT-QUENCHET T
565 °C
⇓
AIR-COOLED TO R.T
⇓
DOUBLE-TEMPERED
(550 °C, 2HR. EACH)
⇓
= CARBIDES PARTICLES
IN
TEMPERED-M MATRI

④ M2 : OVERHEAT CONDITION.



AUSTENITIZED
(1,245 °C)
⇓
HOT-QUENCHED T
565 °C
⇓
AIR-COOLED TO R.T
⇓
DOUBLE-TEMPERED
(550 °C, 2 HR. EACH)

STRUCTURE : FUSED & SEPARATE
CARBIDE PARTICLES + TEMPERED MARTENSITE

CEMENTED CARBIDES.

CEMENTED CARBIDES :

CONSIST OF FINELY DIVIDED HARD PARTICLES OF CARBIDES OF REFRACTORY METALS (W, Ti, Ta) SINTERED TOGETHER BY A FILM OF Co-METAL

" USED AS BINDER OF CARBIDES."

USED FOR :

- EXTREMELY HARD & WEAR-RESISTANCE CUTTING TOOLS.
- CUTTING SPEED 5 TIMES THAN HIGH-SPEED STEELS (GREAT COST SAVING.)

PRODUCTION.

CEMENTED W- CARBIDES PRODUCED BY :

BLENDING FINE WC-POWDERS (1-3 μm) WITH Co-METAL POWDER

(WC GRAINS ARE COATED WITH Co)

⇓

SINTERED IN HYDROGEN ABOVE M.P. OF Co

⇓

WC-PARTICLES WETTED BY LIQUID Co

(IMPORTANT IN SINTERING PROCESS)

CEMENTED CARBIDES DIVIDED INTO 2 TYPES :

1) W-CARBIDE TYPE (MAINLY W-CARBIDE)

USED FOR : MACHINING OF CAST IRON, NONFERROUS & NON-METALLIC MATERIALS.

2) MIXED-CARBIDE TYPE (TaC + TiC + WC)

USED FOR : MACHINING OF C-STEELS AND ALLOY STEELS.

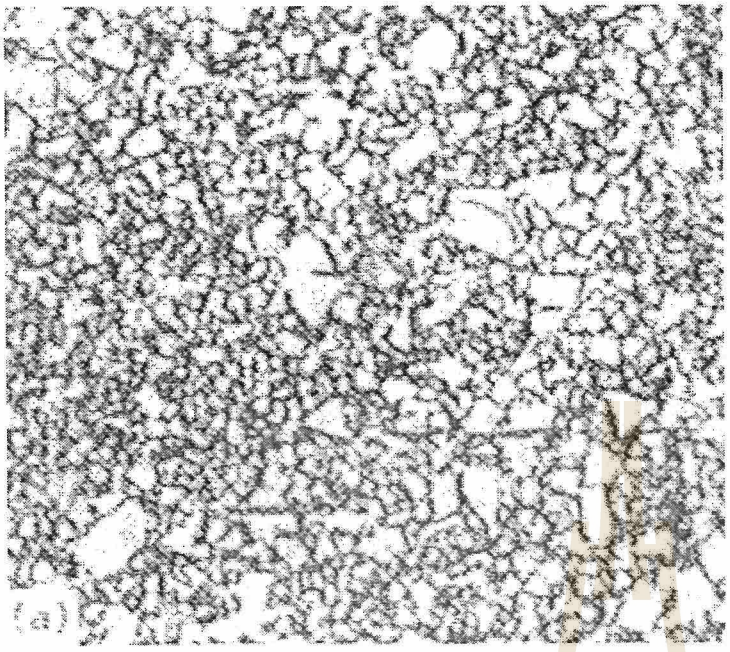
TABLE 9-9
Classification of sintered carbides†

Carbide group	Composition, % (remainder WC)		Rockwell A hardness	Density, g/cm³
	Co	TaC + TiC		
	Straight tungsten carbide			
1	2.5–6.5	0–3	93–91	15.2–14.7
2	6.5–15	0–2	92–88	14.8–13.9
3	15–30	0–5	88–85	13.9–12.5
	Added carbide, predominantly TiC			
4	3–7	20–42	93.5–92.0	11.0–9.0
5	7–10	10–22	92.5–90.0	12.0–11.0
6	10–12	8–15	92.0–89.0	13.0–12.0
	Added carbide, predominantly TaC			
7	4.5–8	16–25	93.0–91.0	12.5–12.0
8	8–10	12–20	92.0–90.0	13.0–11.5
	Added carbide, exclusively TaC			
9	5.5–16	18–30	91.5–84.0	14.8–13.5

Group — Typical uses

1. Finishing to medium roughing cuts on cast iron, nonferrous metals, superalloys, and austenitic alloys; low-impact dies.
2. Rough cuts on cast iron, especially on planers; moderate-impact dies.
3. High-impact die applications.
4. Light high-speed finishing cuts on steel. High crater resistance. Low shock resistance.
5. Medium cuts and speeds on steel. Good crater resistance and moderate shock resistance. Dies with moderate impact involving pickup
6. Roughing cuts on steel. Good shock resistance together with wear and crater resistance. Moderate-impact die applications involving pickup.
7. Light cuts on steel where a combination of edge wear and crater resistance is required.
8. General purpose and heavy cutting of steel requiring resistance to wear and cratering. Also resists abrasive wear caused by scale.
9. Wear-resistant applications particularly involving heat; gauge elements, special machining applications. Special applications involving mechanical shock and heat such as hot trimming of flash.

STRUCTURE OF W- CARBIDE TYPE



WC
IN
Co - MATRIX
↑
BINDER
(94% WC, 6% Co)

BLOCKY SHAPE OF WC GRAINS.

CO- BINDER.

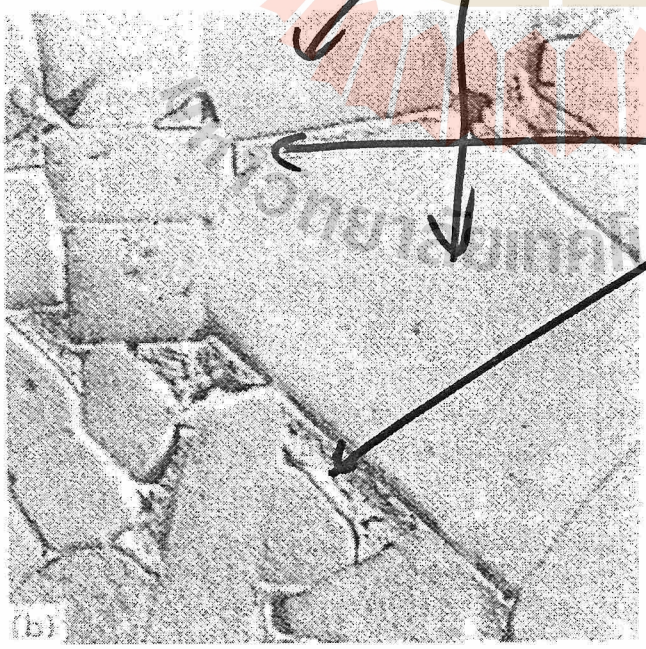
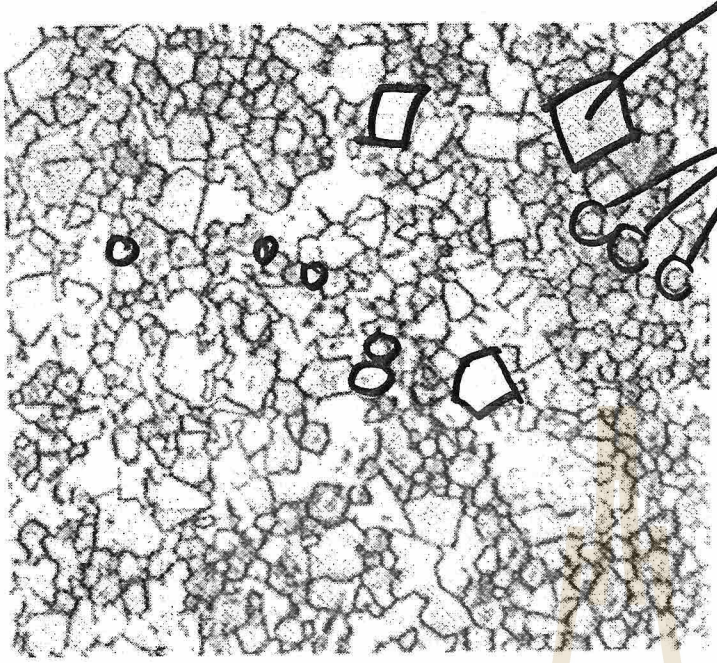


FIGURE 9-31
Cemented carbide containing 94% WC, 6% Co; mixed grain size. Structure consists of tungsten carbide in a matrix of cobalt. (*a*) (Murakami's reagent; ×1500.) (*b*) Electron replica; blocky shapes are carbide grains. (Murakami's reagent; ×15,000.) (*After Metals Handbook, 8th ed., vol. 7, American Society for Metals, Metals Park, Ohio, 1972, p. 128.*)

STRUCTURE OF MIXED-TYPE



ANGULAR SHAPE OF W

ROUNDED OF TaC - TiC - WC SOLID SOLUTION PHASE IN Co - MATRIX

FIGURE 9-32
Cemented carbide containing 72% WC, 11% TaC, 8% TiC, 9% Co; density, 12.6 g cm^3. Light angular particles are WC; dark gray rounded particles are TaC-TiC-WC solid solution phases. The matrix is cobalt. (Murakami's reagent; ×1500.) (*After Metals Handbook, 8th ed., vol. 7, American Society for Metals, Metals Park, Ohio, 1972, p. 130.*)

WC, TiC & TaC CENTERED CARBIDES

IN

Co - MATRIX.

ELEVATED TEMP. HARDNESS OF TOOL MATERIALS

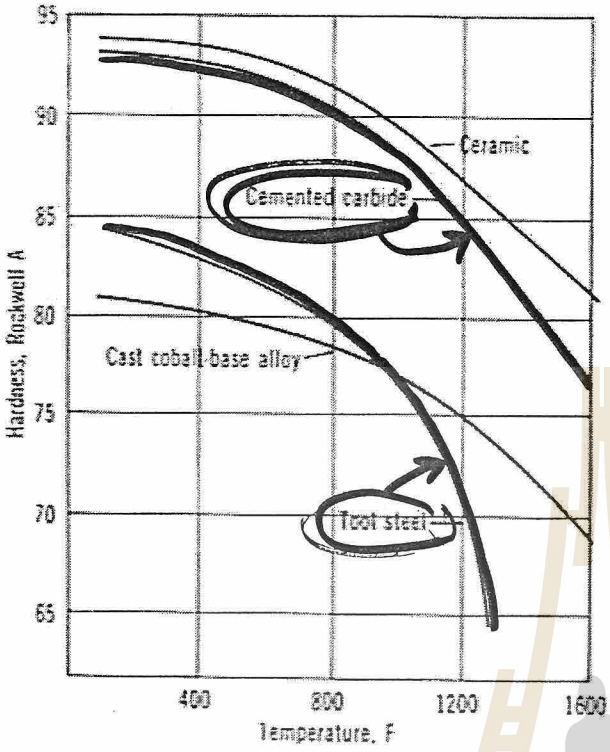


FIGURE 9-33
Effect of elevated temperatures on the hardness of tool materials. (*After E. W. Gobiler, "Advances in Cemented Carbide Tooling," Met. Prog., August 1968, p. 95.*)

(i) CEMENTED CARBIDES

(90 - 95 % Vol. OF CARBIDES)

⇓ HARDER THAN

HIGH-SPEED TOOL STEELS.

(35 % Vol. OF CARBIDES)

(ii) CEMENTED CARBIDES RETAIN HARDNESS (AT CUTTING EDGE) AT HIGH-TEMP. THAN HIGH-SPEED TOOL STEELS & Co-BASE ALLOY.

(IMPORTANT FOR MACHINING AT T > 815 °C)

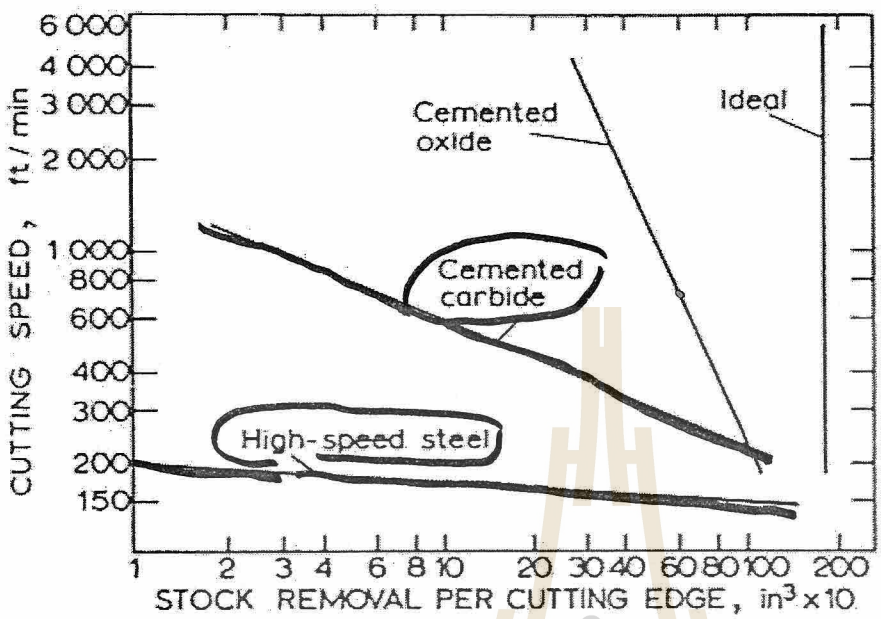


FIGURE 9-34
Cutting speed versus stock removal for various tool materials. (*After H. C. Child, "Materials for Metal Cutting," The Metals Society, 1970, p. 173.*)

- HIGH COMPRESSIVE STRENGTH (UP TO 500 ksi)

↓

RETAIN HIGH STRENGTH AT ELEVATED TEMP.

(EXIST SHARP CUTTING EDGE AT HIGH-SPEED.)

	CUTTING SPEED
(1.) CEMENTED CARBIDE	UP TO 1,000 ft/MIN.
(2.) HIGH-SPEED STEEL	UP TO 200 ft/MIN.

MICROSTRUCTURE OF HIGH-SPEED STEELS.

COARSE & NON-DISSOLVED DURING SOLUTION TREATMENT.

① PRIMARY & SECONDARY CARBIDES ← FINE & PRECIPITATE DURING TEMPERING.

+

② TEMPERED-M MATRIX.

HIGH-C. → FORM PRIMARY CARBIDES
→ PRODUCE HARD MARTENSITE

HIGH HARDNESS & ABRASION RESISTANCE DURING CUTTING.

- LOWER SOLIDUS TEMP.
- DEPRESS $M_s - M_f$ TEMP.
  (LEAD TO FORM RETAINED-γ)

Cr. ≈ 4 % ADDED.

- FORM CARBIDES, $M_{23}C_6$ & M_7C_3
- Cr-CARBIDE DISSOLVED INTO SOLUTION AT NORMAL AUSTENITIZED 1,200-1,300 °C

⇓

INCREASE HARDENABILITY

&

2nd-HARDENING AFTER TEMPERING.

- OXIDATION RESISTANCE AT HIGH-TEMP.

Mo ≈ 10 - 20 % (M-TYPE)

- STRONG CARBIDE FORMER, M_6C
- SMALL AMOUNT CARBIDE DISSOLVED

⇓

TEMPERING RESISTANCE

&

MAINTAIN HIGH HARDNESS AT HIGH-TEMP.

(RED-HARDNESS) ≥ 550 °C

- INDUCE 2nd-HARDENING

V. ≈ 1-5 %V (V_4C_3, VC)

- STRONG CARBIDE FORMER & EXTREMELY HARD
- SMALL AMOUNT DISSOLVED

⇓

IMPROVE HARDNESS & ABRASION RESISTANCE

&

GRAIN REFINING AGENT.

Co ≈ 12 %

- NOT CARBIDE FORMER
- HIGH SOLUBILITY IN γ

⇓

INCREASE RED-HARDNESS

HEAT TREATMENT OF HIGH-SPEED STEEL.

CASTING

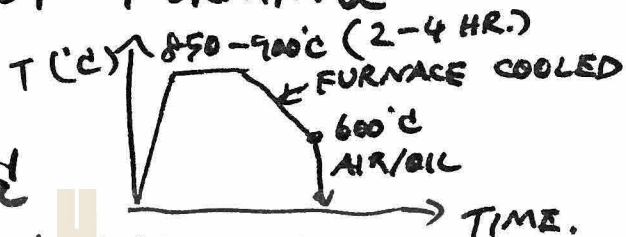
↓

FORGING OR HOT-FORMING

↓

- OFTEN FOR MACHINING
- RELIEF-STRESS
- SUITABLE MICROSTRUCTURE FOR HARDENING.

ANNEALING



α-MATRIX + FINE DISPERSED CARBIDES.
(≈ 300 BHN)

↓

AUSTENITIZED (T ≈ 1,200 - 1,300 °C)

2-5 MIN. HOLDING → MIN. GRAIN GROWTH & DE-C

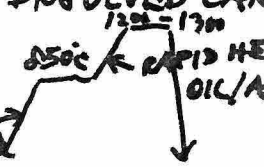
- Fe_4W_2C, Fe_4Mo_2C, VC
- ⇓
- NON-DISSOLVED CARBIDE

900°C → $Cr_{23}C_6$ BEGIN TO DISSOLVED

1,100°C → $Cr_{23}C_6$ COMPLETELY DISSOLVED

1,150°C → M_6C (Mo & W-BASED CARBIDES) BEGIN TO DISSOLVED

>1,150°C → VC STILL NON-DISSOLVED.



↓

(500-600 °C)

AIR/OIL QUENCHED OR SALT BATH.

(M_s ≈ 200 °C, AT R.T. ≈ 80% COMPLETE MARTENSITE)

↓ (2) (3)

DOUBLE OR TRIPLE TEMPERING

↓

TEMPERING. (530-570 °C)

- PRODUCE TEMPERED-M
- TRANSFORMED (DE-STABILIZED) OF RETAINED-γ TO M. AT R.T.
- PRODUCE 2nd-HARDENING (MAX. ≈ 550 °C)

↓

(1.) PRIMARY (NON-DISSOLVED) CARBIDES

(2.) TEMPERED-M WITH 2nd-CARBIDE PRECIPITATED

(3.) UN-TEMPERED-M

(MAY BE 3rd-TEMPERING FOR TEMPER THE UN-MARTENSITE.

FINAL STRUCTURE OF HIGH-SPEED STEEL.

C, Mo, W, Cr, V, Co

① TEMPERED-M MATRIX

+

② PRIMARY & SECONDARY CARBIDES.

NON-DISSOLVED CARBIDE

$\underbrace{Fe_4W_2C,\ Fe_4Mo_2C}_{M_6C}$, VC

STABLE CARBIDES.

DISSOLVED CARBIDES.

W, Mo-CARBIDE, $Cr_{23}C_7$

FINE-PRECIPITATATE CARBI

DURING TEMPERING.

⇓

2nd HARDENING.

HEAT TREATMENT OF HIGH-SPEED TOOL STEEL

W, Mo, Cr, V, Co.

CASTING. → CORE STRUCTURE (SEGREGRATION.)

↓

HOT-FORGING OR HOT-FORMING.

$T \approx 950 - 1{,}050\ ^\circ C$.

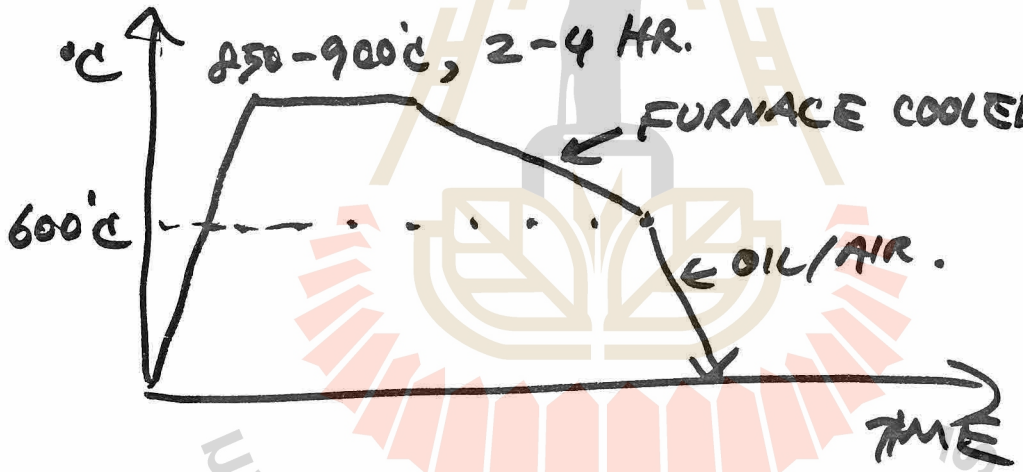
↓

ANNEALING.

(i) SOFTEN FOR MACHINING.

(ii) RELIEF-STRESS.

(iii) SUITABLE MICROSTRUCTURE FOR HARDENING.

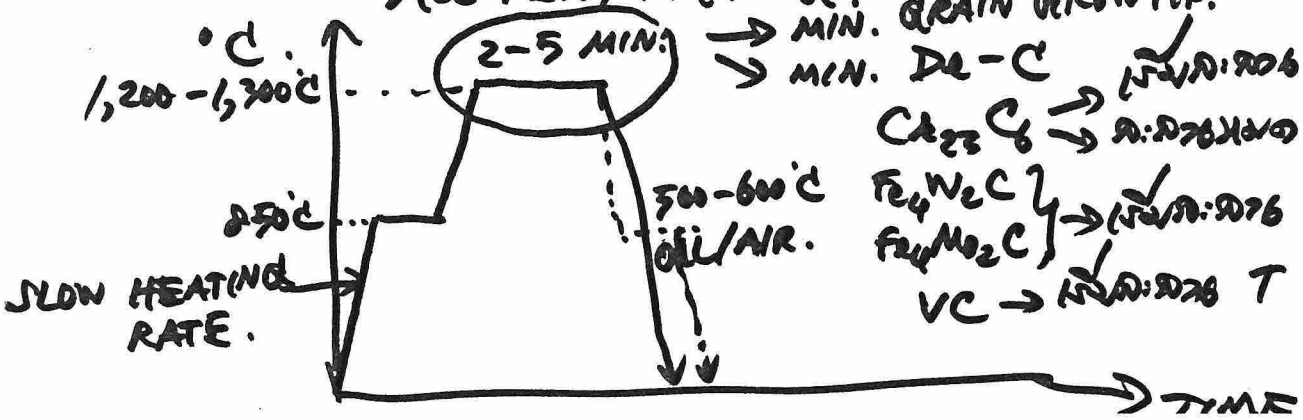


α-MATRIX + CARBIDES PARTICLES.

(≈ 300 BHN) → Fe_4W_2C, Fe_4Mo_2C, $Cr_{23}C_6$, VC

↓

AUSTENITIZING



→ MIN. GRAIN GROWTH.

→ MIN. DE-C

$Cr_{23}C_6$ → เริ่มละลาย ≈ 900 °C

→ สะสมใหม่ ≈ 1,100 °C

Fe_4W_2C, Fe_4Mo_2C → เริ่มละลาย ≈ 1,150 °C.

VC → เริ่มละลาย $T > 1{,}150\ ^\circ C$

↓

AIR/OIL QUENCHED.

(HOT-QUENCH ≈ 500–600 °C)

→ ป้องกันการเกิดการบิดเบี้ยวที่ T สูง (P.)

→ ลดการบิดเบี้ยว, แตกร้าว เนื่องจากการ QUENCH.

$M_s \approx 200$ °C

$M_f <$ R.T.

AT R.T. ≈ 80% COMPLETE MARTENSITIC.

<u>SOME</u> RETAINED-γ.

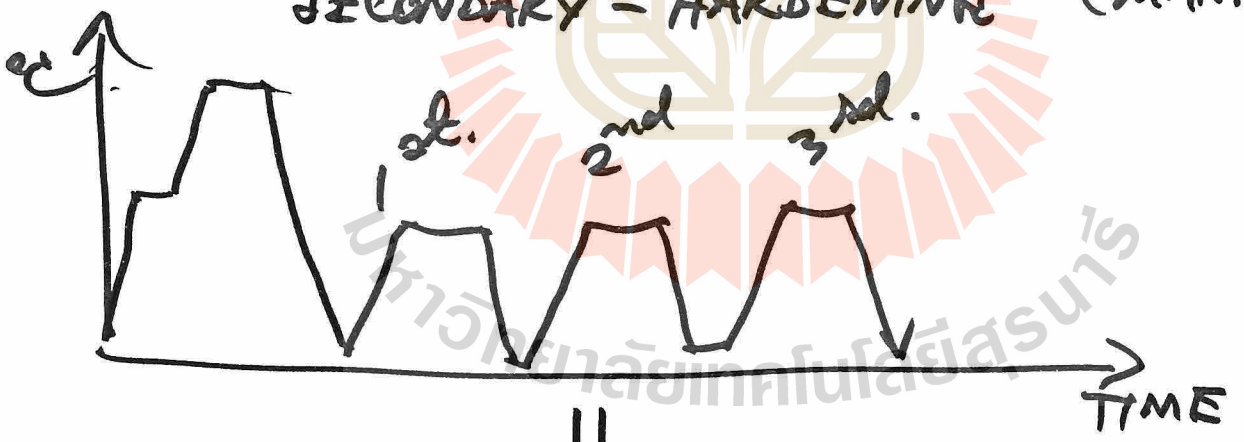
↓

TEMPERING. (T = 530–570 °C)

- PRODUCE TEMPERED-M.
- TRANSFORMED OF RETAINED-γ → M.
- PRECIPITATE OF SECONDARY CARBIDES.

⇓

"SECONDARY-HARDENING" (MAX. ≈ 550 °C)



⇓

<u>STRUCTURES</u>

(1.) PRIMARY (NON-DISSOLVE) CARBIDES.

(2) 2nd CARBIDE PRECIPITATE IN MATRIX.

(3) TEMPERED-M MATRIX.

STAINLESS STEELS.

CORROSION. ⇒ การสูญเสียเนื้อของวัสดุโลหะเกิดจากปฏิกิริยาเคมีกับสิ่งแวดล้อม เช่น สารเคมี, H_2O อากาศ, ดิน

CORROSION REACTION ส่วนใหญ่เป็น

ELECTROCHEMICAL CORROSION.

เกิดจากอะตอมโลหะ: (Me) สูญเสีย e^- กลายเป็นไอออน (Me^+) ⇒ เกิดการกัดกร่อน/สูญเสียเนื้อวัสดุ

∴ ELECTROCHEMICAL CORROSION ⇒ จะมีการเกิดปฏิกิริยาที่มีการให้ และการรับ e^- เกิดขึ้น.

EX. การกัดกร่อนของ Zn ใน HCl SOLUTION.

$$Zn + 2HCl \longrightarrow ZnCl_2 + H_2$$

หรือ $$Zn + 2H^+ \longrightarrow Zn^{2+} + H_2$$

โดย $Zn \longrightarrow Zn^{2+} + 2e^-$; เกิดปฏิกิริยาที่ให้ e^-

OXIDATION REACTION

หรือ "ANODIC REACTION"

และ: $2H^+ + 2e^- \longrightarrow H_2$; เกิดปฏิกิริยาที่รับ e^-

REDUCTION REACTION

หรือ "CATHODIC REACTION"

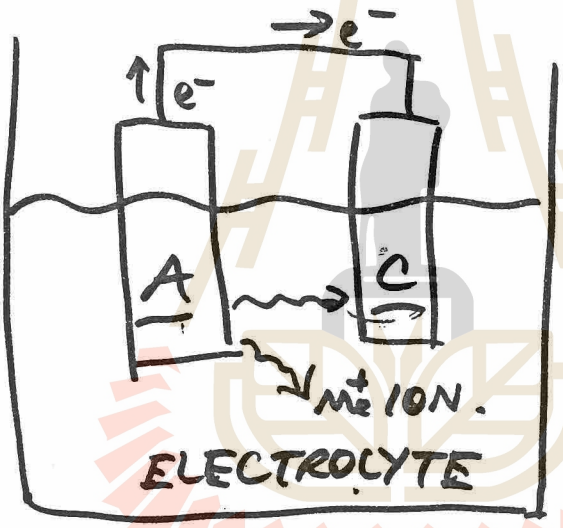
องค์ประกอบของ ELECTROCHEMICAL CELL.

① ANODE ⇒ ให้ e^- (เกิดการเกิดออก)

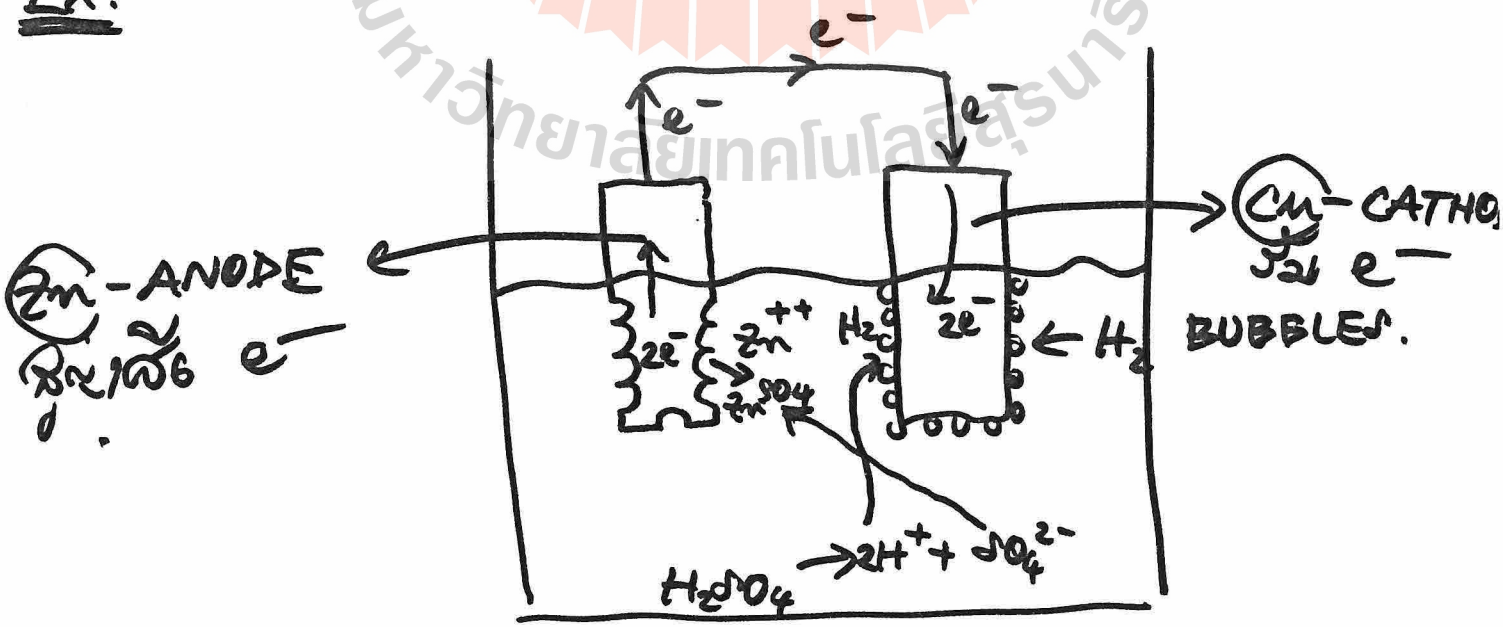
② CATHODE ⇒ รับ e^-

③ CONNECTING PART ⇒ ตัวเชื่อม เพื่อให้เกิดการเชื่อมหรือสัมผัสกัน เพื่อให้เกิดการไหลของ e^- จาก A → C

④ ELECTROLYTE ⇒ ตัวกลาง/ตัวนำ เพื่อให้เกิดวงจรไฟฟ้าขึ้นอย่างสมบูรณ์



Ex.



อุณหภูมิแวดล้อมไฟฟ้า

ELECTROPOTENTIAL. OR. EMF.

เปรียบเทียบแรงดันไฟฟ้าของโลหะแต่ละชนิดกับแรงดันไฟฟ้าของ HYDROGEN ภายใต้ T = 25 °C และ ELECTROLYTE ที่มี ION เข้มข้น 1 MOLAR.

OXIDATON - REACTION (METAL ION)		ELECTRO POTENTIAL (V) (E_0)
$Au \rightarrow Au^{3+} + 3e^-$	มีความโน้มเอียงการสูญเสีย e^-	CATHODIC
$Ag \rightarrow Ag^+ + e^-$	น้อยกว่า HYDROGEN.	
$Cu \rightarrow Cu^{2+} + 2e^-$		+
⋮		
$H_2 \rightarrow 2H^+ + 2e^-$		0.000 ⇐ REF.
⋮		
$Pb \rightarrow Pb^{2+} + 2e^-$	มีความโน้มเอียงการสูญเสีย e^-	
$Ni \rightarrow Ni^{2+} + 2e^-$	มากกว่า HYDROGEN.	
$Fe \rightarrow Fe^{2+} + 2e^-$		−
$Cr \rightarrow Cr^{3+} + 3e^-$		
$Zn \rightarrow Zn^{2+} + 2e^-$		ANODIC.

เป็น ANODIC ในตอนแรก ภายหลังฟอร์มฟิล์ม Cr_2O_3 จะมีความต้านทานเป็น CATHODIC.

⇓

หยุดการเกิดการกัดกร่อน "PASSIVE STATE" (เกิด PASSIVE FILM)

STAINLESS STEELS.

⇒ EXCELLENT CORROSION RESISTANCE

⇓

% Cr > 12 %

⇓

PASSIVE FILM.

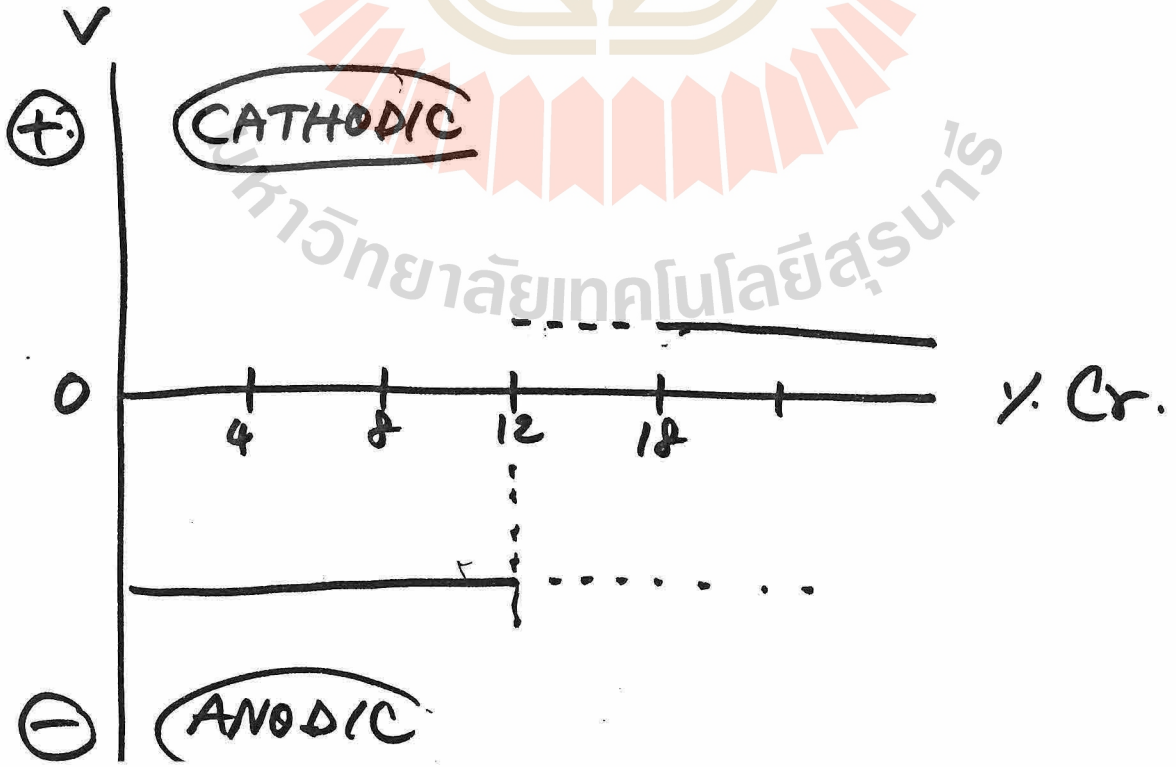
⇓

Cr FORM THIN PROTECTIVE OXIDE FILM (Cr_2O_3)

- EXTREMELY ADHERENT & RESIST TO CHEMICAL ATTACK
- IF PASSIVE FILM DAMAGED BY ABRASION OR SCRATCHING, HEALING PROCESS OR REPASSIVATION OCCURS IMMEDIATELY.

⇓

INCREASE % Cr → INCREASE CORROSION AND OXIDATION RESISTANCE

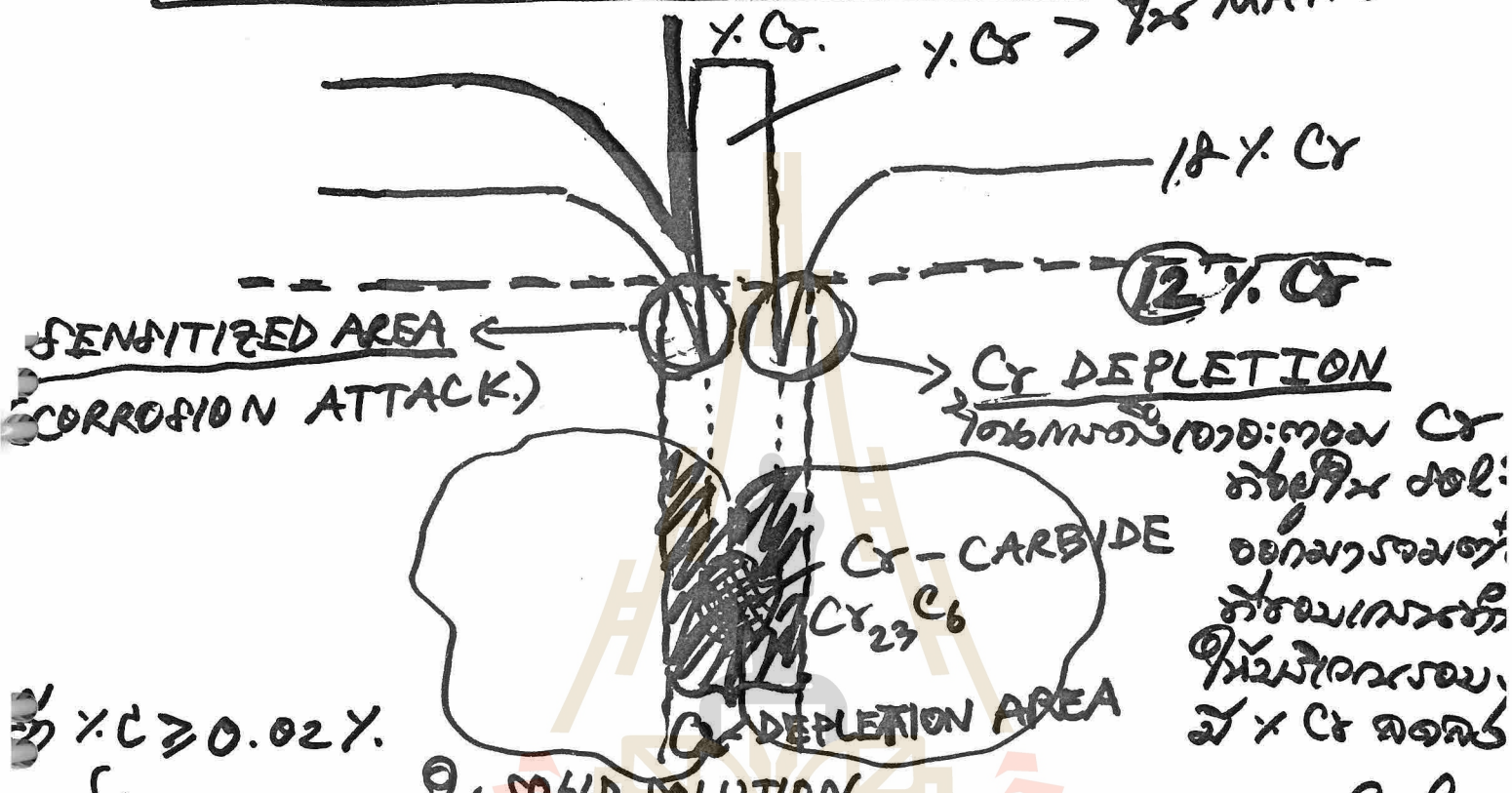


18-8 STAINLESS STEELS.

STAINLESS STEEL ARE SUSCEPTIBLE TO HIGHLY LOCALIZED FORM OF ATTACK "SENSITIZED"

⇓ เมื่อได้รับความร้อนระหว่างการหลอม อยู่ในช่วง 450 – 800 °C

"INTERGRANULAR CORROSION"



ถ้าเกิดการเชื่อมต่อ Cr ถ้าจะเกิด ส่วนออกมารวมตัวกับ C ที่อยู่ในเกรนที่ให้มีปริมาณรอบๆ มี % Cr ลดลง

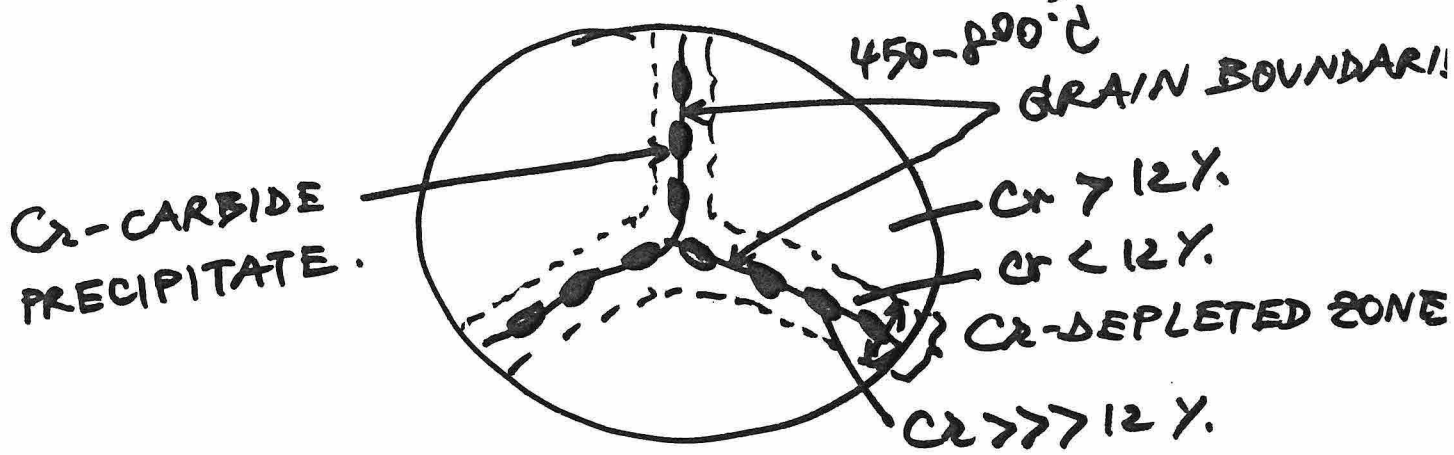
ถ้า % C ≥ 0.02 %

↓

C-ATOM ใน SOLID SOLUTION. แทรกตัวออกมาอยู่ตามขอบเกรนรวมตัวกับ Cr ฟอร์มเป็น Cr-RICH CARBIDE ($Cr_{23}C_6$)

∴ % Cr ที่เติมควรจะมากกว่า 12 % Cr

(≃ 15 – 18 % Cr MIN.)



การแก้ไข & ป้องกันการเกิด INTERGRANULAR CORROSION

① HEAT TREATMENT.

AUSTENITIZED (T ~ 1,050 °C) ← ให้ Cr-CARBIDE ที่ตกตะกอนเข้าไปอยู่ใน γ-SOLID SOLUTION

↓

WATER-QUENCHED ← เพื่อไม่ให้ C & Cr มารวมตัวกันเกิดเป็น CARBIDE อยู่ตามขอบเกรนได้อีก

② หลีกเลี่ยงการ TEMPER ช่วง T ≈ 450 - 800 °C เพื่อป้องกันการเกิด PRECIPITATES ของ Cr-CARBIDES ($Cr_{23}C_6$) ตามขอบเกรน (SENSITIZATION)

③ ลด %C ให้ต่ำลงอีก ≈ 0.03 %C เพื่อให้ C จะมาอยู่ใน FERRITE ให้หมด.

④ เพิ่ม %Cr ให้สูงมากๆ (≈ 18-20 %Cr) เพื่อให้ Cr ที่ขอบเกรนมี > 12 %Cr

⑤ เติม CARBIDE FORMER (STABILIZER) เช่น Ti, Nb, Mo, W, V ซึ่งจะมารวมตัวกับ C ได้ดีกว่า Cr.

เช่น

$$\%Ti = 5 \times (\%C + \%N) \leftarrow 321$$ (TiC, TiN)

$$\%Nb = 10 \times (\%C + \%N) \leftarrow 347$$

↓

เป็นการ "STABILIZED STAINLESS STEEL"

FORM TiC & NbC แทน $\boxed{Cr_{23}C_6}$

EX. WELDING OF STAINLESS STEEL.

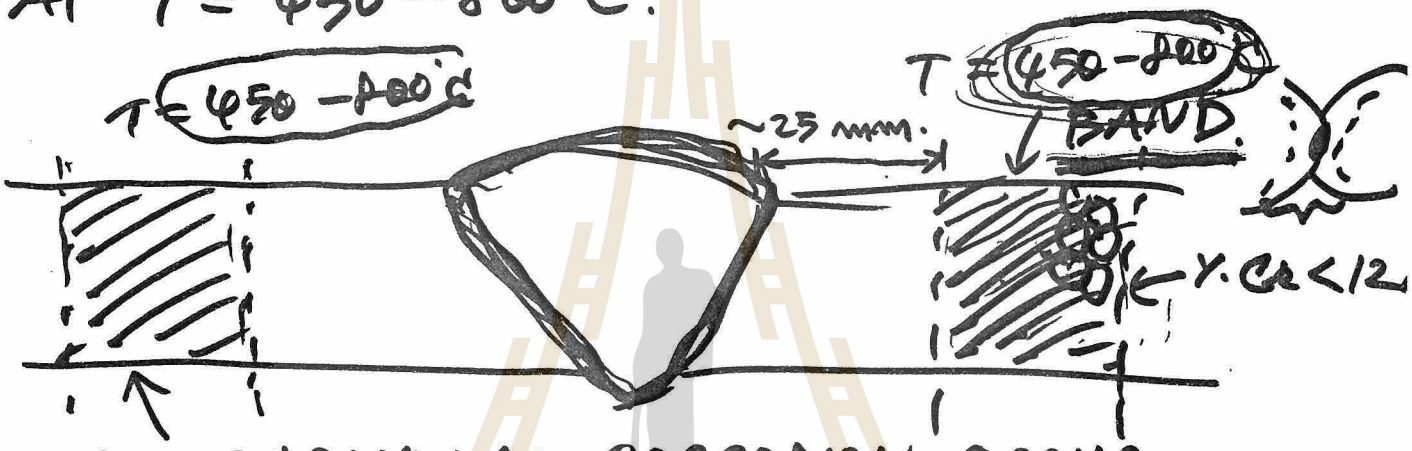
(i) SLOW COOLING FROM SOLUTION TREATMENT AT 1,050 °C OR AFTER WELDING THROUGH THE "SENSITIZATION TEMP." (450 - 800 °C)

↓

$Cr_{23}C_6$ PRECIPITATE.

(ii) STRESS RELIEVING AFTER WELDING OR SERVIC

AT T = 450 - 800 °C.



INTERGRANULAR CORROSION OCCUR DUE TO PRECIPITATE OF $Cr_{23}C_6$ (% Cr AT THIN AREA < 12 % Cr)

CALL "WELD DECAY"

แก้ไขโดย (4) ทางหลังการเชื่อมให้ทำการเย็นตัวมาอย่างรวดเร็ว (WATER-QUENCH)

(1) ใช้ STAINLESS ที่มี %C ต่ำ, < 0.06 % C หรือใช้ L-GRADE (0.03 % C MAX.) 304L, 316L

(2) STABIZED โดยการเติม Ti & Nb

↓ GRADE 321 ↓ GRADE 347

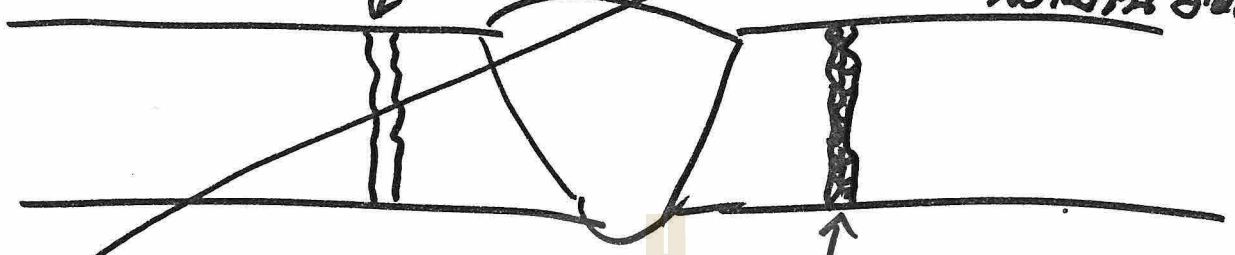
โดย C รวมตัวกับ Ti & Nb เป็น TiC & NbC แทน $Cr_{23}C_6$ (ลดการ DEPLETION ของ Cr)

(3) ทำการอบอุ่นที่ T = 1,050 °C เพื่อ QUENCH ด้วย H_2O.

Ex. INTERGRANULAR CORROSION IN STABILIZED 321 (Ti) & 347 (Nb)

ใช้ที่ TEMP. สูงไม่
จะตกตะกอนของ Ti C
แต่: NbC จะตกตะกอน
ที่ไม่ค่อยมาก ของ

DURING WELDING
HAZ - ZONE, T > 1,150 °C



TiC & NbC
จะตกตะกอนที่ SOLUTION. บางส่วน.

↓

C INTO SOLUTION → รวมตัวกับ Cr เกิดเป็น $Cr_{23}C_6$
ตาม: เส้นตัวหนา T ~ 450 - 800 °C

⇓

ผลที่ตามมา: มีความเสี่ยงเกิด THIN LINE INTERGRANULAR CORROSION

⇓

CALL "KNIFE - LINE ATTACK"

MELTING POINT

Nb - CARBIDE DISSOLVES
Cr - CARBIDE DISSOLVES

1,230 °C

Nb - CARBIDE PRECIPITATES
Cr - CARBIDE DISSOLVES

790 °C

Cr - CARBIDE PRECIPITATES

510 °C

NO REACTIONS.

ROOM TEMP.

CLASSIFICATION OF STAINLESS STEELS.

1. FERRITIC STAINLESS STEELS
2. MARTENSITIC STAINLESS STEELS
3. AUSTENITIC STAINLESS STEELS
4. PRECIPITATION-HARDENING STAINLESS STEEL
   - EASY TO FABRICATION
   - HIGH STRENGTH
   - GOOD DUCTILITY
   - EXCELLENT CORROSION RESISTANCE
5. DUPLEX STAINLESS STEELS.

MIXED MICROSTRUCTURE

AUSTENITE + FERRITE.

50% 50% → AIM

40% 60% → COMMERCIAL.

→ HIGH Cr : 19 – 32 %

→ Mo UP TO 5 %

→ LOWER Ni THAN AUSTENITIC STAINLESS STEEL

(1) FERRITIC STAINLESS STEELS.

α-STABILIZER.

Fe – Cr BINARY ALLOY. ⇒ % Cr = 12 – 30 %

TYPICAL TYPE ⇒ 430 (17% Cr, 0.12 % C)

434 ⇒ 430 + 1.0 % Mo

436 ⇒ 434 + Nb.

HIGH – Cr GRADE ⇒ HIGH – TEMP. SERVICE (RESISTANCE TO CORROSION AND SCALING AT HIGH – TEMP

⇒ 442 : 20.5 % Cr, 0.20 % C

446 : 25 % Cr, 0.20 % C

ถ้าเติม Al เพื่อเพิ่ม OXIDATION RESISTANCE ที่ T สูง.

Cr.

LOW-COST.

TABLE 7-1*a*

Chemical compositions and typical applications of wrought ferritic stainless steels†

AISI type	Chemical composition wt% Cr	C (max)	Mo	Al	Other‡	Typical applications
405	13.0	0.08		0.20		Nonhardenable grade for assemblies where air-hardening types such as 410 or 403 are objectionable. Annealing boxes; quenching racks; oxidation-resistant partitions.
409	11.0	0.08			Ti 6 × C	General-purpose construction stainless, Automotive exhaust systems; transformer and capacitor cases; dry fertilizer spreaders; tanks for agricultural sprays.
430	17.0	0.12				General-purpose nonhardenable chromium type. Decorative trim, nitric acid tanks; annealing baskets; combustion chambers; dishwashers; heaters; mufflers; range hoods; recuperators; restaurant equipment.
434	17.0	0.12	1.0			Modification of type 430 designed to resist atmospheric corrosion in the presence of winter road-conditioning and dust-laying compounds. Automotive trim and [illegible]ers.
436	17.0	0.12	1.0		Nb 5 × C	Similar to types 430 and 434. Used where low "roping" or "ridging" required. General corrosion and heat-resistant applications such as automobile trim.
442	20.5	0.20				High chromium steel, principally for parts which must resist high service temperatures without scaling. Furnace parts; nozzles; combustion chambers.
446	25.0	0.20				High resistance to corrosion and scaling at high temperatures, especially for intermittent service; often used in sulfur-bearing atmosphere. Annealing boxes; combustion chambers; glass molds; heaters; pyrometer tubes; recuperators; stirring rods; valves.

ทนต่อการเกิด INTERGRANULAR CORROSION

ใช้งานที่ TEMP. สูง, ทนความร้อน

ใช้งานประเภทเตา อุปกรณ์เตา

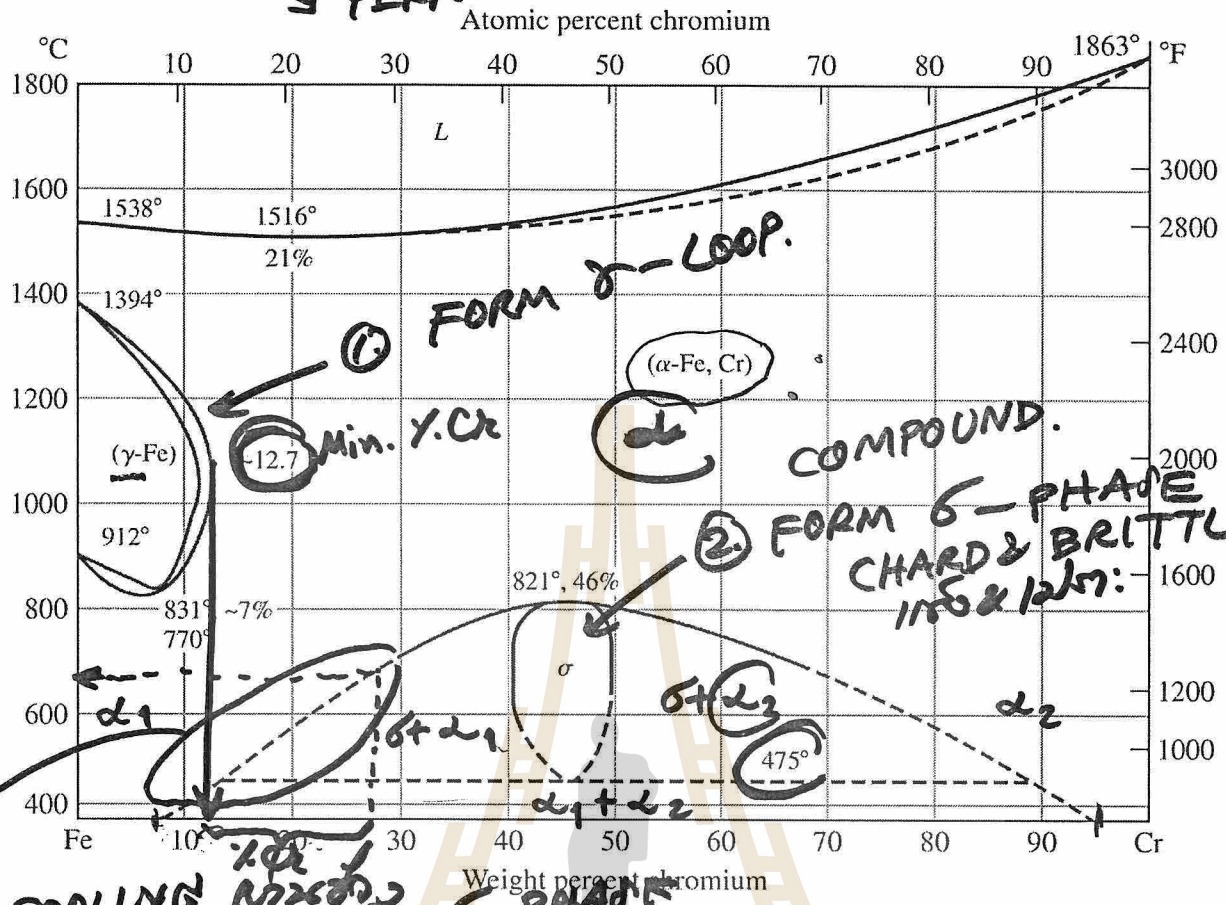
+ อาจเติม Al ⇒ เพิ่มความต้านทาน "OXIDATION RESISTANCE"

† After "ASM Databook," *Met. Prog.*, mid-June 1979, vol. 116, no. 1.

‡S: 0.030% max; P: 0.045% max; Si: 1.00% max.

Fe–Cr ALLOYS.

→ FERRITE STABILIZER.



① FORM γ-LOOP.

Min. % Cr

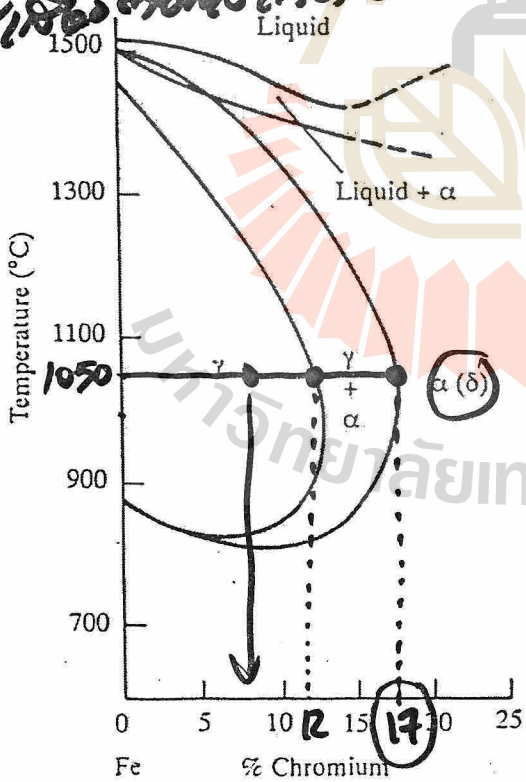
COMPOUND.

② FORM σ-PHASE (HARD & BRITTLE) เกิดที่ 12%:

α_1 $\sigma+\alpha_1$ $\sigma+\alpha_3$ α_2 $\alpha_1+\alpha_2$

SLOW COOLING ทำให้เกิด σ-PHASE

Cr ⇒ STABILIZE – α



TEMPERED AT 400–550°C

⇓

475°C EMBRITTLEMENT.

⇓

PRECIPITATE OF Cr-RICH PHASE

⇓

REDUCE TOUGHNESS.

Figure 5.2 *Fe–Cr alloys containing 0.1% C*

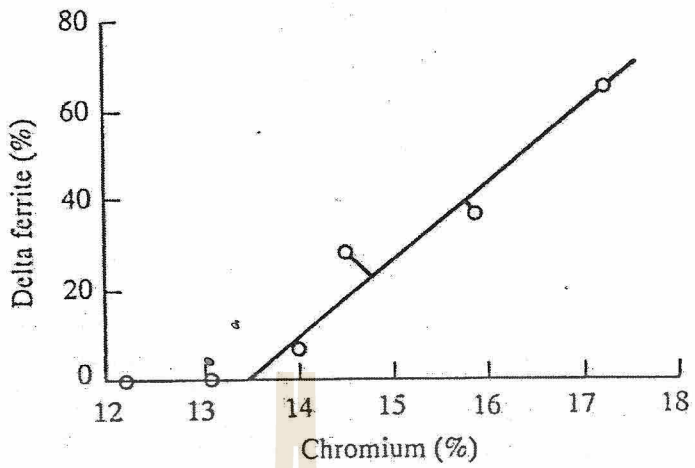
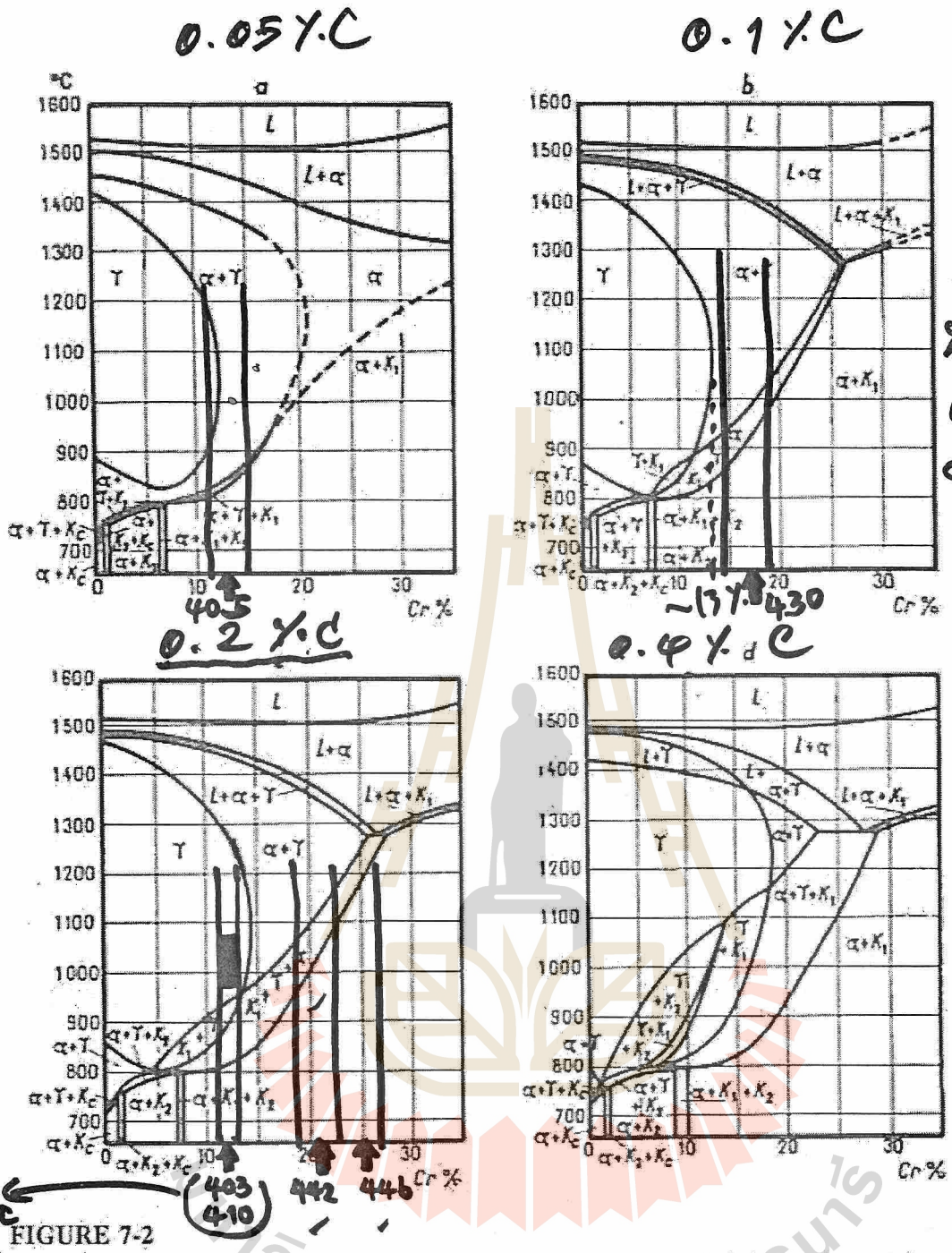


Figure 5.3 *Effect of chromium content on 0.1% carbon steels solution treated at 1050°C (After Irvine* et al.[1]*)*



ARTENSITIC
TAINLESS
STEEL.

FIGURE 7-2
Iron-chromium phase diagrams for different carbon contents: (*a*) 0.05% C; (*b*) 0.1% C; (*c*) 0.2% C; (*d*) 0.4% C. [*After K. Bungardt, E. Kunze, and E. Horn, Archiv. Eisenhuttenw. 29(1958):193, as presented in L. Colombier and J. Hochmann, "Stainless and Heat Resisting Steels," Edward Arnold Ltd., London, 1967, p. 11.*]

AT 0.1%C
สำหรับ
FERRITIC
STAINLESS
ควรมี %Cr
มากกว่า 13%
ขึ้นไป

%C เพิ่ม, %Cr ต้องเพิ่มสูงขึ้นด้วย
สำหรับ FERRITIC STAINLESS STEEL.
เพื่อให้ได้ FERRITIC MATRIX. และมี %Cr
ละลายอยู่ใน MATRIX > 12%

② MARTENSITIC STAINLESS STEELS.

$\boxed{\text{Fe-Cr ALLOY}}$ ⇒ %Cr ≈ 12–17 %

WITH C = 0.15–1.0 %C

⇓

MARTENSITIC STRUCTURE

BY QUENCHING FROM γ-REGION.

⇓

HIGH STRENGTH & HARDNESS

WITH POOR CORROSION RESISTANCE.

TYPICAL GRADE ⇒ 410 (12.5 %Cr, 0.15 %C MA

MACHINE PART, PUMP SHAFT,

BOLTS & BUSHINGS.

⇒ 440C (17.0 %Cr, 1 %C) HIGH-C

1 %C → ENLARGE γ-LOOP

HIGH-HARDNESS GRADE.

%Cr สูง, %C สูง

$Cr_{23}C_6$

$M_{23}C_6$

← เกิด NON-DISSOLVED CARBIDE ใน

AFTER AUSTENITIZED

AT 1,050 °C.

⇓

"CUTLERY GRADE"

มีด, อุปกรณ์ในการตัด, มีดผ่าตัด.

% Cr ต่ำ, % C สูงขึ้น
ทำให้ขยาย γ-LOOP ของ Fe-Cr DIAGRAM

TABLE 7-4
Chemical compositions and typical applications of wrought martensitic stainless steels†

QUENCH ของเกิด MARTENSITE

AISI type	% Cr	% C	% Ni	% Mo	% V	% W	% Other‡	*Typical applications*
403	12.2	0.15 max						"Turbine quality" grade. Steam turbine blading and other highly stressed parts *including jet engine rings.*
410	12.5	0.15 max						General-*purpose heat-treatable* type. Machine parts; pump shaft; bolts; bushings; coal chutes; cutlery; finishing tackle; hardware; jet engine parts; *mining machinery; rifle* barrels; screws; valves.
414	12.5	0.15 max	1.8					Higher carbon modification of type 410. Cutlery; surgical instruments; valves; wear-resisting parts; glass molds; hand tools; vegetable choppers.
420	13	Over 0.15						*High-hardenability steel.* Springs; tempered rules; machine parts; bolts; mining machinery; scissors; ships belts; spindles; valve seals.
422	12	0.22		1.0	0.25	1.0		High strength and toughness at service temperatures up to 1200°F. Steam turbine blades; fasteners.
431	16	0.20 max	1.8					Special-purpose hardenable steel used where particularly high mechanical properties are required. *Aircraft fittings;* beater bars; paper machinery; bolts.
440A	17	0.72						Hardenable to higher hardness than type 420; with good corrosion resistance. Cutlery; bearings; surgical tools.
440B	17	0.85						Cutlery grade. Cutlery; valve parts; instrument bearings.
440C	17	1.07						Yields highest hardnesses of hardenable stainless steels. Balls, bearings; races; nozzles; balls and seats for oil well pumps; valve parts.

มาก % Cr

% C ≈ 1 %
ENLARGE γ-LOOP.
HIGHEST HARDNESS GRADE.

NON-DISSOLVED CARBIDE ในเนื้อวัสดุ.

†After "ASM Databook," *Met. Prog.*, mid-June 1979, vol. 116, no. 1.
‡S:0.030% max; P: 0.040% max; Si: 1.00% max.

- HIGH STRENGTH & HARDNESS.
- POOR CORROSION RESISTANCE THAN FERRITIC AND AUSTENITIC GRADE.

③ AUSTENITIC STAINLESS STEELS.

Fe-Cr-Ni ALLOYS ⇒ %Cr = 16-25 %.

%Ni = 7-20 %.

FOR γ-STRUCTURE.

18-8
Cr Ni

→ γ-MATRIX WITH NO CARBIDE

→ BETTER CORROSION RESISTANCE

→ HIGH DUCTILITY & FORMABILITY.

TYPICAL GRADE ⇒ 301 (17% Cr, 7% Ni, 0.15 % C)

18-8
304 (19% Cr, 9% Ni, 0.08% C)

304L → % C = 0.03 %
(LOW-C)

↑ CORROSION RESISTANCE IN Cl- ENVIRONMENT. ← 316 (17% Cr, 12% Ni, 0.08% C)
WITH 2.5 % Mo

ADD Ti ← 321 & 347 → ADD Nb

STABILIZED FOR WELDMENT.

(18% Cr, 11 % Ni, 0.08% C)

จะทำให้เกิด INTERGRANULAR CORROSION.

309 & 310 ↑%Cr, ↑%Ni

↓

FOR HIGH CORROSION RESISTANCE & OXIDATION AT HIGH-TEMPERATURE.

- γ-MATRIX (Ms LOWER THAN R.T.)
- HIGH FORMABILITY (DUCTILITY)
- HIGH CORROSION RESISTANCE.

TABLE 7-6
Chemical compositions and typical applications of wrought austenitic stainless steels†

AISI type	Chemical compositions, wt% Cr	Ni	C (max)	Mn	Mo	Other ‡	Typical applications
301	17	7	0.15				High work-hardening rate; used for structural applications where high strength plus high ductility is required. Railroad cars; trailer bodies; aircraft structurals; fasteners; automobile wheel covers, trim; pole-line hardware.
302	18	9	0.15				General-purpose austenitic stainless steel. Trim; food-handling equipment; aircraft cowlings; antennas; springs; cookware; building exteriors; tanks; hospital, household appliances; jewelry; oil refining equipment; signs.
304	19	9	0.08				Low-carbon modification of type 302 for restriction of carbide precipitation during welding. Chemical and food processing equipment; brewing equipment; cryogenic vessels; gutters; downspouts; flashings.
304L (LOW C)	19	10	0.03				Extra-low-carbon modification of type 304 for further restriction of carbide precipitation during welding. Coal hopper linings; tanks for liquid fertilizer and tomato paste.
309 (ทนความร้อน)	23	13.5	0.20				High-temperature strength and scale resistance. Aircraft heaters; heat-treating equipment; annealing covers; furnace parts; heat exchangers; heat-treating trays; oven linings; pump parts.
310 (เพิ่ม CORROSION RESISTANCE)	25	20.5	0.25				Higher elevated-temperature strength and scale resistance than type 309. Heat exchangers; furnace parts; combustion chambers; welding filler metals; gas turbine parts; incinerators; recuperators.
316	17	12	0.08		2.5 (เพิ่ม Mo)		Higher corrosion resistance than types 302 and 304; high creep strength. Chemical and pulp handling equipment; photographic equipment; brandy vats; fertilizer parts; ketchup cooking kettles; yeast tubs.
316L (LOW C)	17	12	0.03		2.5		Extra-low carbon modification of type 316. Welded construction where intergranular carbide precipitation must be avoided. Type 316 applications requiring extensive welding.

*เพิ่มความแข็งแรงได้
- COLD-WORKING A→M
- SUB-ZERO QUENCHING. A→M

TABLE 7-6 (*Continued*)

AISI type	Chemical compositions, wt% Cr	Ni	C (max)	Mn	Mo	Other ‡	Typical applications
321	18	10.5	0.08			Ti 5 × C	Stabilized for weldments subject to severe corrosive conditions, and for service from 800 to 1600°F. Aircraft exhaust manifolds; boiler shells; process equipment; expansion joints; cabin heaters; fire walls; flexible couplings; pressure vessels.
347	18	11	0.08			Nb 10 × C	Similar to type 321 with higher creep strength. Airplane exhaust stacks; welded tank cars for chemicals; jet engine parts.
201	17	4.5	0.15	6			High work-hardening rate; low-nickel equivalent of type 301. Flatware; automobile wheel covers, trim.
202	18	5	0.15	8.75			General purpose low-nickel equivalent of type 302. Kitchen equipment; hub caps; milk handling.

† After "ASM Databook," *Met. Prog.*, vol. 116, no. 1, mid-June 1979.

‡ Mn: 2.00% max; S: 0.030% max; P: 0.045% max; Si: 1.00% max.

γ-STABILIZER.

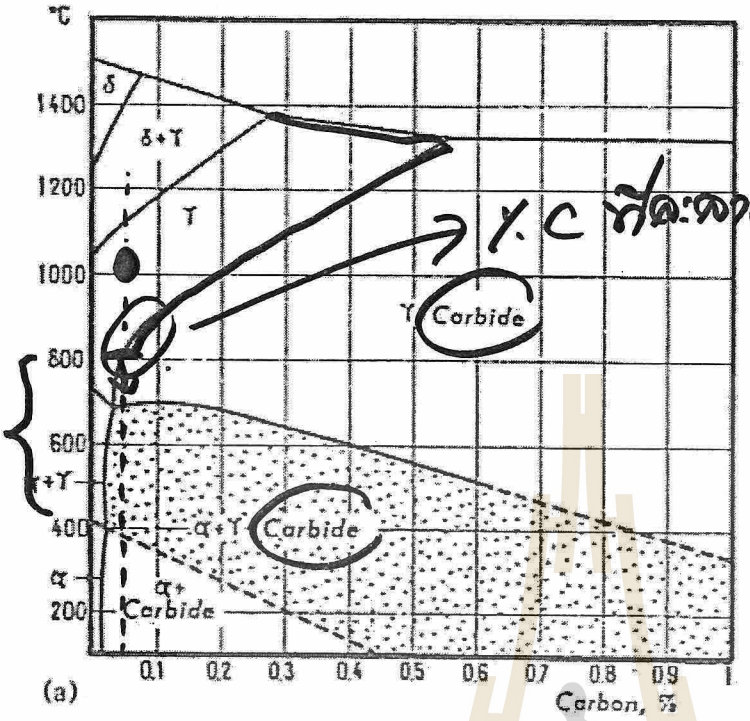
STABILIZED GRADE.

INTERGRANULAR CORROSION.

TiC

NbC

$Cr_{23}C_6$

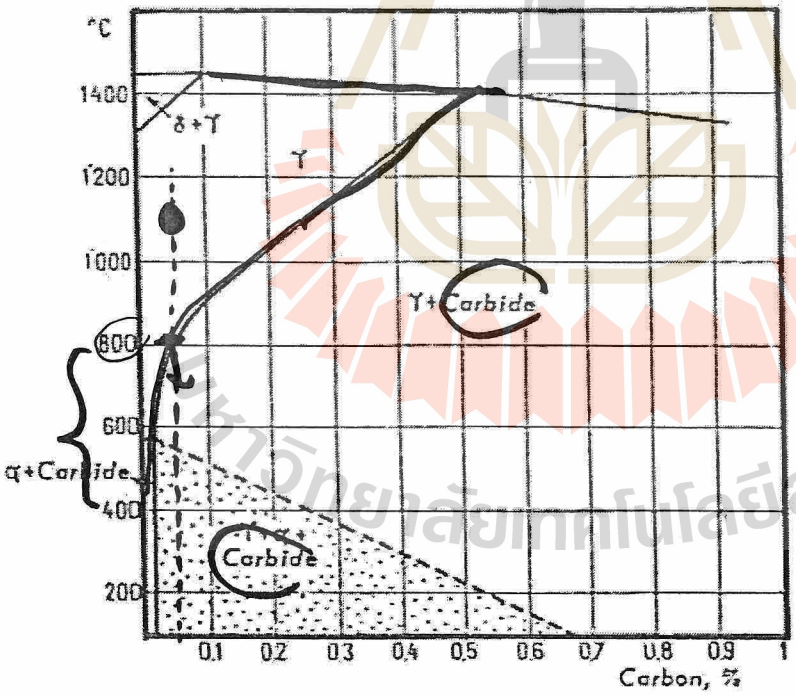


(a)

%C ที่ละลายใน γ ลดลงอย่างรวดเร็ว

4 %Ni , 18 %Cr

FIGURE 7-3
Phase diagrams for Fe–18% Cr-C alloys containing (*a*) 4% Ni and (*b*) 8% Ni. (*From L. Colombier and J. Hochmann, "Stainless and Heat Resisting Steels," Edward Arnold Ltd., London, 1967, p. 16.*)



(b)

8 %Ni , 18 %C

FIGURE 7-3 (*Continued*)

M_s ⇒ 304 −50 °C

⇒ 304 −250 °C

PRECIPITATION-HARDENING STAINLESS STEELS.

Ex. GRADE 17-7PH ← %Cr & %Ni SAME AS 301 (17%Cr, 7%Ni, 0.15%C MAX)

%C	%Cr	%Ni	%Al	%N
0.07	17.0	7.1	1.2	0.04

17-4PH → ใช้ใน ชม.

FOR PRECIPITATION HARDENING

MILL ANNEALED (1,063 °C) ⇒ CONDITION "A"
(MATRIX OF γ WITH STRINGERS OF δ-FERRITE)

↓ ขึ้นรูป/ม้วนรูป.

FABRICATION

↓

AUSTENITE CONDITIONING (760 °C, 90 MIN.)
(γ → M)

C & Cr REMOVE FROM γ TO PRECIPITATE $Cr_{23}C_6$
TO DE-STABILIZED γ (γ → M), ↑M_s.

↓

TRANSFORMATION
(AIR-COOLED TO 16 °C) ⇒ "T" CONDITION

↓ AGING

PRECIPITATION HARDENING.
(T = 480 - 650 °C, 90 MIN., AIR-COOLED)
CONDITION "TH"

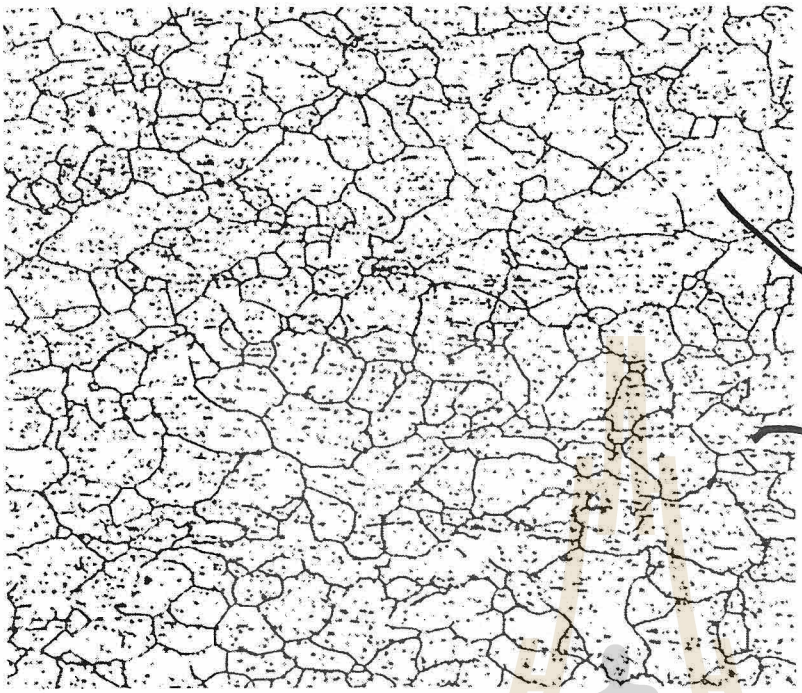
Al IN MARTENSITE COMBIDE WITH Ni TO PRECIPITATE NiAl AND Ni_3Al

⇓

	Y.S.	T.S.	%EL	HRc
17-7PH :	1,276 MPa	1,379 MPa	9%	43
301 :	276 MPa	759 MPa	60%	

0.12 % C MAX.
17 % Cr

FERRITIC STAINLESS STEEL (430)



ANNEALED AT 788°

⇓

FERRITE MATRIX

+

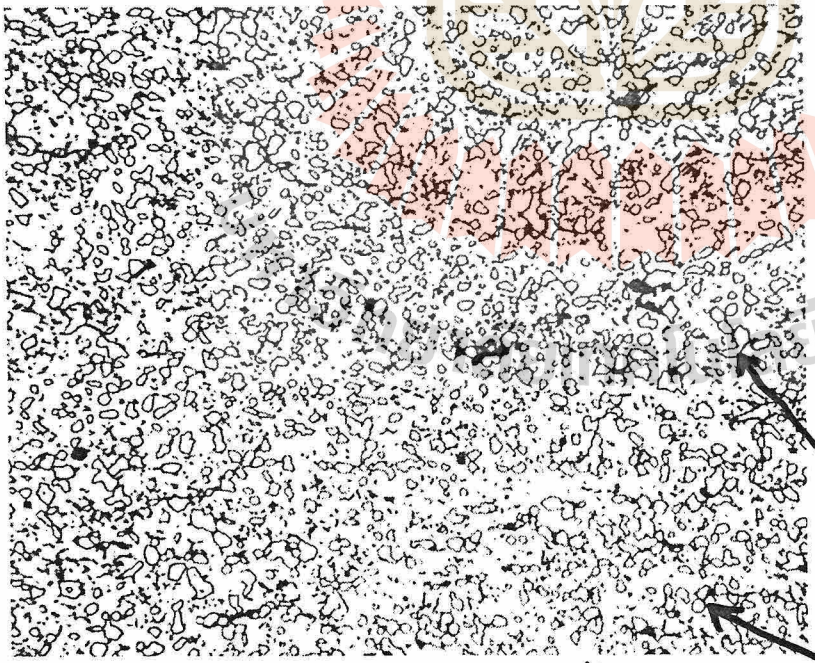
DISPERSED CARBIDE

HIGH

1.1 % C

17 % Cr

MARTENSITIC STAINLESS STEEL (440C)



AUSTENITIZED
(1,010 °C)

↓

AIR-COOLED

⇓

PRIMARY CARBIDES

+

MARTENSITE MATRIX

NON-DISSOLVED CARBIDE

"CUTLERY GRADE"

⇓

HIGHEST HARDNESS GRADE

18-8 0.08% C
19% Cr
9% Ni

AUSTENITIC STAINLESS STEEL (304)

ANNEALED, 5 MIN. AT 1,065 °C

↓

AIR-COOLED

⇓

AUSTENITE MATRIX

INTERGRANULAR CORROSION IN 304.

FIGURE 7-27
Typical intergranular attack of solution-treated type 304 stainless steel in boiling nitric-dichromate solution. (*a*) 4-h exposure; 500×. (*b*) 8-h exposure; 150×. [*After K. T. Aust, J. S. Armijo, and J. H. Westbrook, Trans. ASM 59(1966):544.*]

Table 9.12 Typical mechanical properties and applications of stainless steels

Alloy number	Chemical composition (wt %)*	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation in 2 in (%)	Typical applications
			Ferritic stainless steels					
430	17 Cr, 0.012 C	Annealed	75	517	50	345	25	General-purpose, nonhardenable; uses: range hoods, restaurant equipment
446	25 Cr, 0.20 C	Annealed	80	552	50	345	20	High-temperature applications; heaters, combustion chambers
			Martensitic stainless steels					
410	12.5 Cr, 0.15 C	Annealed	75	517	40	276	30	General-purpose heat-treatable; machine parts, pump shafts, valves
		Q & T†						
440A	17 Cr, 0.70 C	Annealed	105	724	60	414	20	Cutlery, bearings, surgical tools
		Q & T†	265	1828	245	1690	5	
440C	17 Cr, 1.1 C	Annealed	110	759	70	276	13	Balls, bearings, races, valve parts
		Q & T†	285	1966	275	1897	2	
			Austenitic stainless steels					
301	17 Cr, 7 Ni	Annealed	110	759	40	276	60	High work-hardening rate alloy; structural applications
304	19 Cr, 10 Ni	Annealed	84	580	42	290	55	Chemical and food processing equipment
304L	19 Cr, 10 Ni, 0.03 C	Annealed	81	559	39	269	55	Low carbon for welding; chemical tanks
321	18 Cr, 10 Ni, Ti = 5 × %C min	Annealed	90	621	35	241	45	Stabilized for welding; process equipment, pressure vessels
347	18 Cr, 10 Ni, Cb (Nb) = 10 × C min	Annealed	95	655	40	276	45	Stabilized for welding; tank cars for chemicals
			Precipitation-hardening stainless steels					
17-4PH	16 Cr, 4 Ni, 4 Cu, 0.03 Cb (Nb)	Precipitation-hardened	190	1311	175	1207	14	Gears, cams, shafting, aircraft and turbine parts

*Balance Fe.
†Quenched and tempered.

Table 5.2 *British Standard 1449: 1983: Steel Plate, Sheet and Strip Part 2: Stainless and Heat Resisting Steels*
Properties minima unless stated

Grade	Composition (maxima unless stated)									Condition	Tensile strength R_m N/mm²	Proof stress		Elongation[1] % min	Hardness[2] HV max
	C	Si	Mn	P	S	Cr	Mo	Ni	Others			$R_{p0.2}$ N/mm²	$R_{p1.0}$ N/mm²		
Austenitic Steels															
284S16	0.07	1.00	7.00/10.00	0.060	0.030	16.5/18.5	—	4.0/6.50	N 0.15/0.25	Softened	630	300	335	40	220
301S21	0.15	1.00	2.00	0.045	0.030	16.0/18.0	—	6.0/8.0	—	Softened	540	215	250	40	220
304S11	0.030	1.00	2.00	0.045	0.030	17.0/19.0	—	9.0/12.0	—	Softened	480	185	215	40	185
304S15	0.06	1.00	2.00	0.045	0.030	17.5/19.0	—	8.0/11.0	—	Softened	500	195	230	40	190
304S16	0.06	1.00	2.00	0.045	0.030	17.5/19.0	—	9.0/11.0	—	Softened	500	195	230	40	190
304S31	0.07	1.00	2.00	0.045	0.030	17.0/19.0	—	8.0/11.0	—	Softened	500	195	230	40	190
305S19	0.10	1.00	2.00	0.045	0.030	17.0/19.0	—	11.0/13.0	—	Softened	490	185	220	40	185
309S24	0.15	1.00	2.00	0.045	0.030	22.0/25.0	—	13.0/16.0	—	Softened	510	205	240	40	205
310S24	0.15	1.00	2.00	0.045	0.030	23.0/26.0	—	19.0/22.0	—	Softened	510	205	240	40	205
315S16	0.07	1.00	2.00	0.045	0.030	16.5/18.5	1.25/1.75	9.0/11.0	—	Softened	510	205	240	40	205
316S11	0.030	1.00	2.00	0.045	0.030	16.5/18.5	2.0/2.5	11.0/14.0	—	Softened	490	190	225	40	195
316S13	0.030	1.00	2.00	0.045	0.030	16.5/18.5	2.5/3.0	11.5/14.5	—	Softened	490	190	225	40	195
316S31	0.07	1.00	2.00	0.045	0.030	16.5/18.5	2.0/2.5	10.5/13.5	—	Softened	510	205	240	40	205
316S33	0.07	1.00	2.00	0.045	0.030	16.5/18.5	2.5/3.0	11.0/14.0	—	Softened	510	205	240	40	205
317S12	0.030	1.00	2.00	0.045	0.030	17.5/19.5	3.0/4.0	14.0/17.0	—	Softened	490	195	230	40	195
317S16	0.06	1.00	2.00	0.045	0.030	17.5/19.5	3.0/4.0	12.0/15.0	—	Softened	510	205	240	40	205
320S31	0.08	1.00	2.00	0.045	0.030	16.5/18.5	2.0/2.5	11.0/14.0	Ti 5C/0.80	Softened	510	210	245	40	205
320S33	0.08	1.00	2.00	0.045	0.030	16.5/18.5	2.5/3.0	11.5/14.5	Ti 5C/0.80	Softened	510	210	245	40	205
321S31	0.08	1.00	2.00	0.045	0.030	17.0/19.0	—	9.0/12.0	Ti 5C/0.80	Softened	500	200	235	35	200
347S31	0.08	1.00	2.00	0.045	0.030	17.0/19.0	—	9.0/12.0	Nb 10C/1.00	Softened	510	205	240	35	200

Grade	Composition (maxima unless stated)									Condition	Tensile strength R_m N/mm²	Proof stress $R_{p0.2}$ N/mm²	Elongation[1] % min	Hardness[2] HV max	
	C	Si	Mn	P	S	Cr	Mo	Ni	Others					Plate	Sheet/ Strip
Ferritic Steels															
403S17	0.08	1.00	1.00	0.040	0.030	12.0/14.0	—	1.00	—	Softened	420	245	20	190	175
405S17	0.08	1.00	1.00	0.040	0.030	12.0/14.0	—	1.00	Al 0.10/0.30	Softened	420	245	20	190	175
409S19	0.08	1.00	1.00	0.040	0.030	10.5/12.5	—	1.00	Ti 6C/1.0	Softened	350	200	20	190	175
430S17	0.08	1.00	1.00	0.040	0.030	16.0/18.0	—	1.00	—	Softened	430	245	20	190	175
434S17	0.08	1.00	1.00	0.040	0.030	16.0/18.0	0.90/1.30	1.00	—	Softened	430	245	20	—	185
Martensitic Steels															
410S21	0.09/0.15	1.00	1.00	0.040	0.030	11.5/13.5	—	1.00	—	Softened	—	—	—	190	185
420S45	0.28/0.36	1.00	1.00	0.040	0.030	12.0/14.0	—	1.00	—	Softened	—	—	—	230	220

1. Elongation measured on flat test pieces using 50mm gauge length or $5.65\sqrt{S_o}$. For cylindrical test pieces, a gauge length of $5.65\sqrt{S_o}$ is used.
2. For items of adequate thickness the Brinell hardness test may be used, applying the same limiting HB hardness values as given for HV.

Table 5.3 *Comparative international stainless steel grades*

British	*French*	*German*	*Italian*	*Japanese*	*Swedish*	*USA*
301S21	Z12CN17.08	1.4310	X12CrNi 17 07	SUS301	14 23 31	301
304S31				SUS302	14 23 32	302
304S15 304S16	Z6CN18.09	1.4301	X5CrNi 18 10	SUS304	14 23 33	304
304S11	Z2CN18.10	1.4306	X2CrNi 18 11	SUS304L	14 23 52	304L
305S19	Z8CN18.12		X8CrNi 18 12	SUS305		305
309S24	Z15CN24.13		X16CrNi 23 14	SUS309		309
310S24	Z12CN25.20	1.4845	X22CrNi 25 20	SUS310S	14 23 61	310
315S16					14 23 40	
316S31 316S33	Z6CND17.11	1.4401 1.4436	X8CrNiMo 17 13	SUS316	14 23 47 14 23 43	316
316S11 316S13	Z2CND17.12	1.4404 1.4435	X2CrNiMo 17 12	SUS316L	14 23 48 14 23 53	316L
317S12	Z2CND19.15	1.4435	X2CrNiMo 18 16	SUS317L	14 23 67	317L
317S16		1.4436		SUS317	14 23 66	317
320S31 320S33	Z8CND17.12	1.4571 1.4573			14 23 50	
321S31	Z6CNT18.12	1.4541	X6CrNiTi 18 11	SUS321	14 23 37	321
347S31	Z6CNNb 18.11	1.4550	X6CrNiNb 18 11 X8CrNiNb 18 11	SUS347	14 23 38	347
403S17	Z6C13	1.4000	X6Cr 13	SUS403	14 23 01	403
405S17	Z6CA13	1.4002	Z6CrAl 13	SUS405		405
409S19		1.4512				409
430S17	Z8C17	1.4016	X8Cr 17	SUS430	14 23 20	430
434S17	Z8CD17.01	1.4113	X8CrMo 17	SUS434	14 23 25	434
410S21	Z12C13	1.4006 1.4024	X12Cr 13	SUS410	14 23 02	410
420S45	Z30C13		X30Cr 13	SUS420J2	14 23 04	420

After British Steel Stainless.[4]

Table 5.7 *Compositions of commercial grades of controlled-transformation stainless steels*

Grade	*C%*	*Mn%*	*Si%*	*Cr%*	*Ni%*	*Mo%*	*Cu%*	*Co%*	*Al%*	*Ti%*
Armco 17-4PH	0.04	0.5	0.3	16.5	3.5		3.5			
AM350	0.1	0.5	0.3	17	4.2	2.75				
Stainless W	0.07	0.5	0.3	17	7				0.2	0.7
Armco 17-7PH	0.07	0.5	0.3	17	7				1.1	
Armco 17-5PH	0.07	0.5	0.3	15	7	2.5			1.2	
FV 520(S)	0.07	1.5	0.5	16	5.5	2	1.5			0.1
SF 80T	0.08	0.2	2.0	17	4	1	1.2	2		

Table 5.8 *Compositions of high-alloy austenitic and duplex stainless steels*

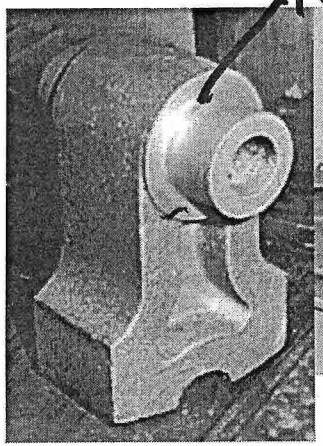
Alloy designation	*Chemical composition (wt %)*						
	C	*Cr*	*Mo*	*Ni*	*Cu*	*N*	*Others*
316L	0.03	17	2.25	12	–	–	–
316LM	0.03	17	2.75	12	–	–	–
317L	0.03	18	.5	15	–	–	–
317LN	0.03	18	4.5	13	–	0.15	
317LM	0.03	18	4.5	15	–	–	–
317LMN	0.04	18	6	14	–	0.15	2.1Nb+Ta,
94L	0.02	20	3	25		–	2.5Co, 1W
254SMo	0.02	20	6.5	18	2	0.12	5Co, 1.5W
Incoloy 825	0.03	22		42		–	3.65Nb+Ta
Hastelloy G	0.05	22	7	44	1.9	–	3W
			9		–		1.25Co, 4W
Hastelloy G-3	0.015	22	13	41	–	–	–
Inconel 625	0.05	22	16	61	–	–	0.75W
Hastelloy C-22	0.015	22	3		–	–	
Hastelloy C-276	0.02	25	3.5		0.75	–	
22/5	0.03					0.15	
Zeron 100	0.03					0.25	

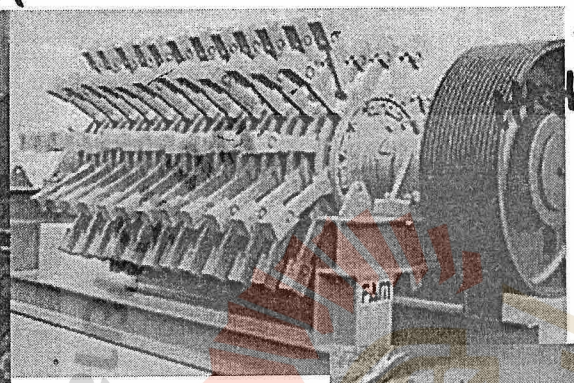
After Lane and Needham.[12]

Applications

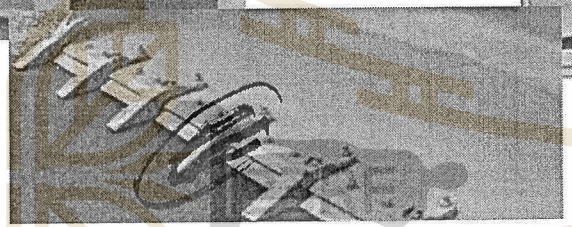
DUCTILITY
IMPACT RESISTANCE.
(INSIDE)

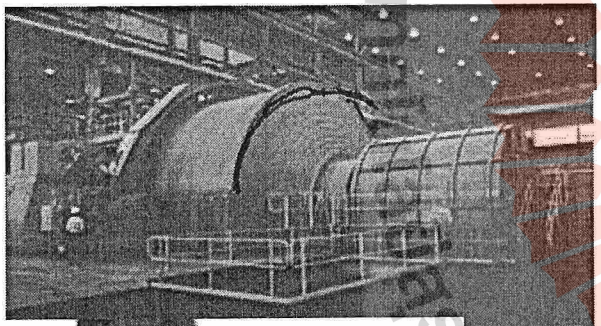
HAMMER

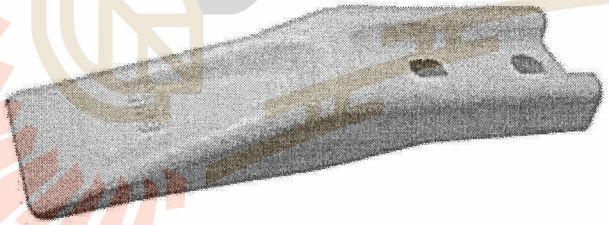


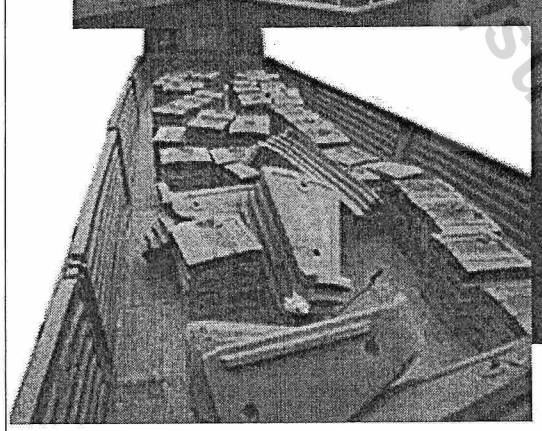


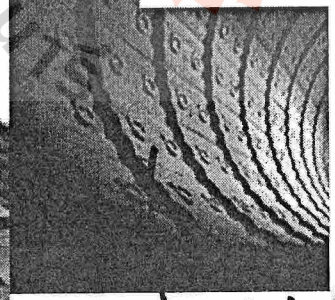
SURFACE
HARDNESS
↓
ABRASION
RESISTANCE



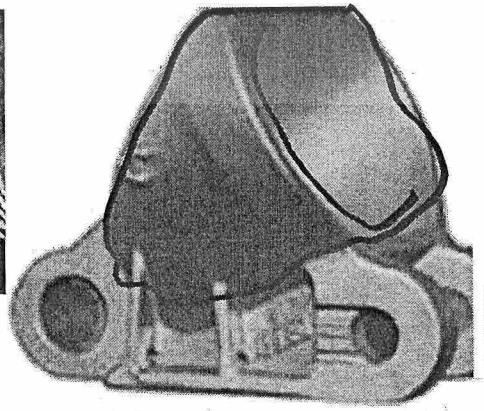


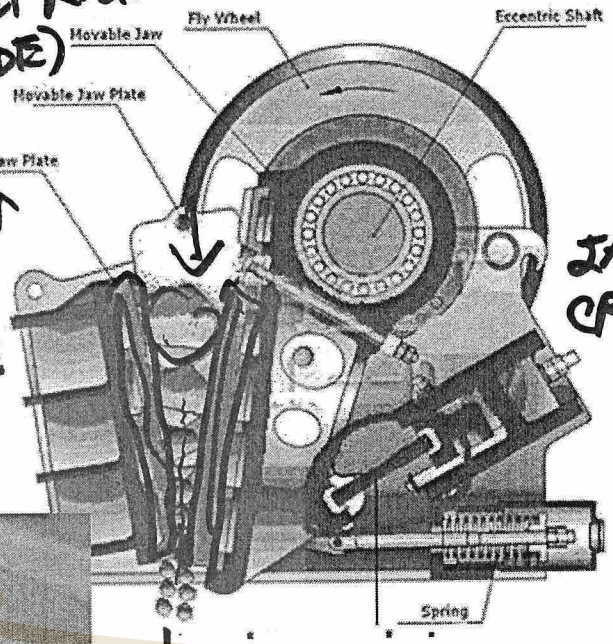




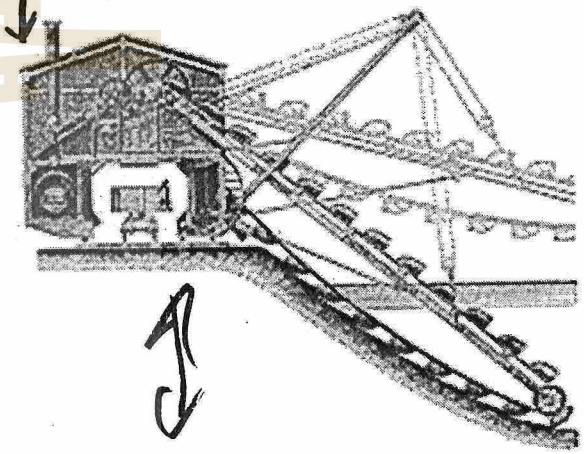


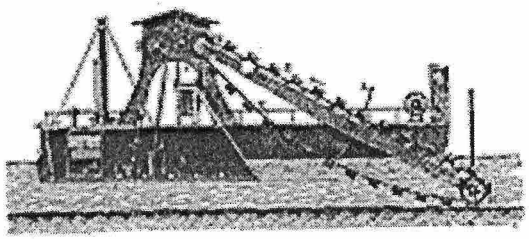
BALL MILL



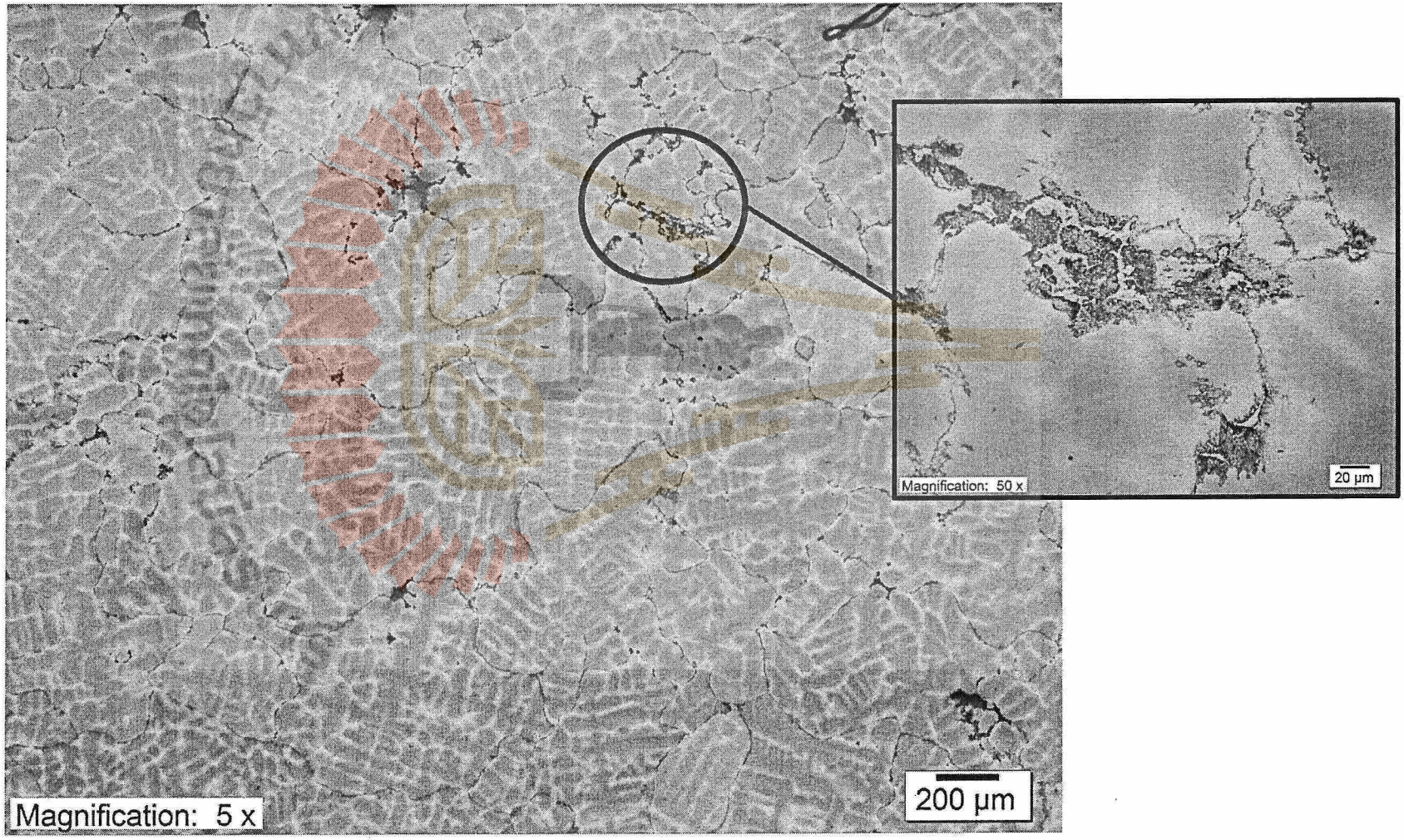


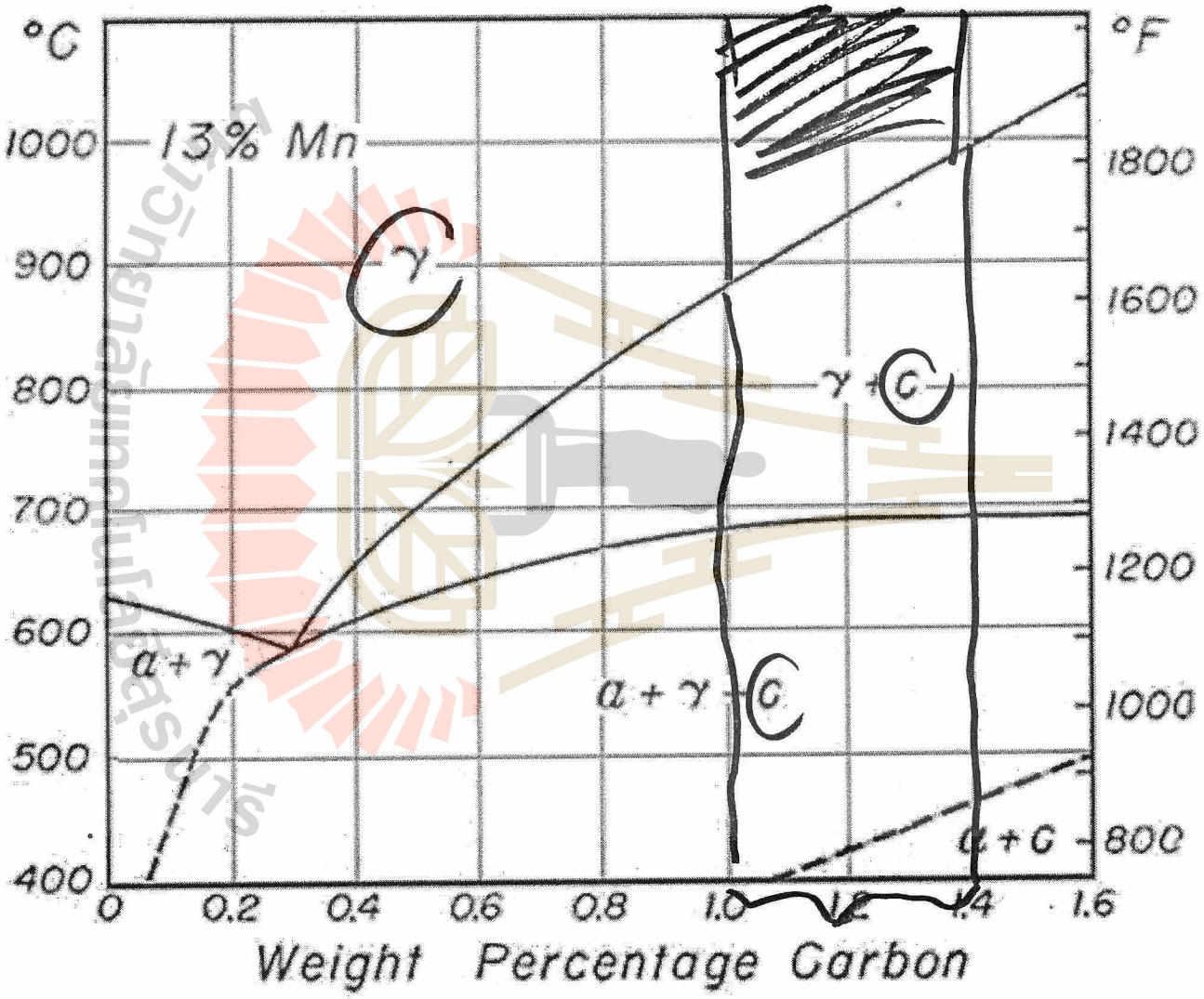
JAW
CRUSHER.





As - Cast




°C
°F
13% Mn
γ
γ + C
α + γ
α + γ + C
α + C
1000
900
800
700
600
500
400
1800
1600
1400
1200
1000
800
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Weight Percentage Carbon

"Wear Resistance Steel" → Sir. Robert Abbott Hadfield. 1882

High - Mn Steel (Hadfield's Steel)

C	Si	Mn
0.9 - 1.4%	0.4 - 1.0%	10 - 14 %

Si → CASTABILITY.

Mn → γ-STABILIZER, FORM CARBIDE

m.p. ≈ 1,400 °C เกิด γ ได้ที่ R.T.

Density ≈ 7.87 g/cm³

Alloying Elements

γ-stabilizer → เพิ่มความเหนียวเมื่อ Ni

- Cr (1-2.5%)
- Ni
- Mo (1-2%) → Mo_2C เกาะ (Fe, Mn)
- V → VC

เพิ่ม T.S., Y.S. ↓ Y.E.L. ↓

Carbide forming element เพิ่มความแข็งให้ผิวชิ้นงาน ให้ผิวงาน

As cast : γ + $(Fe, Mn)_3C$

Heat treat & quench : γ

heated & hold at 1,000 - 1,100 °C (3 - 6 hrs.) ⇒ water quenched. (H_2O)

* เพื่อให้ผิวงาน Mn - CARBIDE ตกลงอยู่ในเกรน (เพื่อให้ carbide จะสลายตัวกลายเป็นอยู่ใน solid solution.)

→ Coeff. of thermal expansion สูง ⇒ เกิดการบิดตัวเมื่อ heat & co

→ Thermal conductivity ต่ำ

→ แข็งเหนียวกดดันไม่ได้

Properties.

ถูกกลึงแล้ว WORK HARDENING ขึ้นมาก

T.S. 70 - 80 kg/mm²

Y.S. 35 - 37 kg/mm²

$\frac{Y.S.}{T.S.} \approx 0.50$

Y.E.L. 30 - 50 % ความเหนียว.

High strength

High toughness

Resistance to we

Heavy impact loadi

Charpy Impact V-notch 10 - 14 kg.m/cm²

Hardness 170 - 185 H_B ⇒ หลังจากตีไปที่ผิวงานใหญ่ๆ จะทำให้ hardness ถึงถึง ~55

(เกิด work hardening)

γ → martensite

case 550 H_B martensite

core 170-185 H_B austenite

ถ้าใส่ Cr, Mo, V ⇒ เหนียวขึ้น (เพราะต้องใส่ผิวงาน carbide)

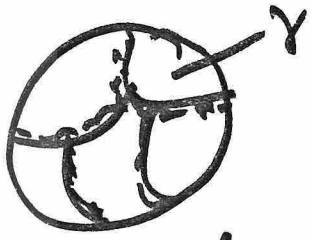
ชิ้นงานหนาๆ ⇒ เหนียวขึ้น (เพราะเกิด heat loss ตามขอบ)

การเชื่อม.

- เชื่อมหลังอบอ่อน
- ไม่ต้อง Pre-heat
- ใช้ลวดเชื่อม Low-C Austenitic
- หลังเชื่อมไม่ต้องอบคลายความเครียด

Tempered at 350 – 500 °C

$\gamma \rightarrow \alpha + Mn_3C$ อยู่ตามขอบเกรน



ความเหนียว, ทนต่อแรงกระแทกลดลง, เปราะ:
แตกหักได้ง่าย "เรียก Temper Brittleness"

Applications

(i) Jaw-crushing Machinery : Liner plates for ball/rod mills, parts for crushers.

(ii) Dredging equipment : tumblers, buckets, lips, heel plates.

(iii) Track work : points & crossings

Others: Crane track wheels, Digger teeth, axle-ba liners, bottom plate for magnets. Railroads, grinding mill liners, crusher jaws and cones, impact hamm bullet-proof helmets

MICRO-ALLOY STEEL

HIGH STRENGTH LOW ALLOY STEEL

HSLAs.

&

TMCP.

PLAIN-C STEEL

- **LOW-C**
  - C ≤ 0.25%
  - FLAT PRODUCT.
  - STRUCTURAL.
  - (ROLLED)
- MEDIUM-C
  - 0.25 – 0.55%C
  - MACHINE PART
  - (HEAT TREATABLE)
- HIGH-C
  - C > 0.55%
  - TOOL STEEL

ALLOY STEEL

- **LOW ALLOY.**
  - ALLOY < 10%
- HIGH ALLOY
  - ALLOY > 10%

APPLICATION

- BODY PART IN AUTO-INDUSTRY
- CONSTRUCTION OF BUILDING, BRIDGE, PIPLINE, ...

↓

HIGH STRENGTH. LOW-C STEEL

HOT ~~COLD~~-ROLLED PRODUCT : Y.S. > 220 MPa, T.S. > 330 MPa

COLD ~~HOT~~-ROLLED PRODUCT : Y.S. > 280 MPa, T.S. > 370 MPa.

- PRECIPITATION STRENGTHENING*
- REFINING OF FERRITE GRAIN SIZE*
- TRANSFORMATION STRENGTHENING
- DISLOCATION STRENGTHENING
  WORK-HARDENING

⇓

PRODUCED LIGHTER wt. & HIGHER STRENGTH

LOW-C STRUCTURAL STEELS.

USED FOR: BUILDINGS, BRIDGES, PRESSURE VESSE
AND. SHIPS, OFF-SHORE PLATFORM, PIPELIN
(FOR CIVIL & CHEMICAL ENGINEERING.)

FORMER ⇒ C-Mn STEEL
(FERRITE-PEARLITE STRUCTURE.)

↓

ALMOST REQUIRED WELDING.

↓ MARTENSITE FORMED IN HAZ ZON
DURING COOLING ↓

HIGH-C, LEAD TO "COLD CRACKING"

⇓

REQUIRE LOW-C GRADE FOR :—

- IMPROVE WELDABILITY
- HIGH-STRENGTH
- GOOD TOUGHNESS & DUCTILITY.

MODERN DESIGN CONCEPTS

① REFINE α-GRAINS
BY Al-GRAIN-REFINED.
↑ Y.S. & TOUGHNESS
(Y.S. UPTO 300 N/mm²)
WITH
GOOD IMPACT PROPERTY
GOOD WELDING CHARACTERISTICS.

② HIGHER STRENGTH BY.
PRECIPITATION STRENGTHENIN
ADDED SMALL AMOUNT OF
Al, Nb, V, Ti (≤ 0.15 %)
⇓
CALL "MICRO-ALLOY"
OR "HSLAs"
(Y.S. UPTO 500 N/mm²)

OLD TECHNIC.

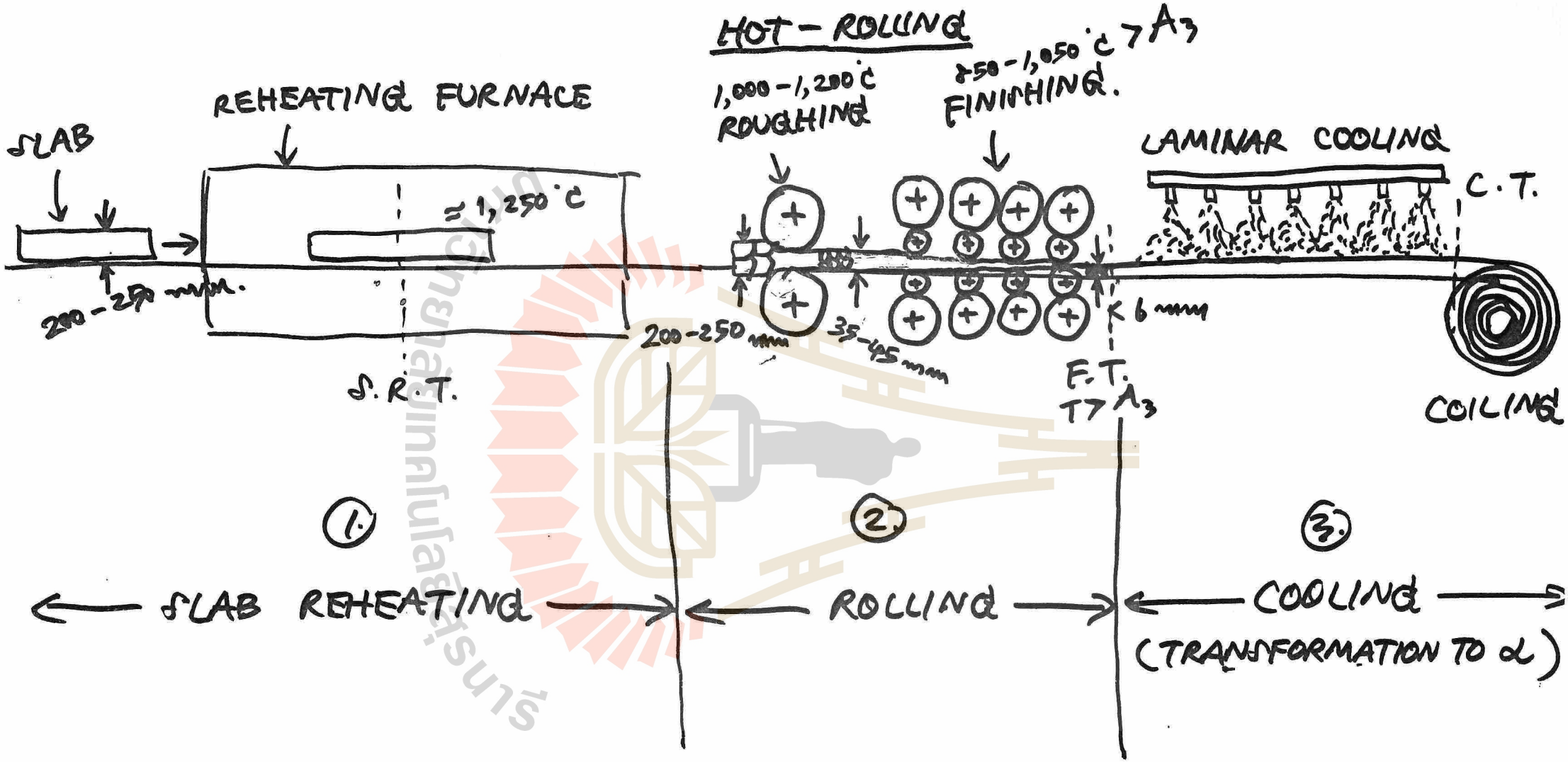
ROLLING + NORMALIZING HEAT-TREAT.

NEW TECHNIC. (1950-1960)

CONTROLLED ROLLING
(PRODUCED FINE-GRAIN IN AS-ROLLED CONDITION)

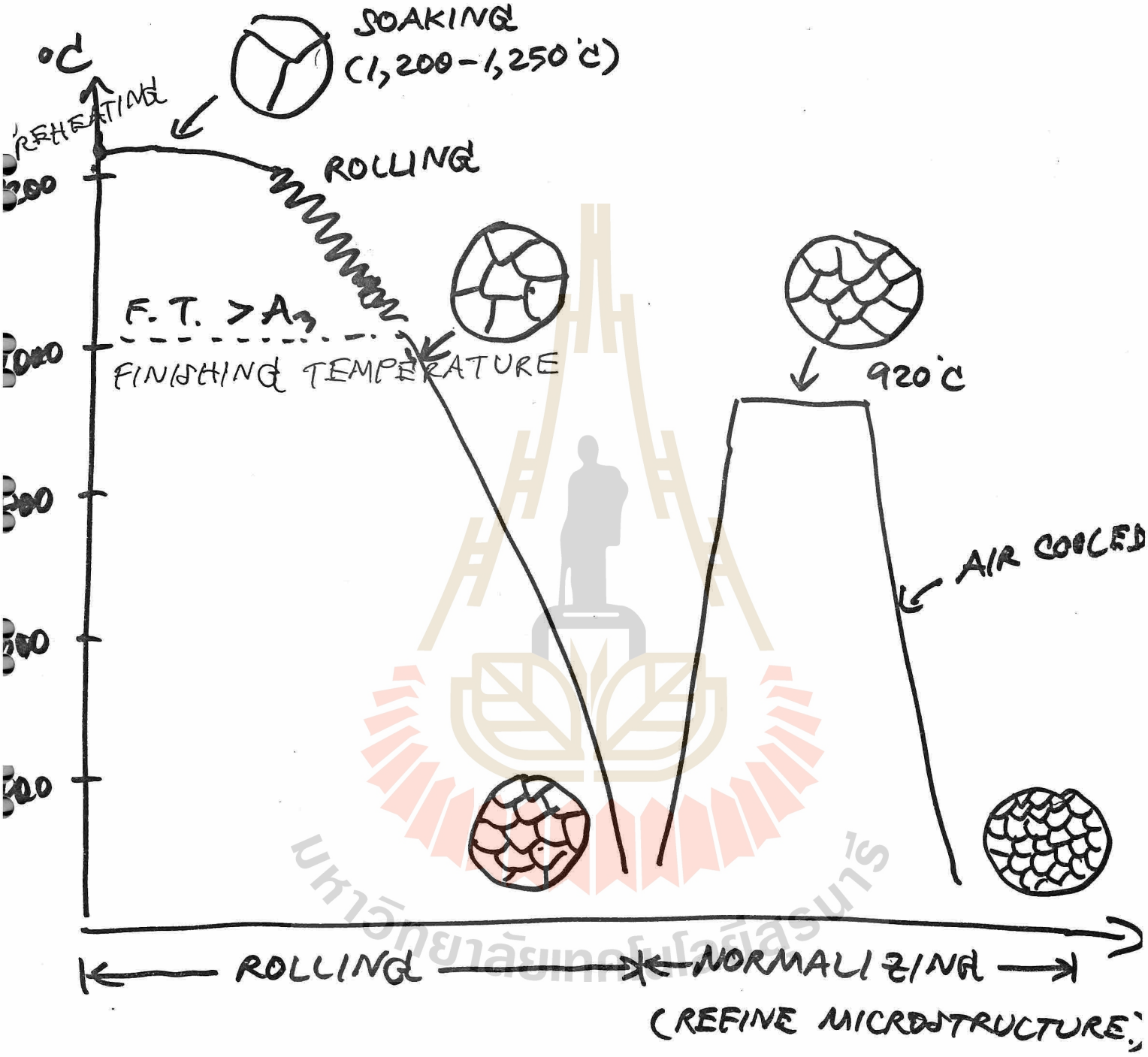
MODERN TECHNIC (1970-1980)

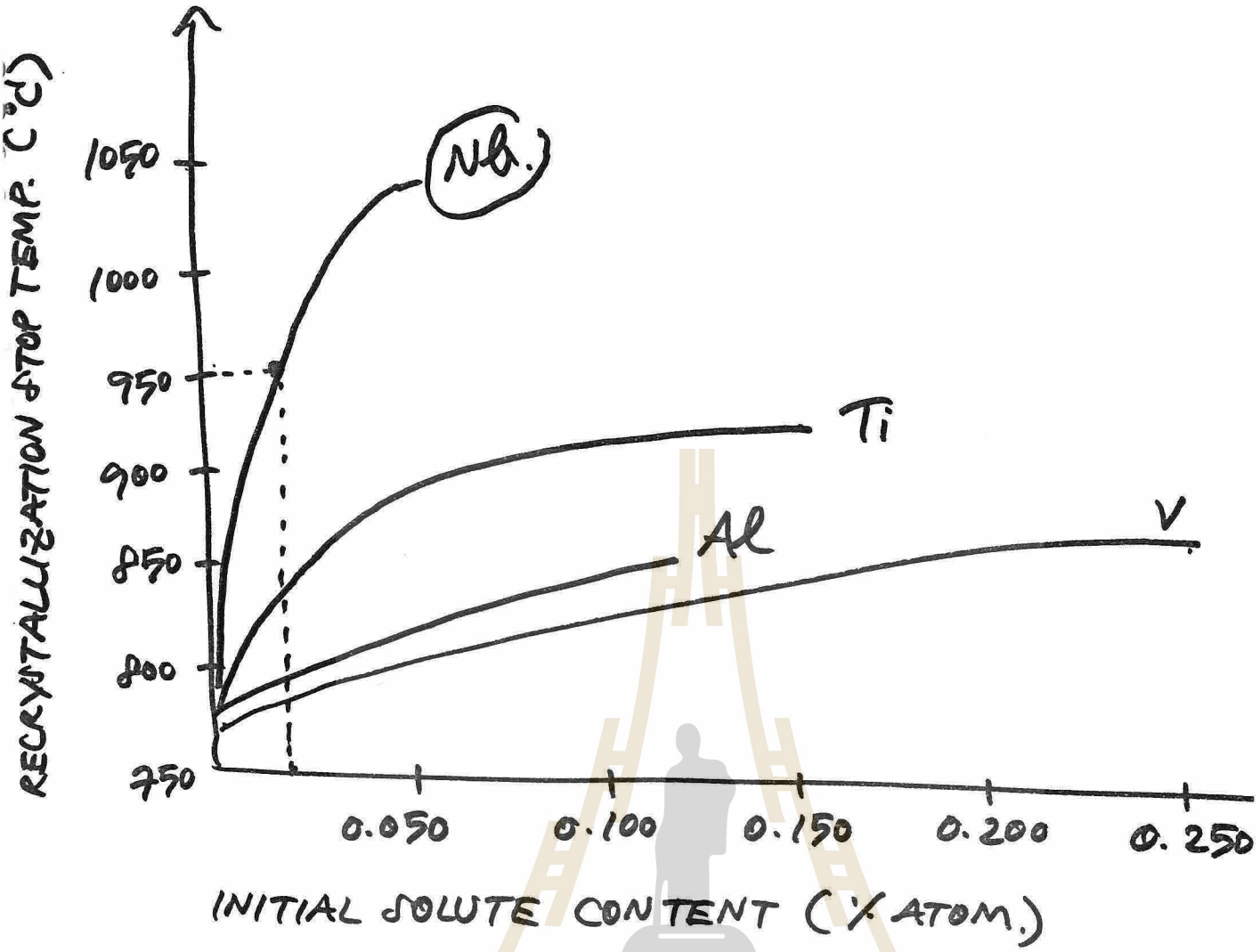
CONTROLLED ROLLING + CONTROLLED COOLING
CONTROLLED PROCESS
"THERMO-MECHANICAL PROCESSING"
"TMCP"


HOT - ROLLING
REHEATING FURNACE
SLAB
≈ 1,250 °C
200 - 250 mm.
S.R.T.
1,000 - 1,200 °C
ROUGHING
850 - 1,050 °C > A3
FINISHING.
200-250 mm
35-45 mm
< 6 mm
F.T.
T > A3
LAMINAR COOLING
C.T.
COILING
1.
2.
3.
SLAB REHEATING
ROLLING
COOLING
(TRANSFORMATION TO α)

TRADITIONAL HOT-ROLLING OPERATION FOR PLATE

"NORMAL ROLLING + NORMALIZING"





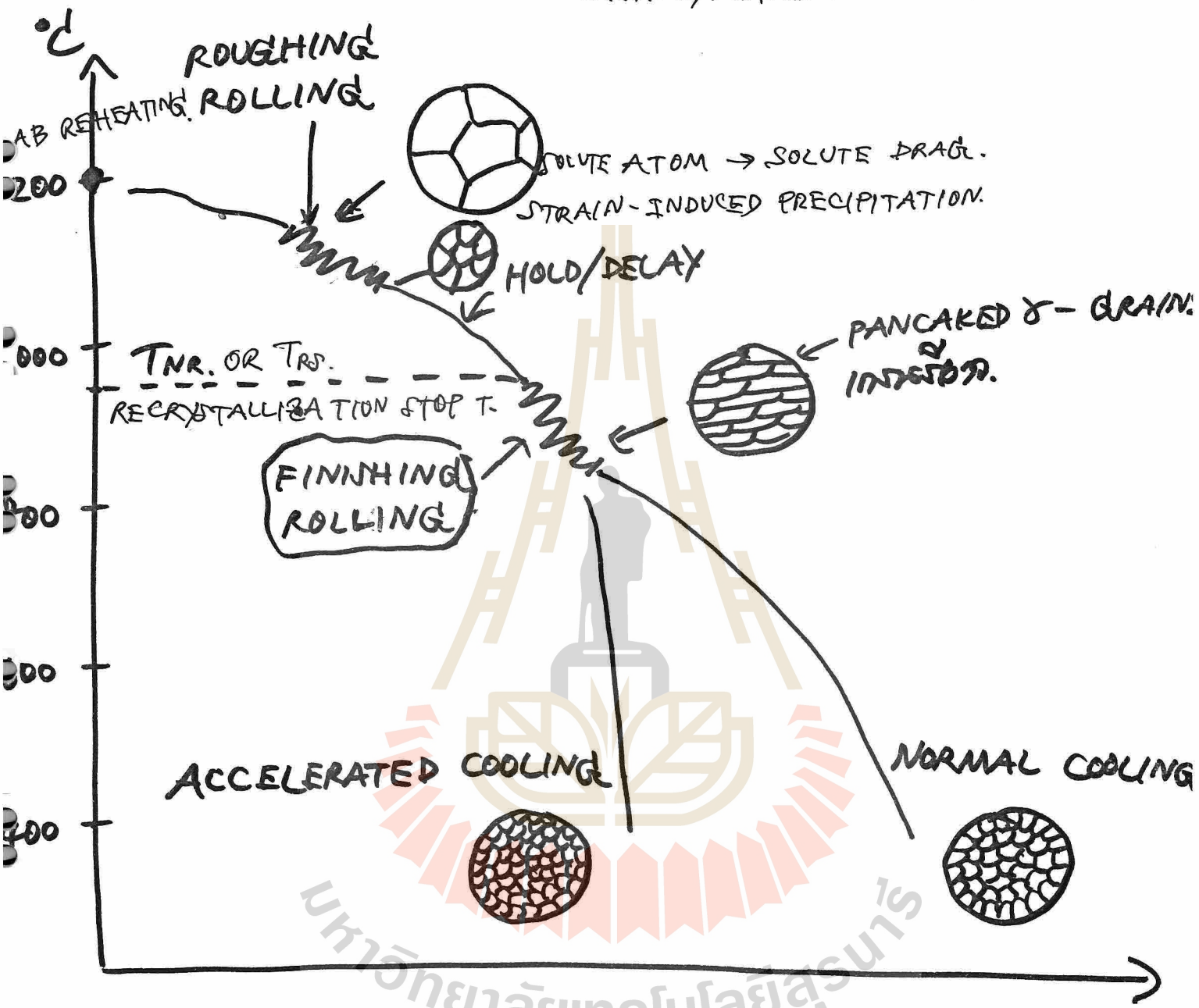
* Nb IS MOST POWERFUL TO RETARD AND RECRYSTALLIZATION STOP OCCUR

THERMO-MECHANICAL PROCESSING (TMCP)

HSLA.

Al, V, Nb, Ti FORM กับ C, N

CARBIDE, NITRIDE ใช้: CARBO-NITRIDE



* ADDING Nb ≈ 0.050% CAN BE RETARD THE RECRYSTALLIZATION (RECRYSTALLIZATION STOP) AT HIGH TEMPERATURE ⇒ ALLOWED FOR CONTROLLED ROLLING.

① SLAB REHEATING.

Al, Nb, V, Ti
↓
MICRO-ALLOYS
HSLA

(i) CONTROL AMOUNT OF MICRO-ALLOYS TAKEN INTO SOLUTION

AlN*, NbC, Nb(CN)*, VN, TiN*, TiC*

* DISSOLVED AT TEMP ≈ 1,150 – 1,300 °C

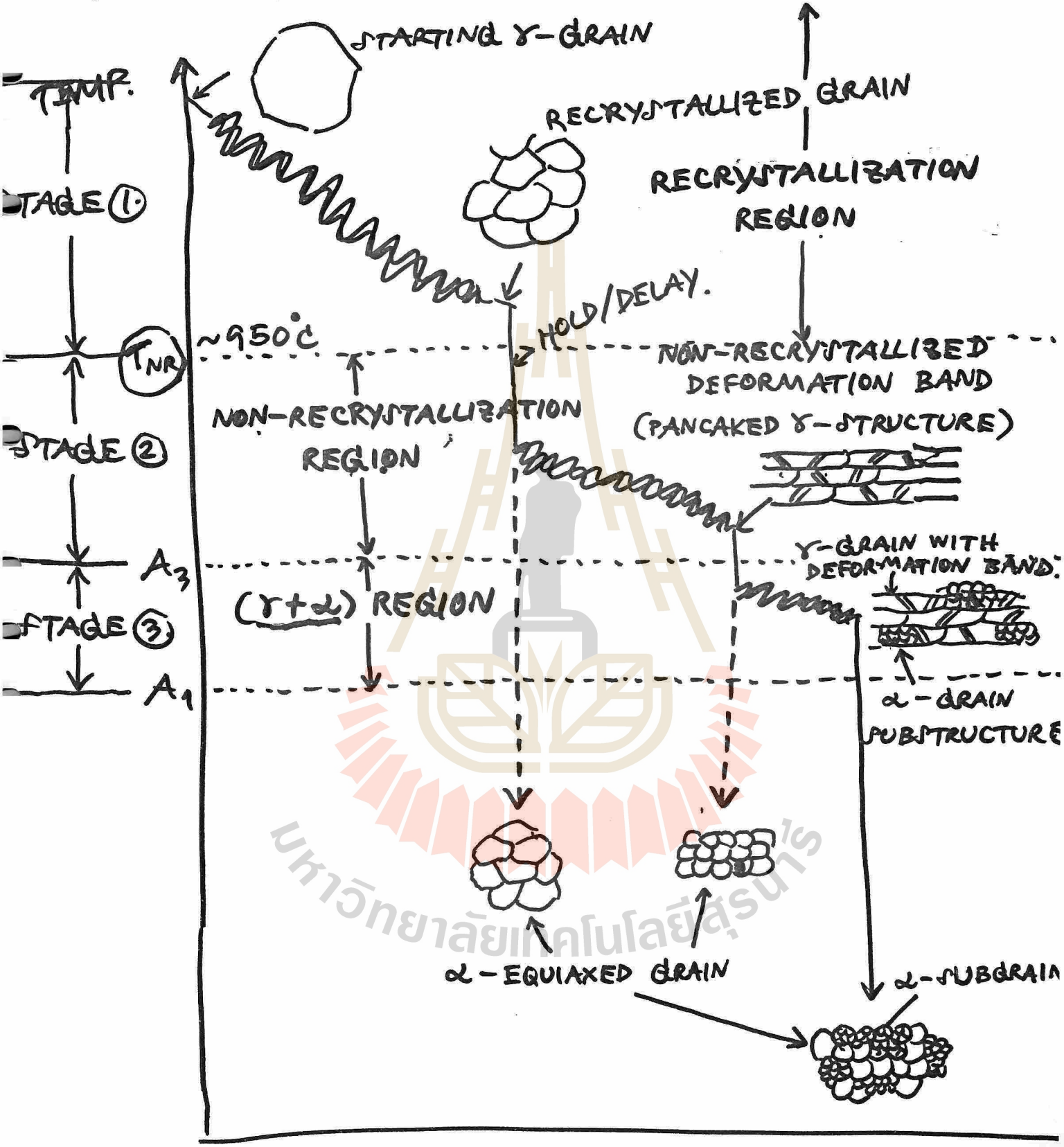
① DISSOLVED
⇓
CONTROL OF RECRYSTALLIZATION
CONTROL OF PRECIPITATION STRENGTHENING.

② NON-DISSOLVED.
Nb, Ti, V
⇓
CONTROL FINE γ-GRAIN SIZE
เกรน γ เล็กจะทำให้ความเครียดสูงขึ้น

(ii) STARTING γ-GRAIN SIZE.

② ROLLING.

3-STAGE IN CONTROLLED ROLLING :



ROLLING JUST BELOW S.R.T. (Stage I)

→ RECRYSTALLIZATION OCCUR

→ REFINE γ - GRAIN

⇓

TEMPERTURE DECREASE DURING ROLLING

→ RECRYSTALLIZATION RETARDED BY SOLUTE ATOM OF Al, Nb, V, Ti

⇓

"SOLUTION DRAG"

→ EFFECT OF Nb (MAJOR) IN :-

RETARDATION OF RECRYSTALLIZATION & GRAIN GROWT

⇓

STRAIN-INDUCED PRECIPITATION OF FINE Nb CCN & TiC DURING ROLLING PROCESS

⇓

RECRYSTALLIZATION MORE DIFFICULT ⇒ STOP

(OCCUR RECRYSTALLIZATION STOP TEMP., T_{NR} OR T_{RS})

PREVENT RECRYSTALLIZATION BEFORE THE NEXT PASS

Stage II ⇓

FINISHING ROLLING BELOW T_{NR} OR T_{RS}.

⇓

NON-RECRYSTALLIZED ELONGATED γ - STRUCTURE

(ELONGATED PANCAKE MORPHOLOGY.)

③ TRANSFORMATION TO FERRITE. (COOLING)

AVERAGE FERRITE GRAIN SIZE RELATED TO :—

(i) THICKNESS OF PANCAKED-γ GRAINS.

(ii) ALLOYS ADDED DEPRESS $\gamma \rightarrow \alpha$ TRANSFORMATI

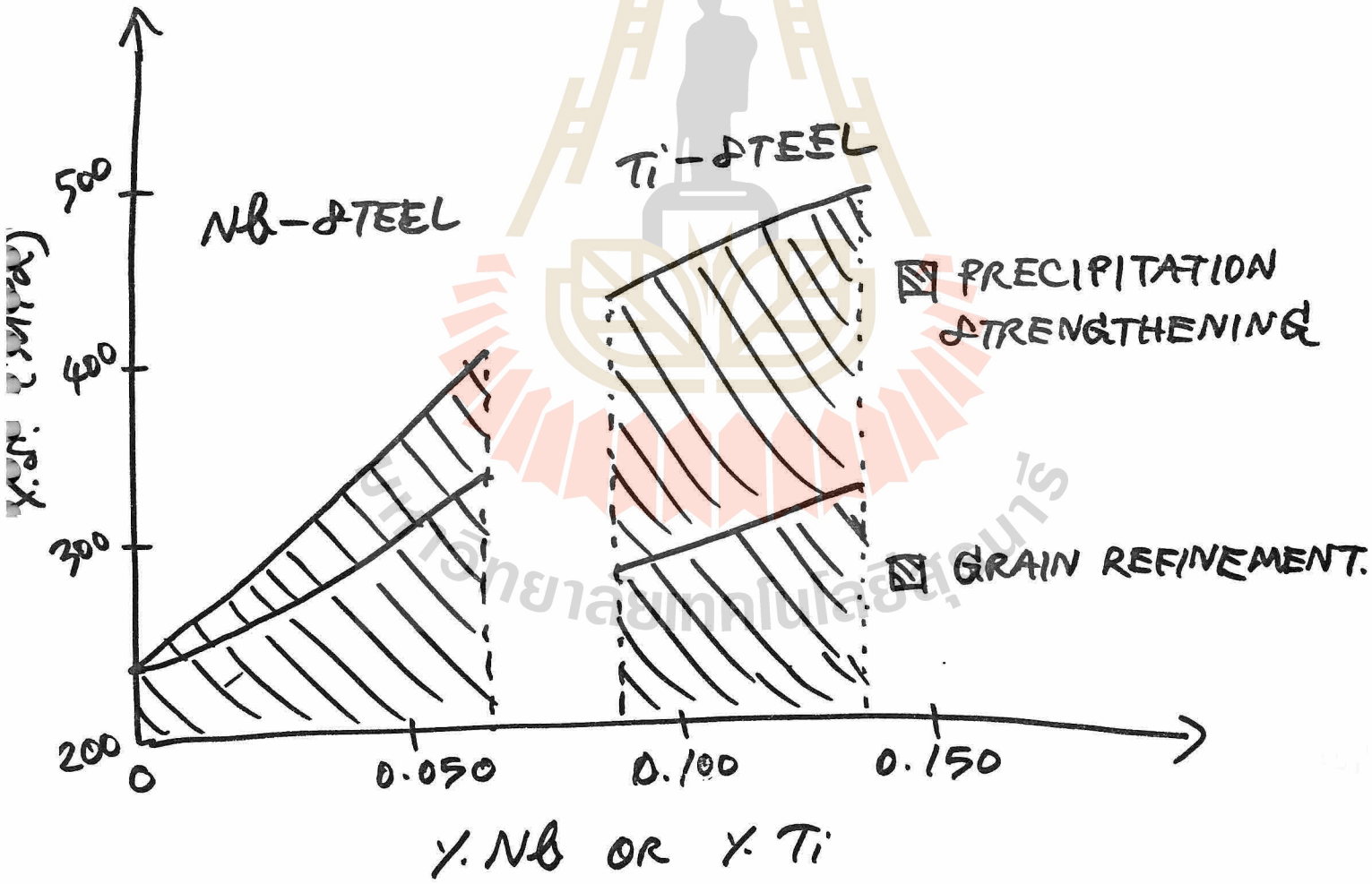
TEMP. $\Longrightarrow$ DECREASE α - GRAIN SIZE

(iii) ACCELERATED COOLING. TO INCREASE STRENGTH & ACHIEVE STRENGTH OF LOWER ALLOY CONTENT.

WELDABLE STRUCTURAL STEEL (BS 4360 : 1986)

GRADE.	% C MAX.	% Mn MAX.	% Nb	% V	T.S. (MPa)	Y.S. (MPa)
40	0.16-0.22	1.5	-	-	340-500	235
43	0.16-0.22	1.5	-	-	430-580	275
50	0.16-0.25	1.5	0.003-0.1	0.003-0.1	490-640	355
55	0.16-0.25	1.5	0.003-0.1	0.003-0.1	550-700	450

Solution Treat. — Drag.



EX. STEEL FOR PIPELINES

AMERICAN PETROLEUM INSTITUTE (API) GRAD

SPECIFICATION. FOR HIGH TEST LINEPIPE

⇓

API 5LX SERIES.

GRADE	WALL THICKNESS. WT (mm)	%C	%Mn	%Nb	%V	%Ti
X65	16	0.02	1.59	0.04	–	0.017
X65	25	0.03	1.61	0.05	–	0.016
X65	25	0.06	1.35	0.04	0.07	–
X70	20	0.03	1.91	0.05	–	0.018
X70	19.6	0.08	1.60	0.04	0.07	–
X80	12	0.07	1.65	0.05	0.075	–
X80	20	0.02	1.95	0.04	–	0.019
X80	19	0.08	1.50	0.052	0.076	–
X80	19	0.036	1.60	0.64	–	–

X 80 ⇒ MEAN YIELD STRENGTH OF 80 ksi

⇓

551 N/mm²

X 70 ⇒ Y.S. OF 70 ksi 483 N/mm²

X 65 ⇒ Y.S. OF 65 ksi 448 N/mm²