# Heat Treatment Technology
# ADI Austempered Ductile Iron

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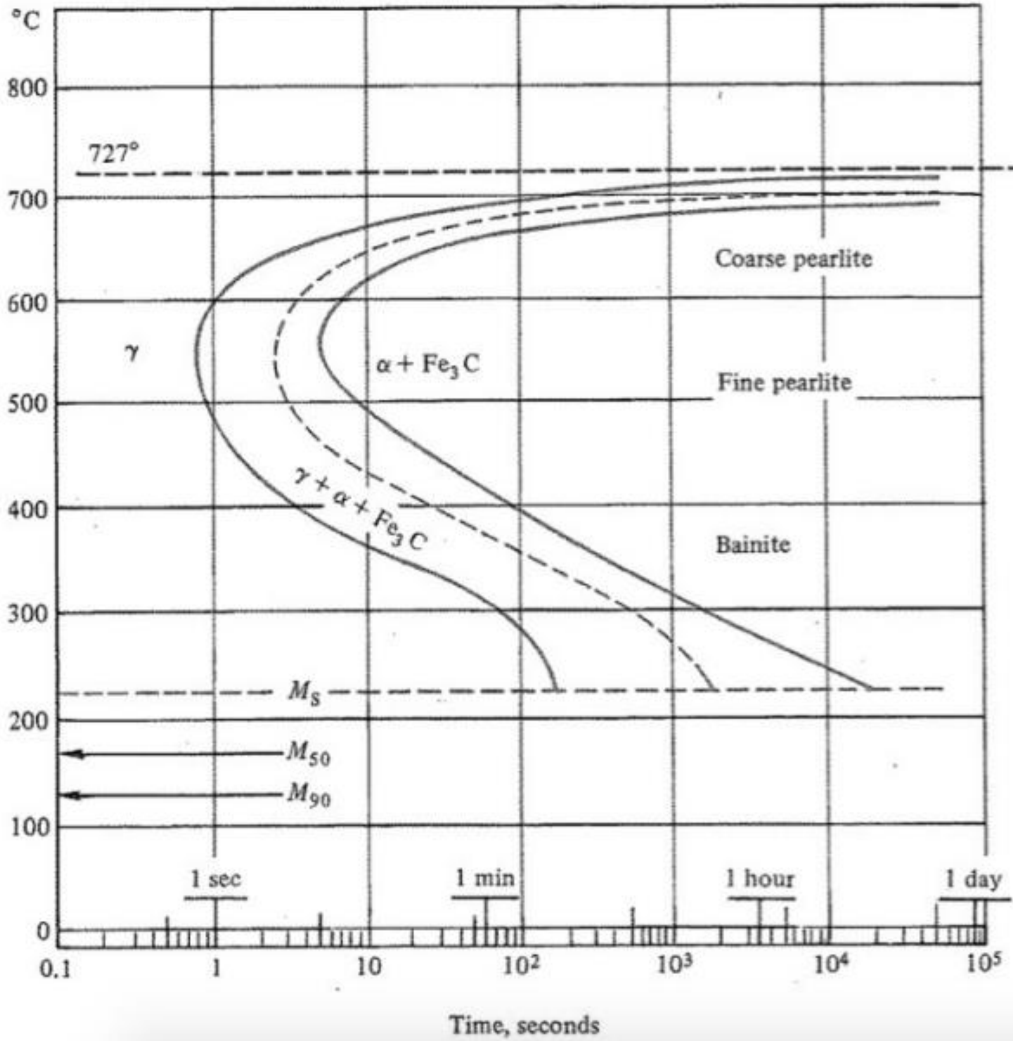
# *ADI Austempered Ductile Iron*

# Terminology

- **Ductile iron**
- **Quenched and tempered HT.**
- **Austempering HT**
- **Martempering HT**



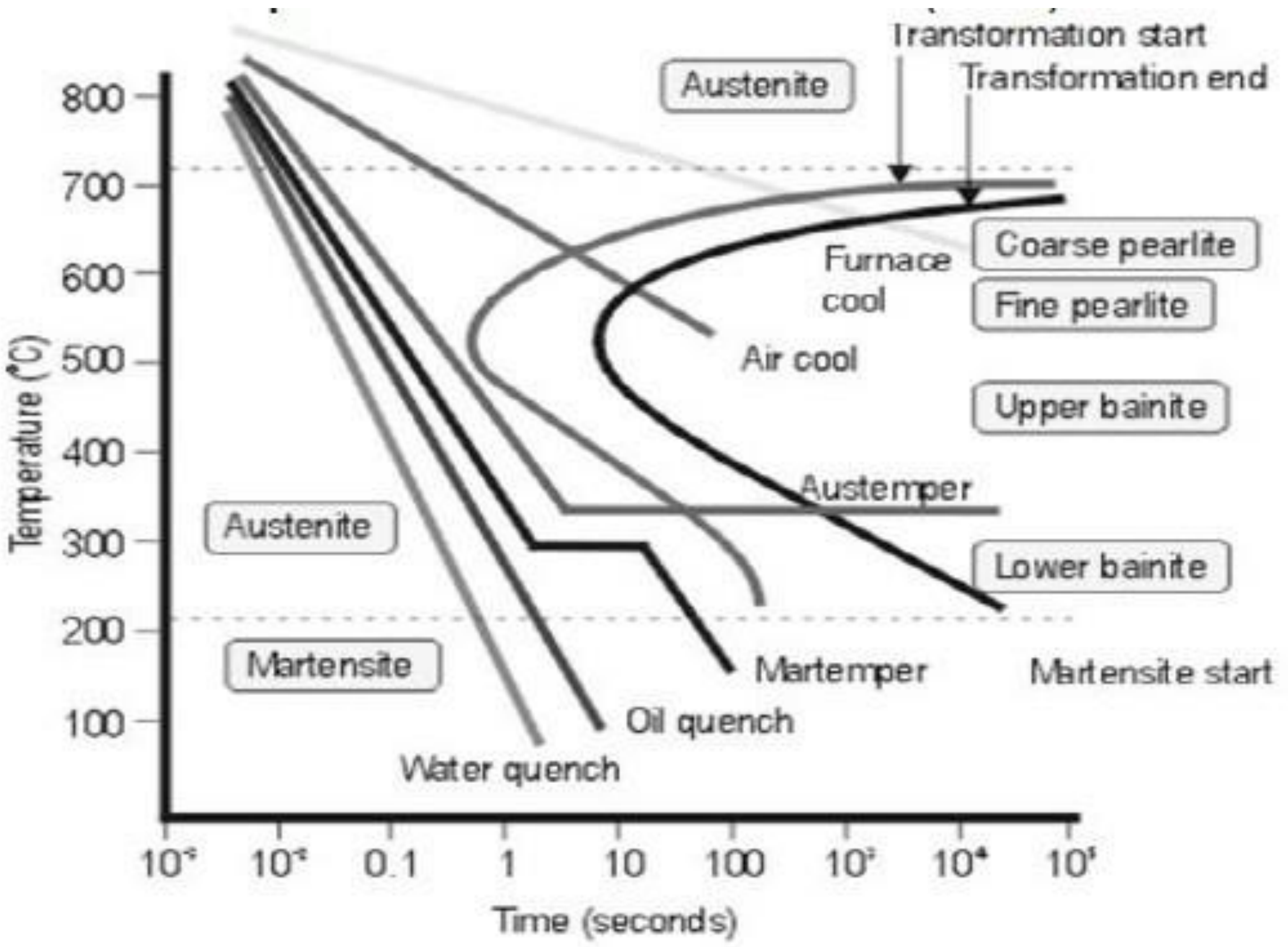




**Fig. (1-a) The Eutectoid Steel TTT Diagram (Steel grade AISI 1080).**
**Fig. (1-b) (Quench + Tempering), Martempering, and Austempering for steel.**

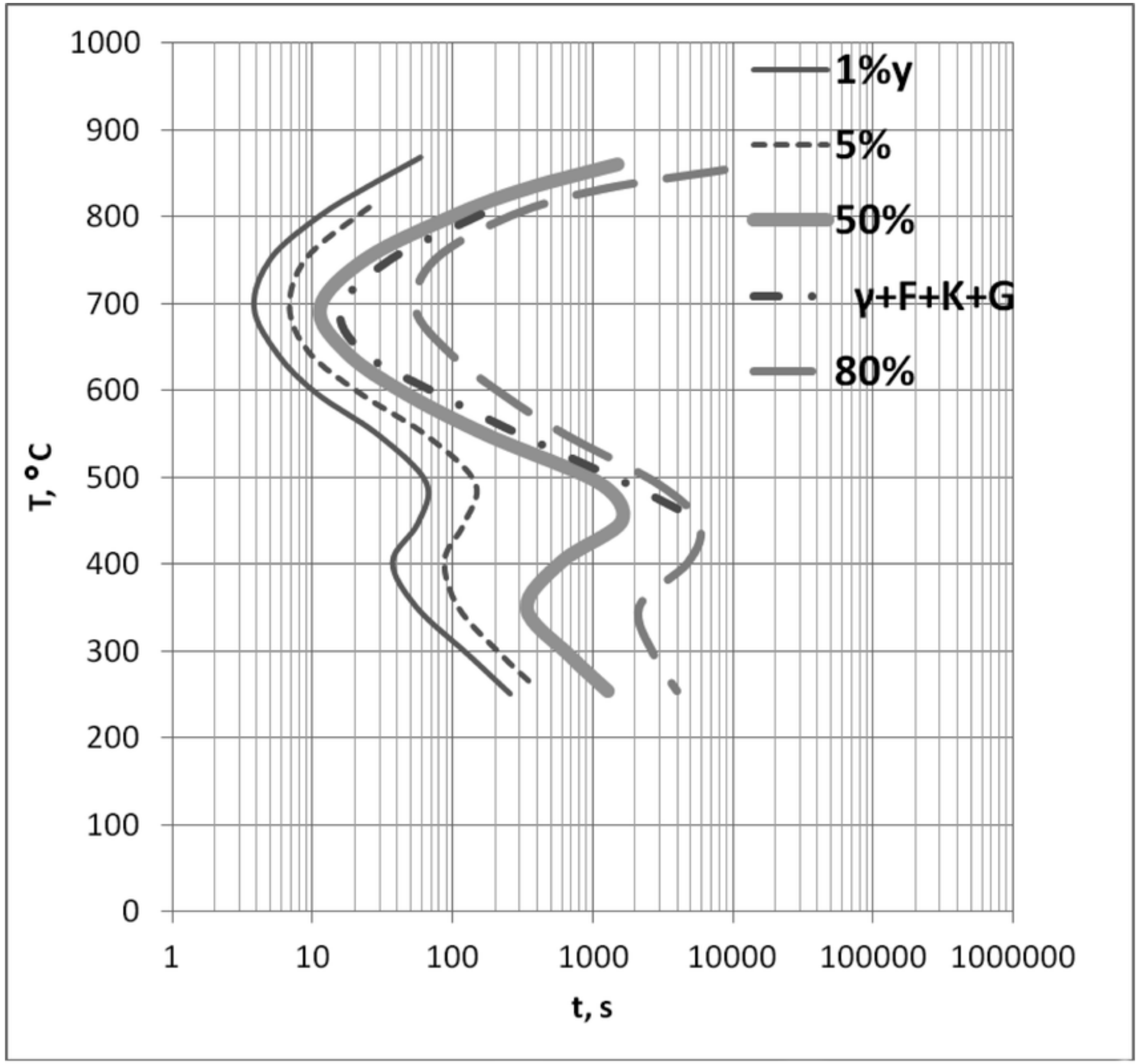



Fig. (1-c) **TTT diagram for the ductile iron** (3.6% C, 0,27% Mn i 1,72% Si )after digitalization

**TTT diagram for the ductile iron – features**

1. **Tow distinct zones:**
   a. **Pearlite matrix zone**
   b. **Bainitic matrix zone**

**2. Ausferrite window (between the unstable austenite boundary line and just before Bainite line.**

the

# *What is ADI (Austempered Ductile Iron)*

- Austempered ductile iron (ADI) (Fig. 2) **is a spheroidal graphite cast iron of bainitic matrix that is competitive with steels**, because of its low cost and good properties. The hardness of the matrix constituent as well as the advantageous mechanical properties justify the growing use of these cast irons.
- Austempered ductile irons **are commonly used in guides and gears, as an alternative to the case-hardened steels**, but are also **used in** the manufacture of **crankshafts instead of using quenched and tempered steels.**
- In these spheroidal graphite bainitic cast irons, average levels of **1000 MPa for tensile strength can be achieved without difficulty, with yield strength of 750 MPa and toughness** (in V notch test) of 15 Jules at room temperature. The use of those

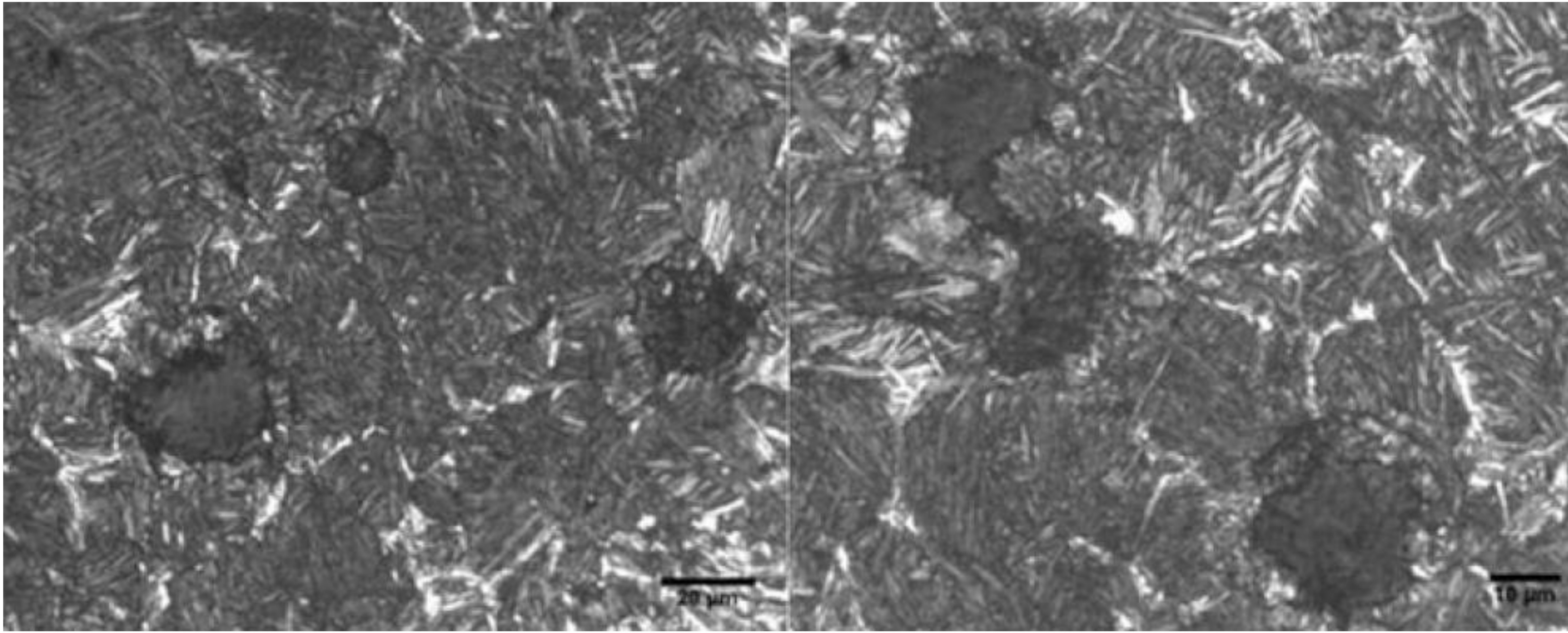
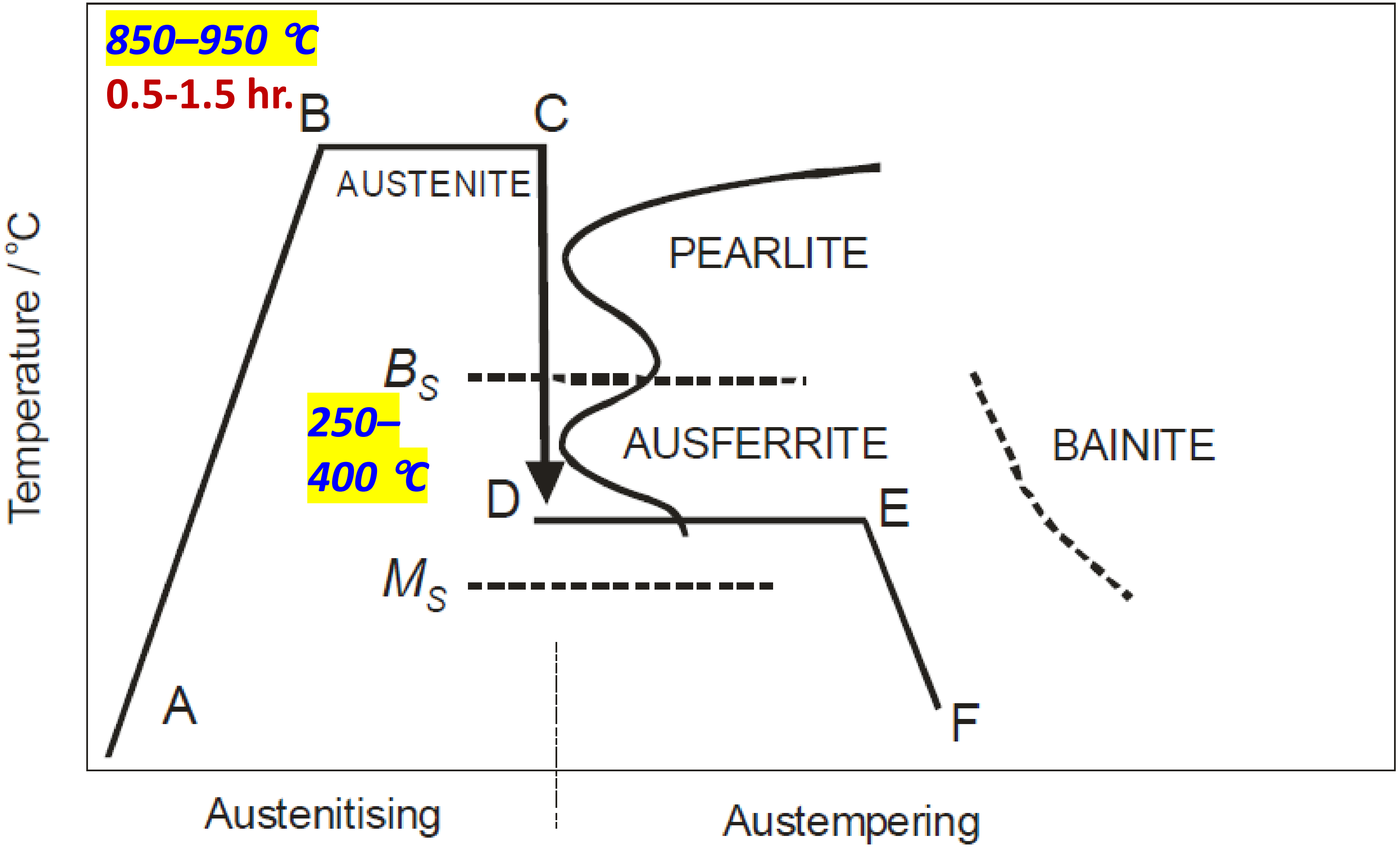



Fig. 2 Austempered ductile iron (spheroidal graphite cast iron of bainitic matrix that is competitive with steels)




## HT Regime

- (A to B) - Heating to the austenitising temperature
- (B to C) – Austenitising (**to dissolve carbon in austenite**).
- (C to D) - Cooling to the austempering temperature (**Quench quickly to avoid pearlite**).
- (D to E) - Isothermal heat treatment at the austempering temperature (**Hold at austempering temperature in a molten salt bath for isothermal transformation to ausferrite**.).
- (E to F) - Cooling to room temperature

**Fig. 3. Schematic of the austempering process of ductile cast iron ADI.**

# Cast irons

- Cast irons are **alloys of iron, carbon, and silicon (it may be considered as Ternary alloy)** in which more carbon is present than can be retained in solid solution in austenite at the eutectic temperature. In gray cast iron, the carbon that exceeds the solubility in austenite precipitates as flake graphite.
- **Gray irons usually contain 2.5 to 4% C, 1 to 3% Si**, **and additions of manganese,** depending on the desired microstructure (as low as **0.1%** Mn in ferritic gray irons and as high as **1.2%** in pearlites iron).
- **Sulphur and phosphorus are also present in small amounts as residual impurities**.

# Introduction

- **Austempered Ductile Iron (ADI)** is a type of ductile iron that **is characterised by** increased toughness, tensile strength and wear resistance compared to normal ductile irons. These properties are **achieved by heat treatment** of an alloyed ductile iron using an austempering process.
- **The mechanical properties of** ductile iron and ADI **are primarily determined by the metal matrix**. The matrix in conventional ductile iron is a controlled mixture of pearlite and ferrite.
- **ADI was discovered almost 50 years** ago and found successful commercial application in 1972 and by 1998 world-wide production was approaching 100,000 tonnes annually.
- **Today ADI has become the material of choice** for the designer, as it offers the best design combinations of low cost, design flexibility, machinability, high strength to weight ratio, good toughness, wear resistance & fatigue strength.
- **Material selection**, processing, cost, product design, ease of availability, environmental impact due to its use, & performance of the final product are inseparable. ADI comes out with high scores on all these counts.

**Fig. 6  Austempered Ductile Iron (ADI) products**

# *Overview to ADI….*

- ADI was **discovered almost 50 years ago** and found successful commercial application in 1972.
- Today ADI has become the material of choice for the designer, as it offers **the best design combinations of low cost, design flexibility, machinability, high strength to weight ratio, good toughness, wear resistance & fatigue strength.**
- ADI is more environment friendly than many competing materials.
- Material selection, processing, cost, product design, ease of availability, environmental impact due to its use, & performance of the final product are inseparable. ADI comes out with high scores on all these counts.

# Making of ADI…

- Molten Cast iron when treated with magnesium results in nodular iron on freezing.
- **Graphite is present in a spheroidal form** rather than as flakes.
- Ductile iron has superior **mechanical properties** as compared to cast iron & is cheaper than malleable iron.
- **Malleable irons** were manufactured by subjecting white cast irons to very long heat treatment cycles, and hence were **very expensive**.
- Ductile iron has **replaced malleable irons** entirely & and steel / cast iron in many applications.
- Ductile iron when **heated to the austenitic range [900$^{o}$C approx**] and **quenched in the range of 250 $^{o}$C to 400 $^{o}$C** gives us Austemperted Ductile Iron [ADI].

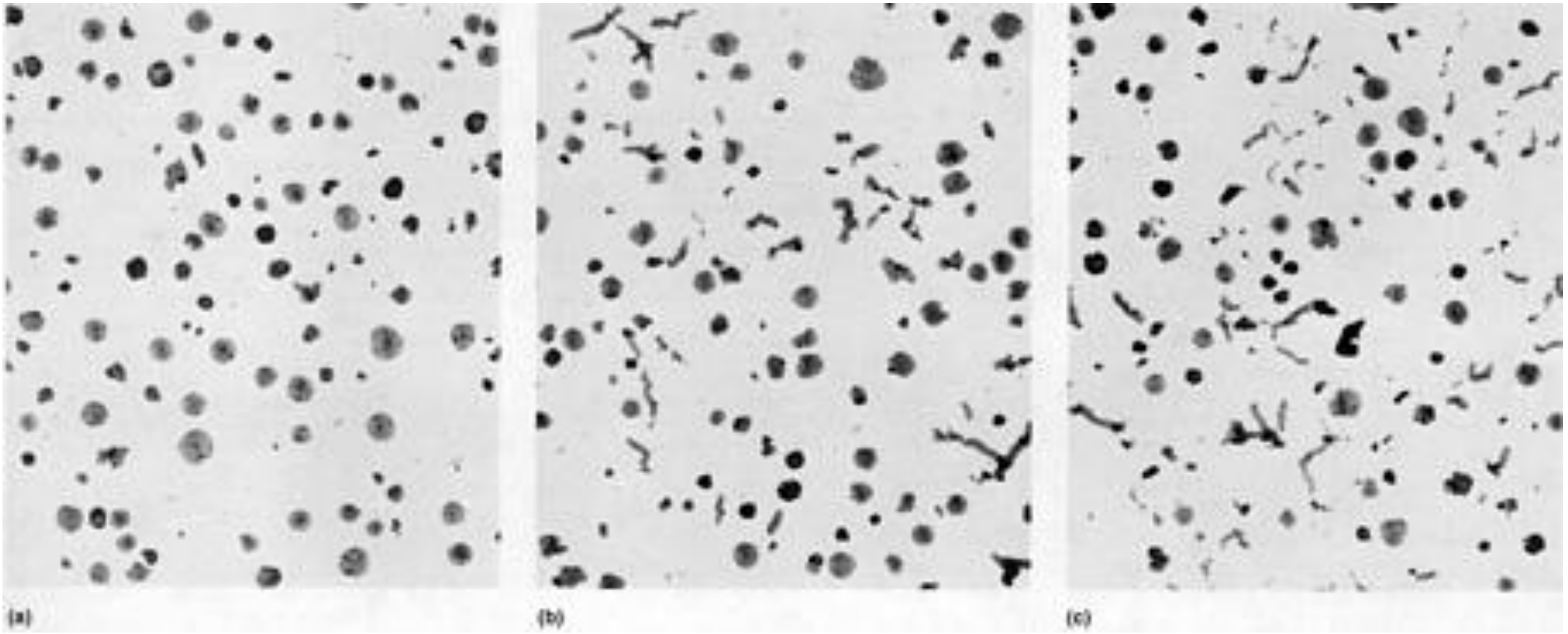
- **Austempered ductile iron (ADI) offers a range of mechanical properties superior to those** of other cast irons and shows **excellent economic competitiveness with steels and aluminum alloys.**
- **ADI is a heat treated form of as-cast ductile iron**. The heat treat process, austempering, was developed with **the intent of improving on the strength and toughness** of ferrous alloys.
- Ductile iron, with **its relative low cost and ease to manufacture,** has been one of the largest beneficiaries of the austempering process.

- **Ductile iron exhibits a linear stress-strain relation, a considerable range of yield strengths, and, as its name implies, ductility.**
- **"Austempering" is a high performance heat treatment for ferrous alloys which produces an engineered, tailorable matrix structure.**
- **This austempered matrix structure gives tensile strength, toughness, impact strength and fatigue properties that are comparable to heat-treated steels. Figure 1 shows the tensile elongation of steel and austempered ductile iron ADI.**

# Prior Metallurgical Parameters to Ensure Success with ADI…

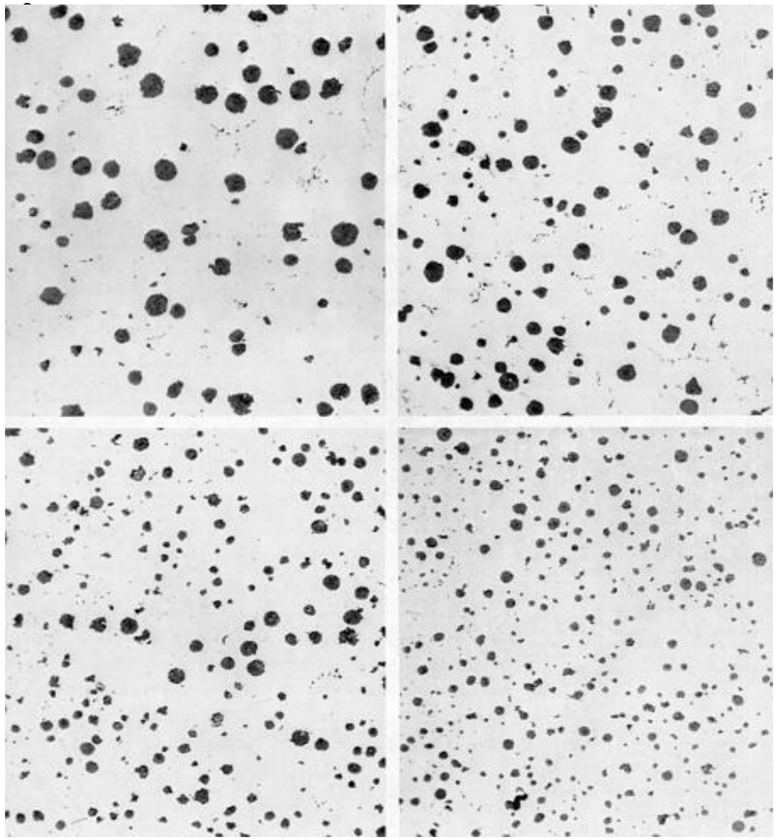
1. **Good foundry practice** to ensure a sound casting free from shrinkage & porosity. ***The austempering process cannot compensate for foundry defects***
2. Maintenance of proper and consistent chemistry. **Recommended limits for chemical composition are as follows**: ***Carbon: 3.5/3.9%; Silicon: 2.3/2.7%; Manganese: 0.25% max; Copper 0.8% max; Nickel:2.0% max; Molybdenum: 0.25% max only for heavy sectioned castings.***
3. ***Nodularity should be more than 80% & Nodule count should be more than 100/mm²***
4. ***Minimum 50% pearlite in the matrix & less than 1% carbides prior to austempering.***

# Nodularity…




Microstructure of ductile irons of varying degrees of nodularity. (a) 99% nodularity. (b) 80% nodularity. (c) 50% nodularity. All unetched. 36×

# Nodule Count…



Series of micrographs depicting increasing nodularity in ductile irons. Upper left: 50 nodules per 10 mm square. Upper right: 100 nodules per 10 mm square. Lower left: 150 nodules per 10 mm square. Lower right: 200 nodules per 10 mm square. As-polished. 100×

# ADI Mechanical Properties

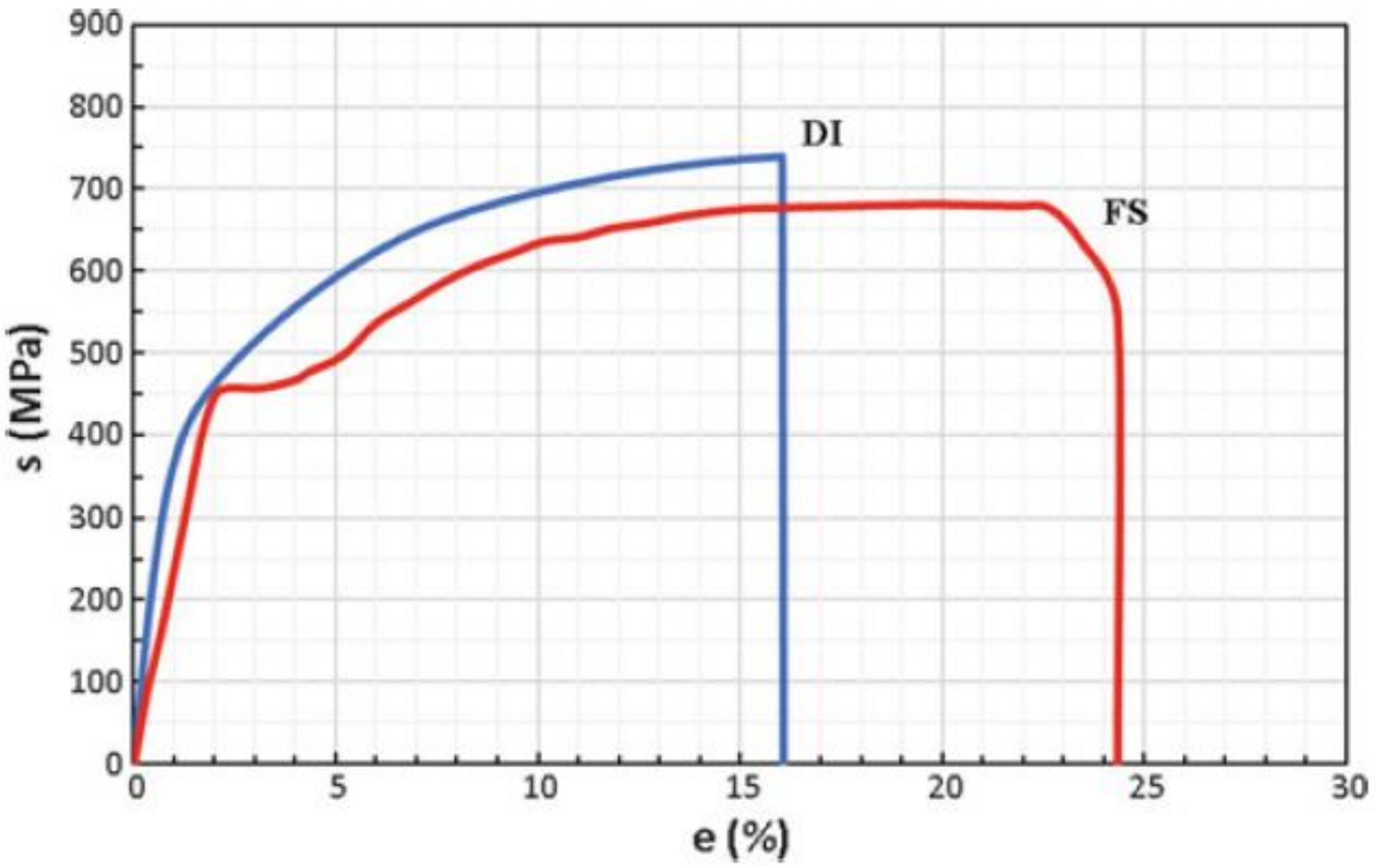



**Fig. 4. Engineering stress–strain curves for the forged steel (FS) and ductile iron (DI)**

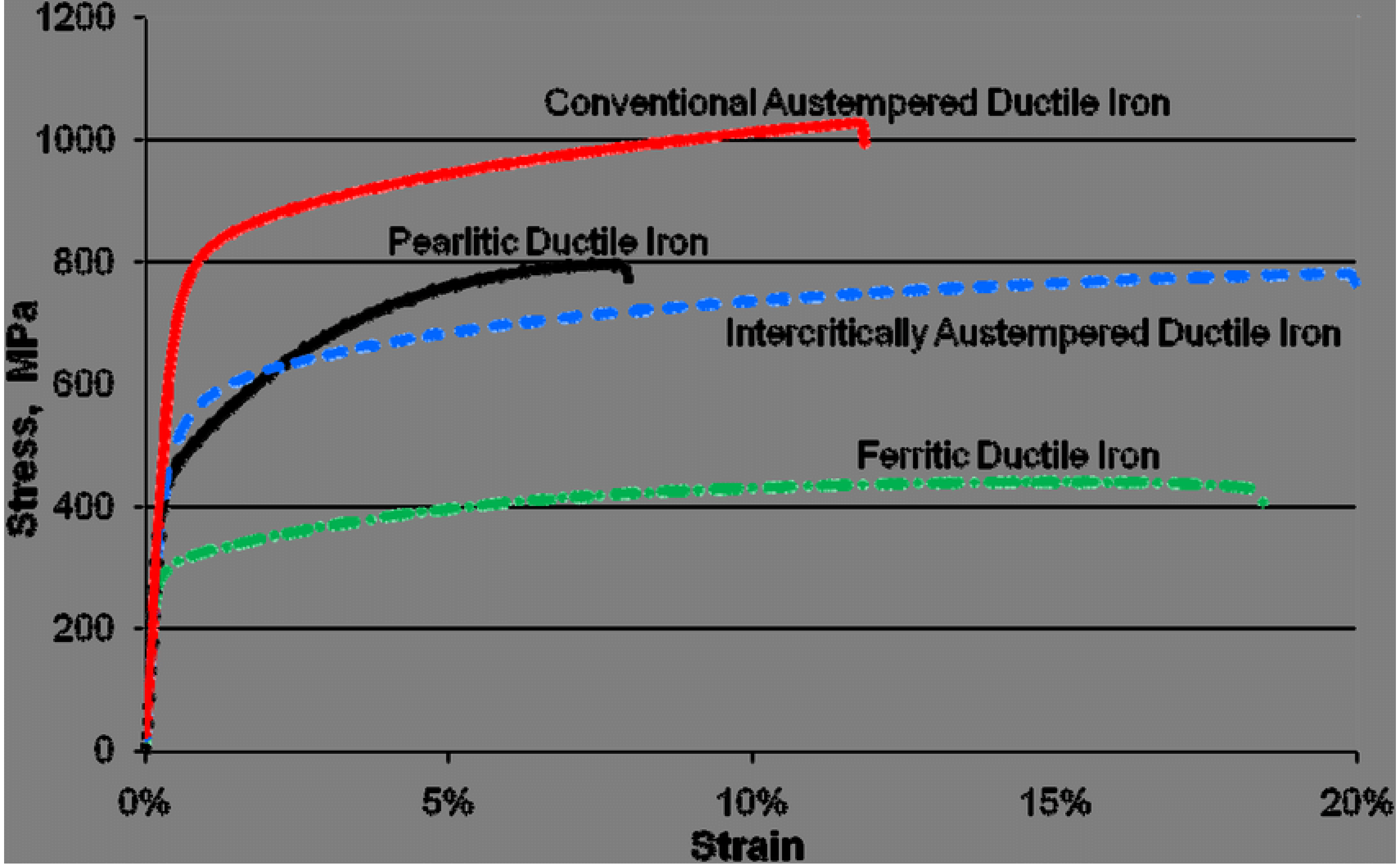
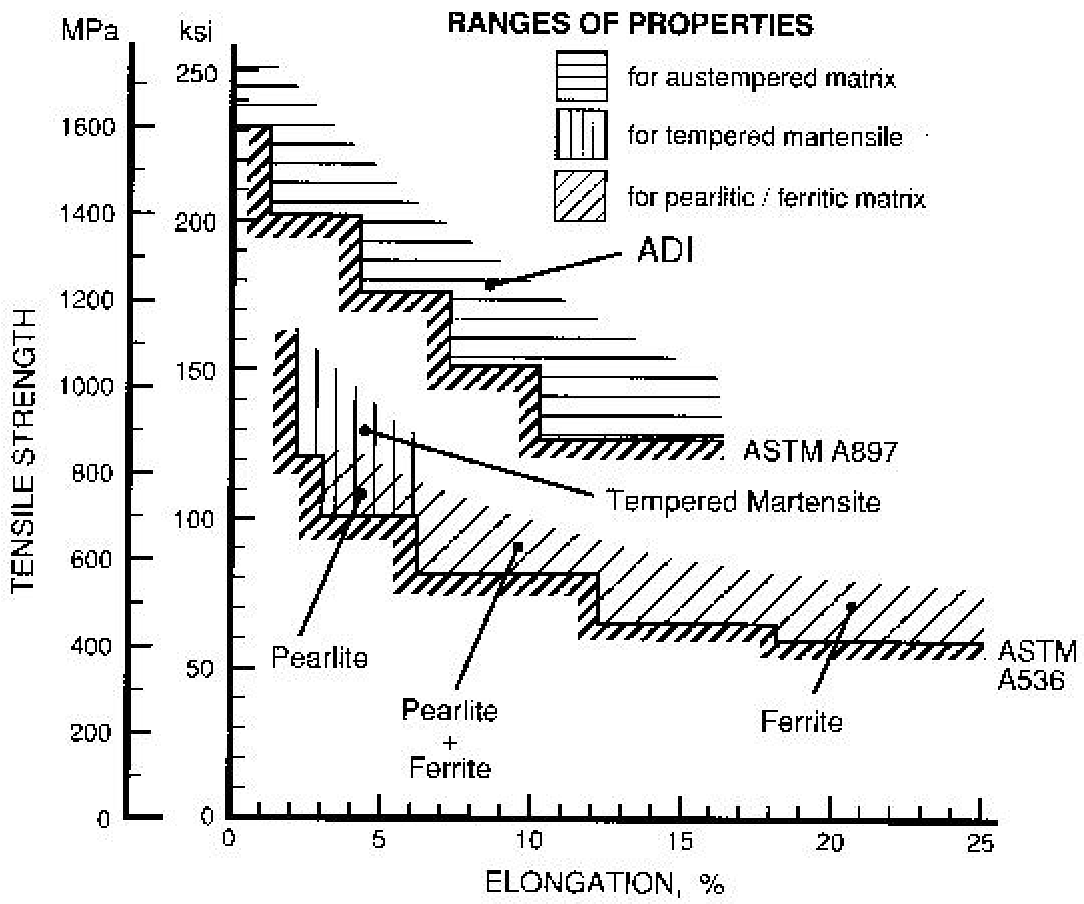



Fig. 5. Stress-strain curves for ferritic ductile iron, pearlitic ductile iron, intercritically austempered ductile iron and conventional austempered ductile iron show the superior combination of strength and ductility for the intercritically austempered ductile iron.

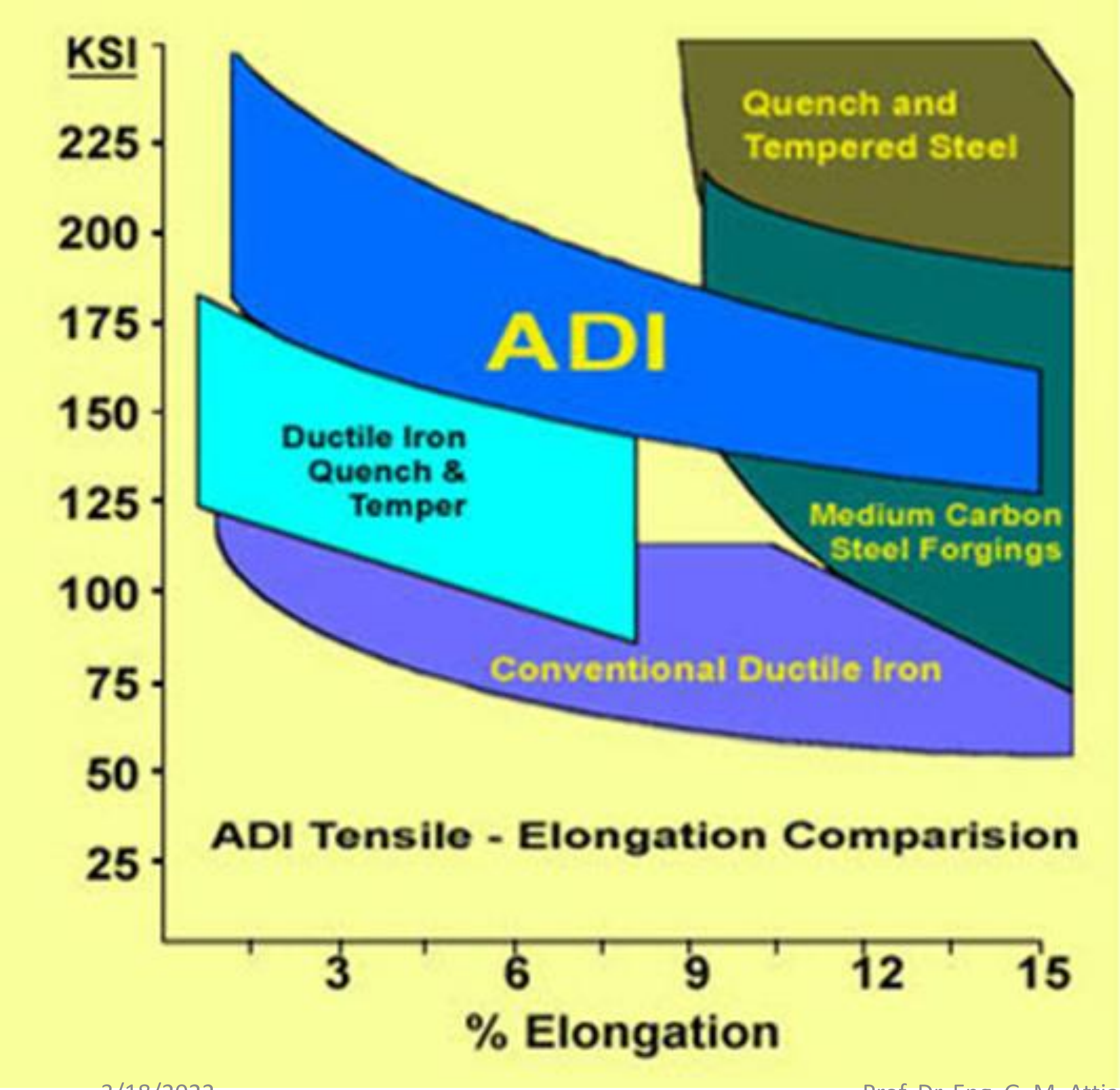
AUSTEMPERED DUCTILE IRON

Tensile properties of ADI and conventional Ductile Iron.




## Mechanical Properties

1. **ADI is a group of materials** whose mechanical properties can be varied over a wide range by a suitable choice of heat treatment. A high austempering temperature, 400˚C, produces ADI with **high ductility**, a **yield strength** in the range of **500 MPa** with **good fatigue** and **impact strength**.
2. **A lower transformation temperature, 260˚C, results in ADI with** very **high yield strength (1400 MPa** (200 MPa)), h**igh hardness, excellent wear resistance, and contact fatigue strength**. This high-strength ADI has lower fatigue strength as-austempered but it can be greatly improved with the proper rolling or grinding regimen. Thus, through relatively simple control of the austempering conditions, ADI can be given a range of properties unequaled by any other material.




***The tensile elongation between steels and austempered ductile iron***

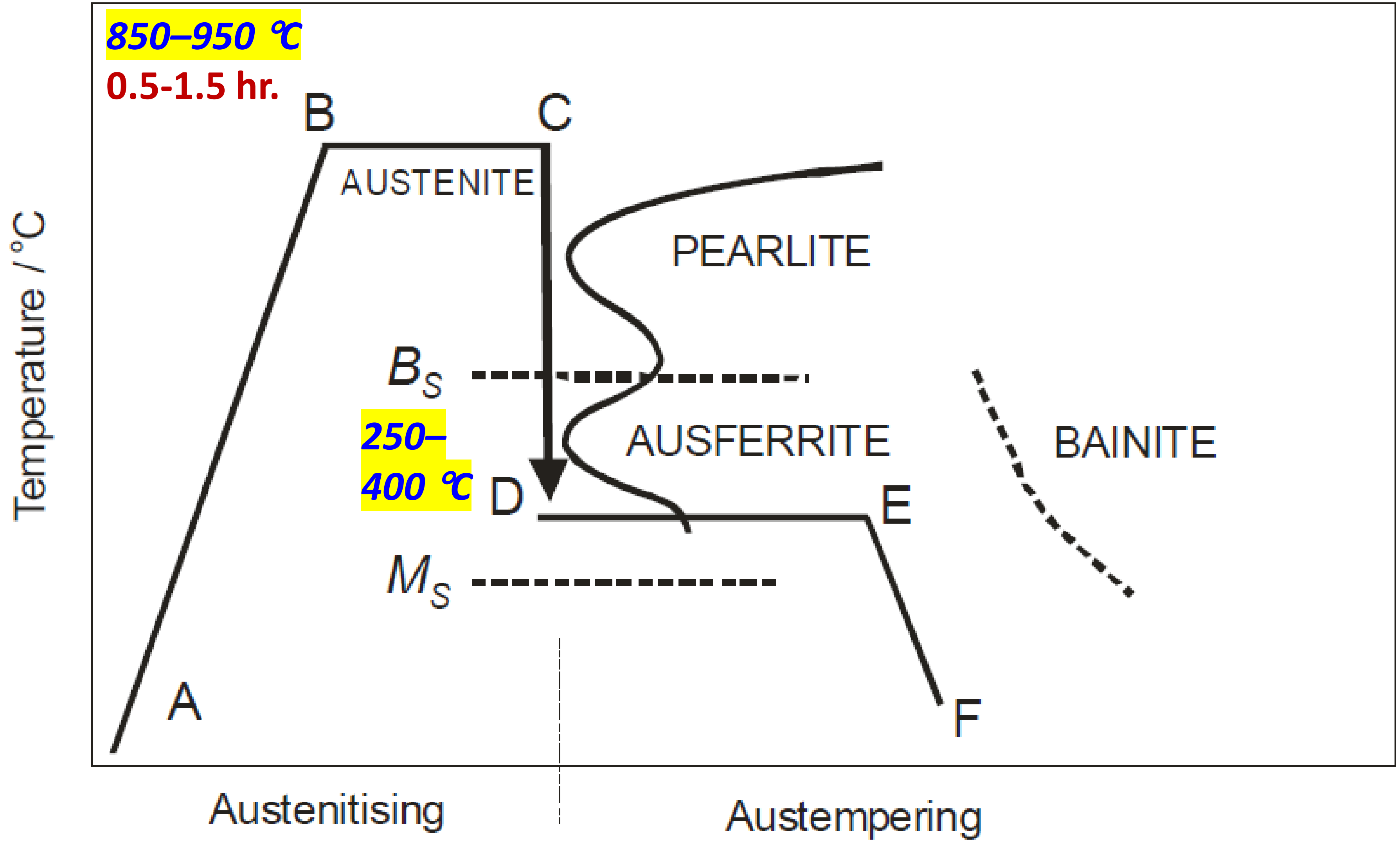
# Heat Treatment Regime

# *ADI (heat treatment regime):*

I. ***Austenitizing:*** During the austempering process, the ductile cast iron is heated up to an austenitizing temperature range (***850–950 ℃)*** for complete homogenization of austenite and then

II. ***Rapid quenching***: Quenched rapidly to an austempering temperature range (**250–400 °C**).

III. ***Austempering*** (Holding isothermally): It is then isothermally heat-treated at that temperature range (***250–400 ℃***) for the transformation of austenite.




## HT Regime

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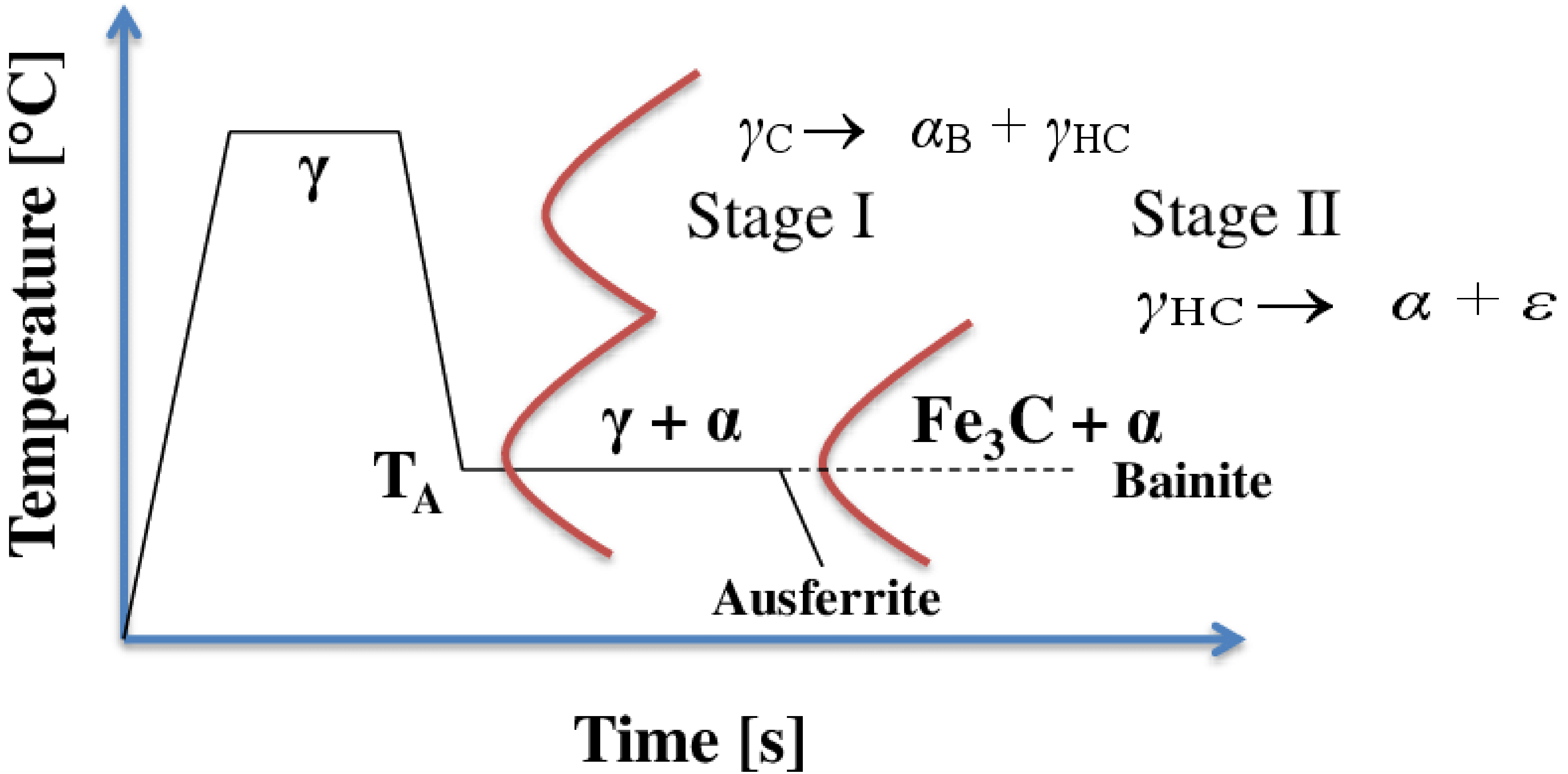
- (E to F) - Cooling to room temperature

**Fig. 1. Schematic of the austempering process**




***The best mechanical properties of ADI occur between the end of Stage I and the start of Stage II of the reaction presented in Fig., which gives the process a characteristic "processing window.***

- **First stage reaction**
- **G** + $\gamma°$ > **G** + **ausferrite** ( acicular ferrite + $\gamma_{HC}$)

- **Second stage reaction**:
- $\gamma_{HC}$ > Bainite (Bainitic ferrite + Carbide)

**G** + acicular ferrite + $\gamma_{HC}$ > **G** + acicular ferrite + Bainite (Bainitic ferrite + Carbide)

- **Ausferrite:** A fine-grain mixture of **acicular ferrite** and **stabilized austenite ($\gamma_{HC}$).**
- **If ADI is held for long time periods at Austempering temperature**, the high carbon austenite **($\gamma_{HC}$)** will eventually undergo a transformation to bainite, the two-phase mixture of ferrite and carbide **($\alpha$ + $Fe_3C$).**
- **The decomposition of $\gamma°$ at high and at lower temperature (400 & 250 °C)**

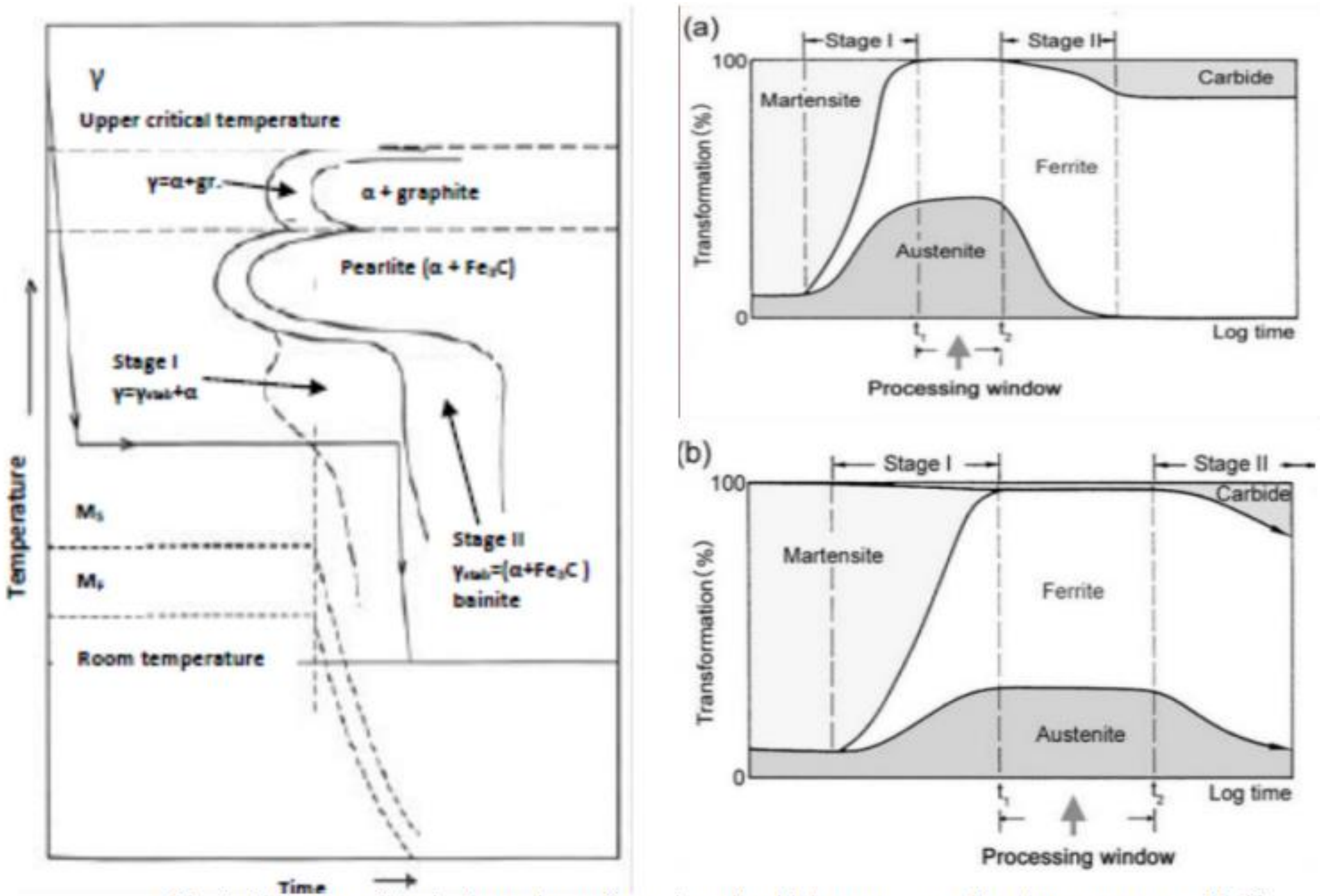
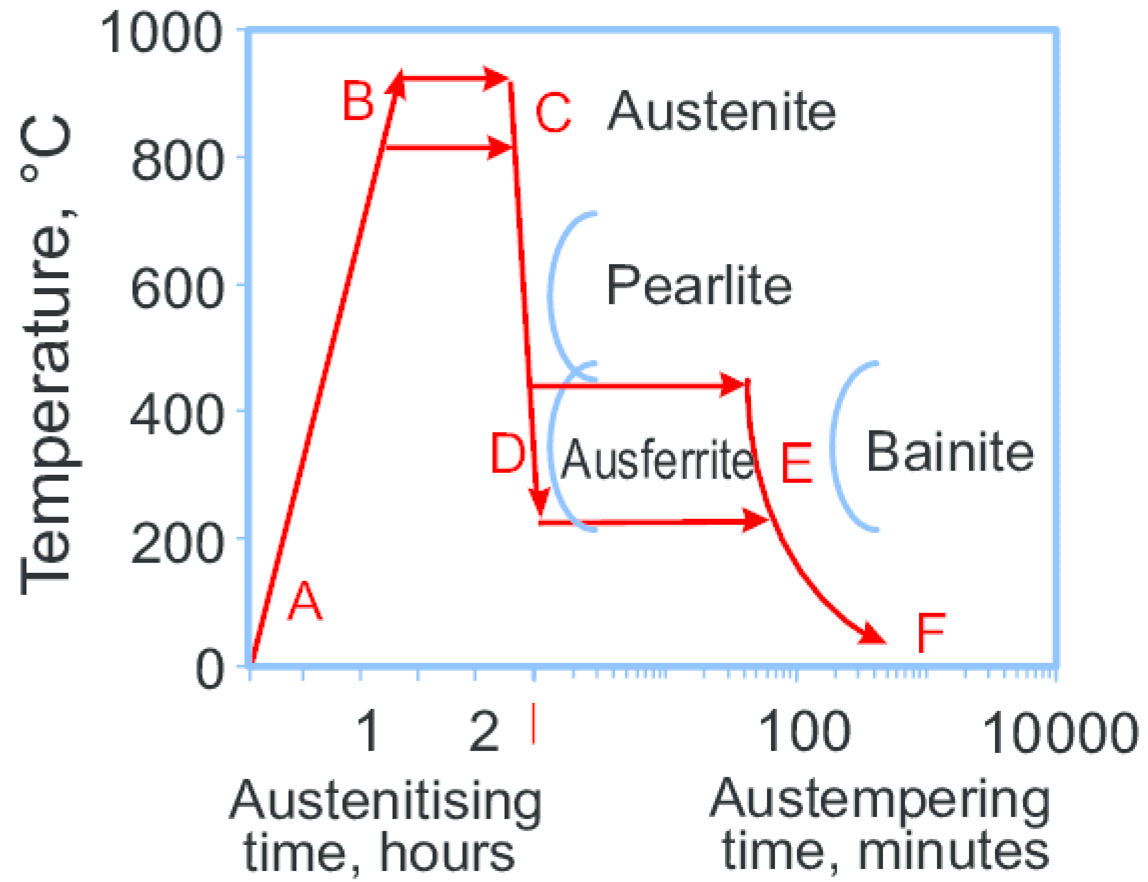
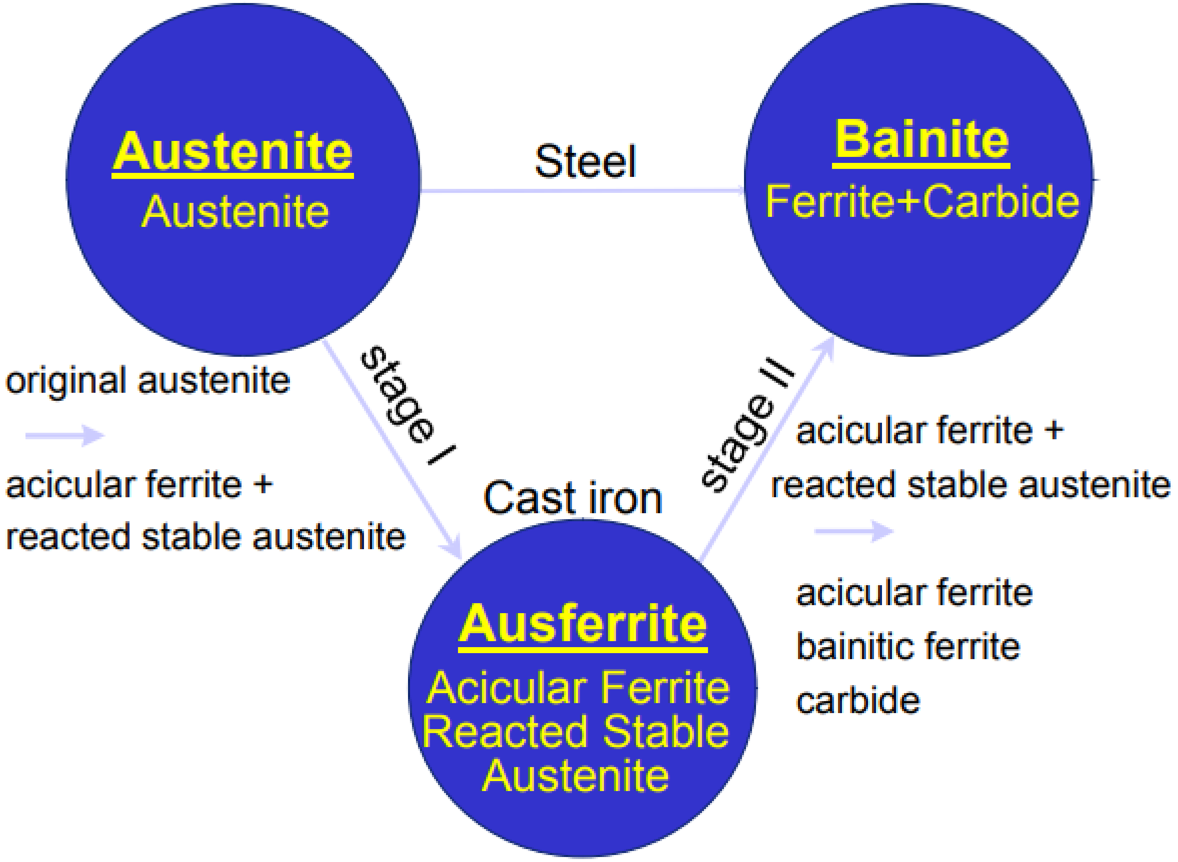



Fig. 1. Flowchart of the isothermal transformation: a) at high temperature, b) at low temperature [1, 2]

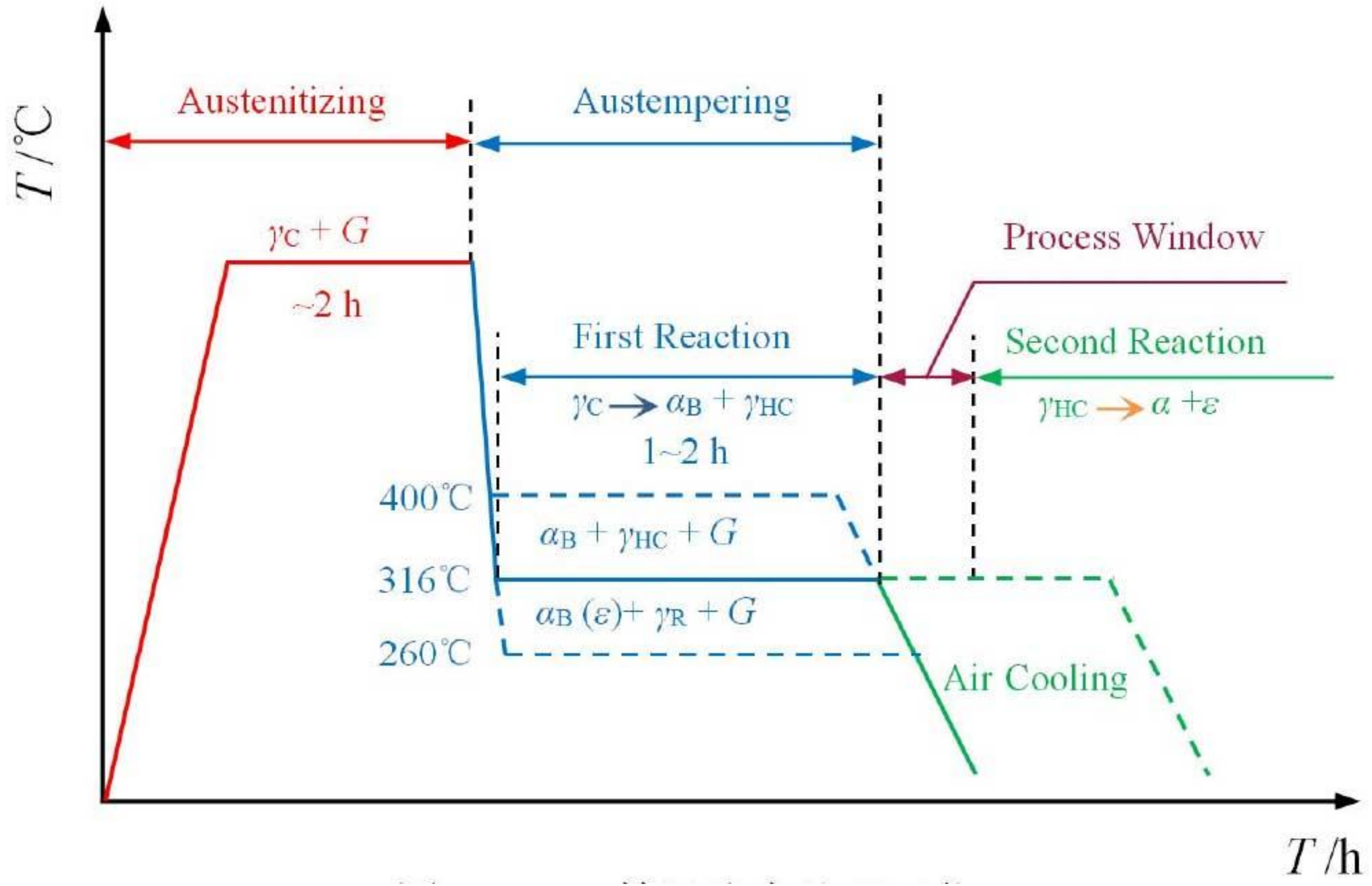
- ***Austempering isothermal transformations at high & low temperatures.***
- ***(See first stage, processing window, and second stage microstructure constituents )***



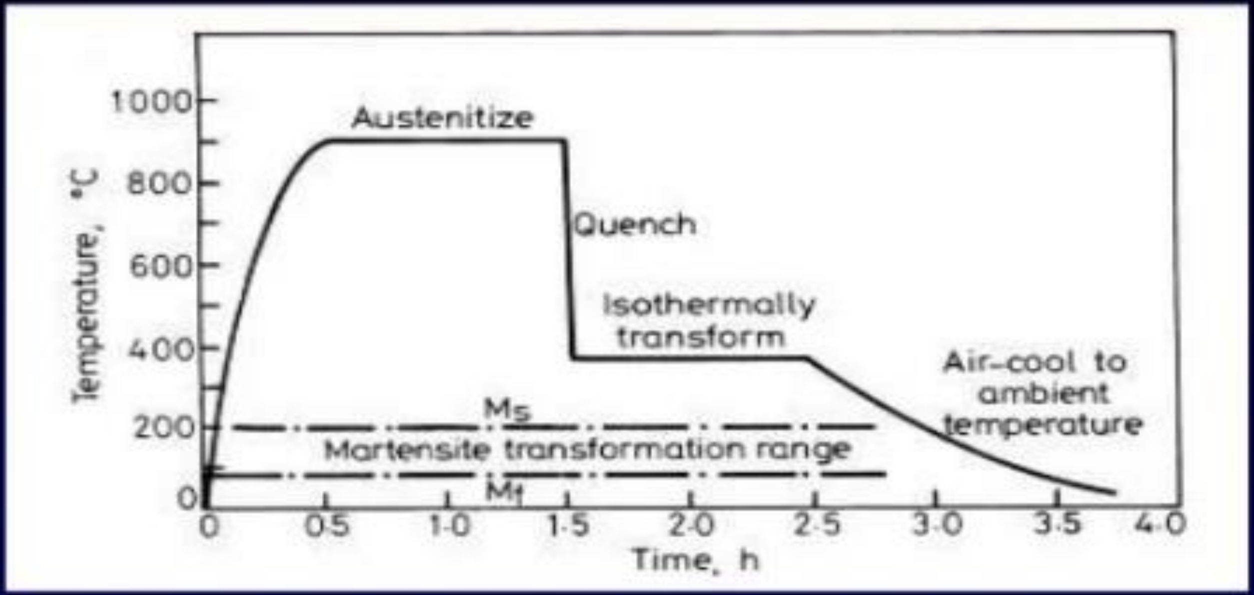



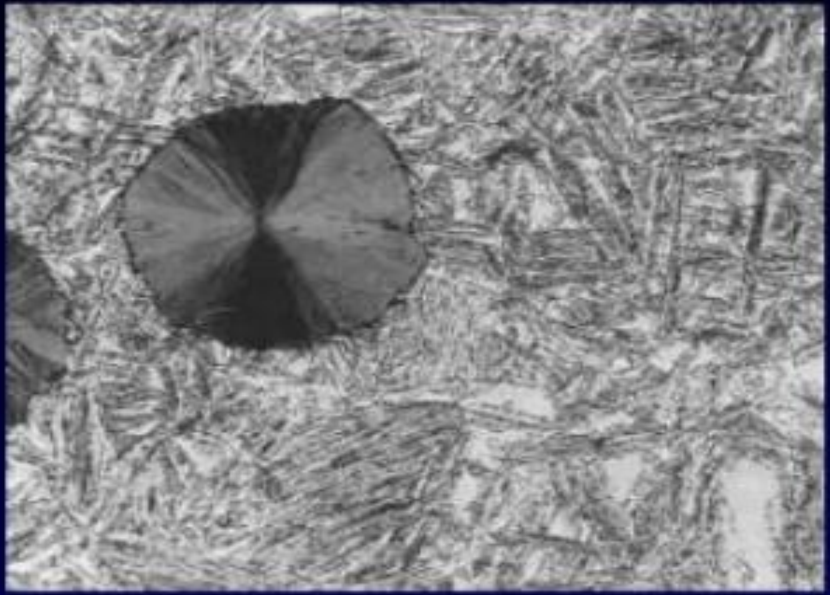

***Differences in austempering reaction in steel and cast iron***

# ADI Process Window



T /℃
Austenitizing
Austempering
γC + G
~2 h
Process Window
First Reaction
Second Reaction
γC → αB + γHC
γHC → α +ε
1~2 h
400℃
αB + γHC + G
316℃
αB (ε)+ γR + G
260℃
Air Cooling
T /h



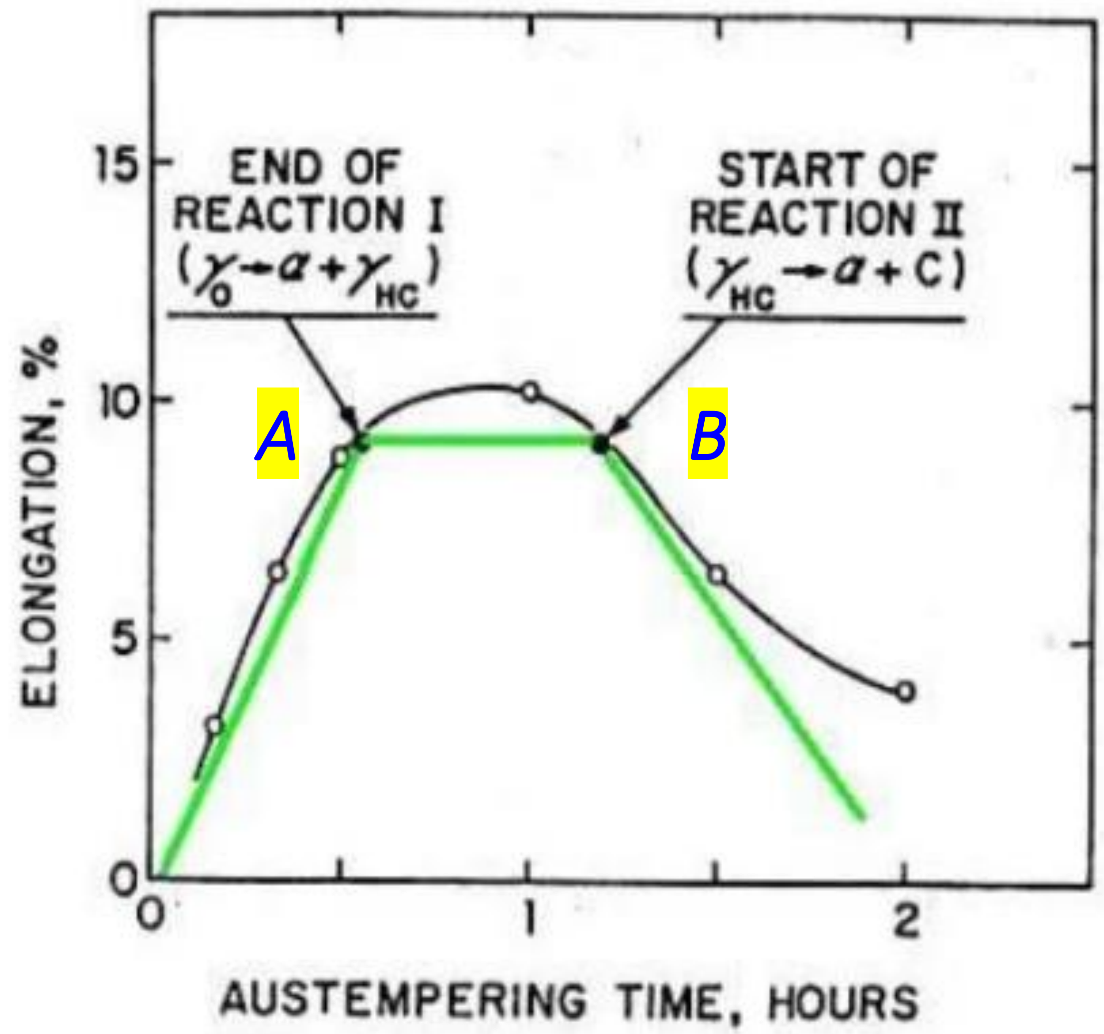
Austempered ductile iron ADI is a relatively new engineering material with exceptional combination of mechanical properties and marked potential for numerous applications.

The attractive properties of ADI return to its distinct and unique microstructure, which consists of fine acicular ferrite within C-enriched stabilized austenite (ausferrite)

The austempering transformation in ADI can be described as two stage reaction:

| | | |
|---|---|---|
| Stage I Reaction: | $\gamma_o \rightarrow \alpha + \gamma_{HC}$ | (toughening) |
| Stage II Reaction: | $\gamma_{HC} \rightarrow \alpha + \varepsilon$ | (embrittlement) |

# Process Window:



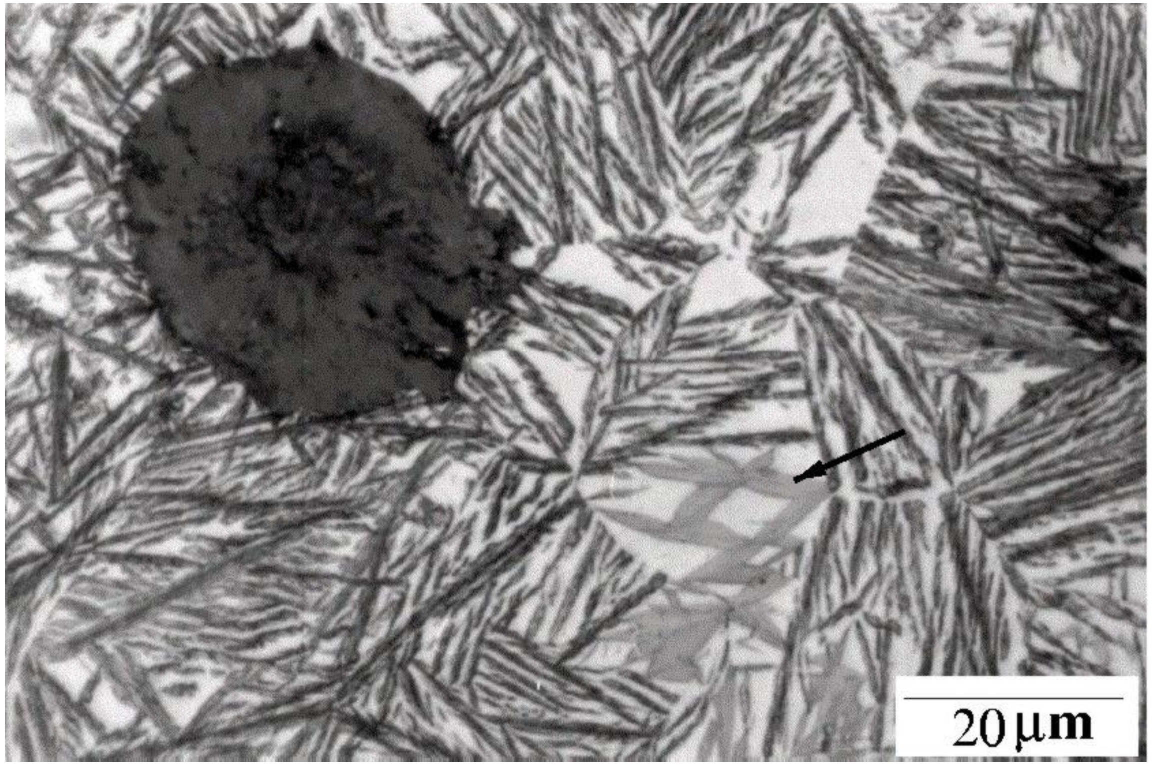

*Idealized characterization of the influence of the two bainite reactions on toughness during austempering. Original austenite ($\gamma_o$), bainitic ferrite ($\alpha$), high-carbon austenite ($\gamma_{HC}$), carbide (c).*

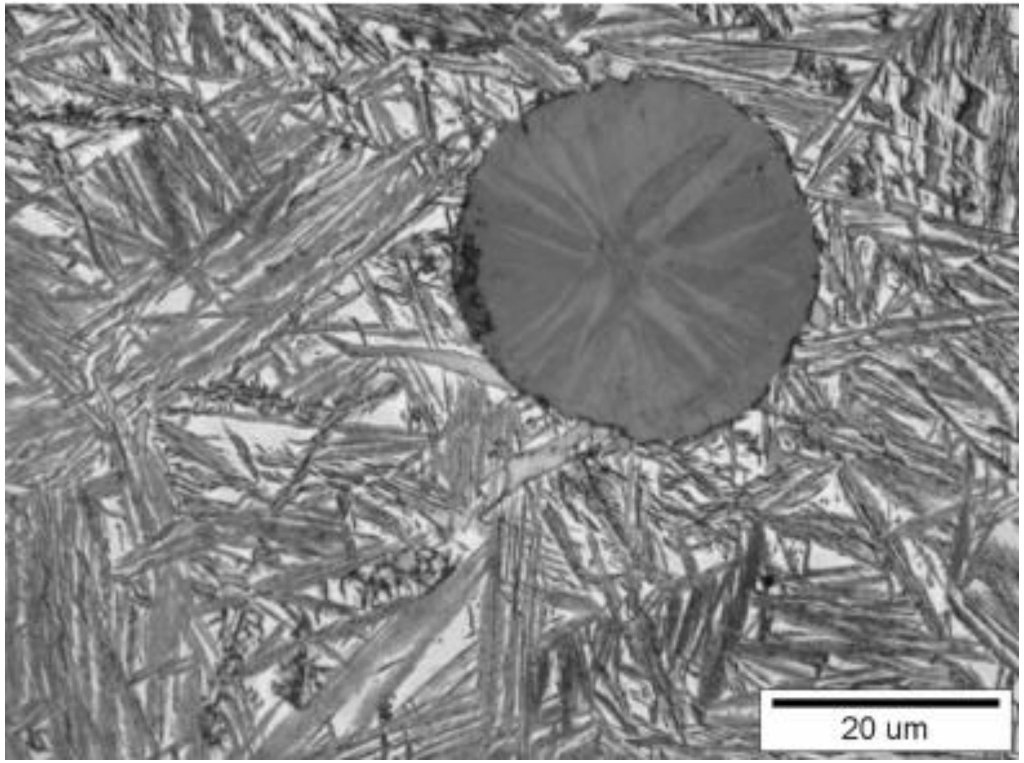
- Processing of the two austempering reactions can be followed by the change of mechanical properties vs. austempering time. Point A: completion of the first reaction. Point B: onset of the second reaction.

- Time interval between A and B "the process window" represents the allowable austempering time for processing to obtain optimum mechanical properties.

# *ADI Austempered Microstructure*

- The ADI attains a unique **ausferritic microstructure consisting of carbon enriched austenite and acicular ferrite** during the austempering process.



# *Effect of Austempering Temperature on Microstructure*

- The morphology of the final two-phase matrix microstructure is determined by the number, shape and size of the initially formed ferrite platelets in the first stage austempering reaction.
- At low ausforming temperatures, an acicular (needle-like) ferritic phase is formed with only a small amount of retained austenite. At the very lowest austempering temperatures, the structure may also contain some martensite. This type of microstructure can provide high tensile strength and hardness but only limited ductility and poor machinability.
- With increased austempering temperatures, the ferrite becomes coarser with increased amounts of retained austenite (up to ~40%); with a typical "ausferrite" structure. This results in a substantial increase in ductility and machinability with a reduction in strength and hardness.

# *Effect of Austempering Temperature on Microstructure*


Typical microstructure obtained by austempering at a low temperature (260°C)


Typical microstructure obtained by austempering at a high temperature (375°C)

# *ADI (microstructure & mech. properties):*

- **The ADI attains a unique *ausferritic microstructure* consisting of *carbon enriched austenite*** and ***acicular ferrite*** during the austempering process.
- **It has a process window, beyond which *the carbon enriched austenite decomposes to carbide (ε) and ferrite.***
- **The mechanical properties of ADI are widely dependent on *the morphology and distribution of the ausferrite phase.***
- The selection of the processing route and its parameters are critical in determining the microstructure of ADI and obtaining the necessary mechanical properties ***(high strength to weight ratio, excellent toughness, and enhanced wear resistance).***

# *ADI (The process parameters):*

**I. Austenitizing temperature**

**II. Holding time at austenitizing temperature**

**III. Cooling rate**

**IV. Quenching temperature (Ausempering temperature)**

**V. Holding time at austempering temperature**

# *ADI (The process parameters):*

- **Effects of Austenitizing temperature and holding time.**
  - The average **carbon content of austenite increased with an increase in austenitization time**.
  - However, **a longer austenitization time resulted in** a **coarse austempered microstructure** containing blocky austenite.

  - Also, **decreasing the austenitizing temperature resulted in a finer microstructure**.
  - The optimum austenitization time is **about 1 -2h for 950 C and 850 C, respectively**.
  - In general, the **increase in austenitization temperature reduce the transformation rate during the austempering process. Also, it increased the incubation time for the transformation. The reduction in the thickness of the ferrite plates was also observed.**
  - **The reduction in austenitization temperature leads to an increase in ADI's hardness due to the reduced retained austenite volume fraction**

# *ADI (The process parameters):*

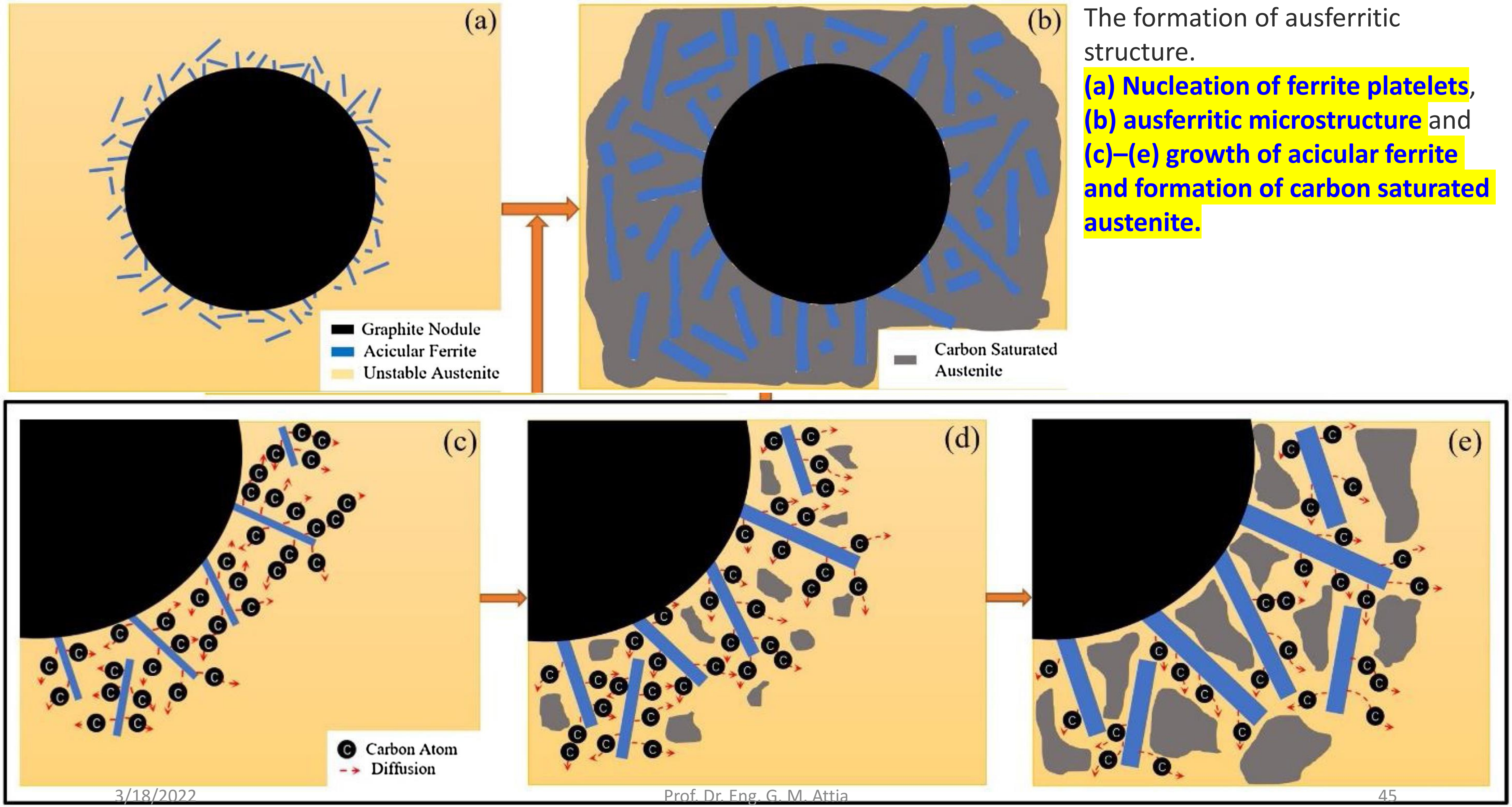
- **Effects of Quenching temperature (Ausempering temperature):**
  - ***At lower austempering temperatures:*** lower retained austenite volume fraction and fine ferritic needles were produced. Hence, higher strength and lower ductility were obtained at lower austempering temperatures.
  - ***At higher austempering temperature***: Coarse feathery ferrite needles and increased ferritic cell size were obtained at higher austempering temperatures.
  - The ductility of the ADI improved with an increase in retained austenite fraction and its carbon content.

- **The unique properties of austempered ductile iron (ADI) are related to the ausferrite matrix (stable high carbon austenite with fine acicular ferrite) formed during the austempering treatment of ductile iron castings.**
- **Ausforming of ADI adds a mechanical processing component to the conventional ADI heat treatment, thus increasing the rate of ausferrite production and therefore leading to a finer and more homogeneous ausferrite product.**
- **The ausforming  by pressing during rolling or forging operations, with reduction in height up to 25-30%, during the austempering schedule just after the quench but before any substantial transformation of austenite.**
- **Ausforming caused a dramatic increase in tensile strength for all investigated alloys and the ductility of Ni-alloyed irons increased, while the ductility of the unalloyed ADI decreased. Ausforming also leads to an increase in both hardness and wear resistance properties.**

# *Austempering Mechanism*

- In the austempering step, the austenitized ductile iron is quickly transferred to another pre-heated furnace, and ***quenched to a low temperature between pearlite formation temperature and martensite formation temperature*** and then held for a certain period.
- ***During this isothermal process***, tiny acicular ferrite is apt to nucleate around the graphite nodules due to high potential energy, ***see Fig.(a).***
- ***Then,*** the ferritic platelets would grow and the carbon saturated austenite would be formed as the diffusion of carbon atoms, ***see Fig. (c)–(e)***.
- ***Finally***, the ideal ADI microstructure should contain acicular ferrite and carbon saturated austenite, which is called as ausferrite, ***see Fig.(b).***

- The morphology of acicular ferrite, volume fraction of stable austenite and carbon content in austenite are **strongly dependent on the austempering temperature and austempering time**. Also, the final mechanical properties of ADI are effectively controlled by these two austempering parameters.
- Thin needle-like ferrite is generated while using low austempering temperature and short holding time. However, needle-like ferrite becomes coarse and feather-like after increasing the austempering temperature or extending the holding time. This is the result of more carbon atoms diffused out of crystal structure with a high rate.
- In addition to changing the morphology of ferrite platelets, the mechanical properties of single-step ADI can also be modified by varying the austempering temperature and austempering time.
- **It can be summarized that** the hardness and tensile strength of single-step ADI decreased, and ductility increased with increasing austempering temperature or extension of holding time. This could be interpreted as more unstable austenite is transformed into acicular ferrite and austenite with high carbon content during the isothermal heat treatment process, and less martensite is formed in the final ADI matrix.




The formation of ausferritic structure.
**(a) Nucleation of ferrite platelets**, **(b) ausferritic microstructure** and **(c)–(e) growth of acicular ferrite and formation of carbon saturated austenite.**

# Advantages 0f ADI…

1. **Lower in cost** when compared to other competing manufacturing methods, such as fabrication, wrought /machined, forged / machined.
2. **Superior mechanical properties as compared to cast iron**, weldments, aluminum alloys, normalized or toughened ductile irons.
3. **Energy consumption** for a finished ADI product is almost half that of a forged, machined & case carburised hardened component, for a similar application.
4. **Ductile irons will exhibit superior damping capacity & machinability as compared to steel.**

# Advantages 0f ADI…

5. ADI has a very low cost to strength ratio when compared to other commonly used engineering materials.

| Material. | Forged Al. | Cast Al. | Cast Steel | Forged Steel | H&T Steel | Ductile Iron | ADI. |
|---|---|---|---|---|---|---|---|
| Unit Cost / Unit Y.S. | 20 | 12 | 6 | 4 | 3 | 2 | 1 |

# Advantages 0f ADI…

6. ADI exhibits transformation induced plasticity [TRIP]. Hence it has superior wear resistance as compared to irons & steels of equivalent hardness values. An ADI with a hardness value of 350 BHN (38 HRC) will have a wear resistance equivalent to a case hardened steel of 60 HRC, making ADI a suitable choice for gears, camshafts, rollers, & other wear parts. Wear resistance of ADI is further enhanced by shot peening.
7. Due to TRIP, ADI also has higher toughness & fatigue strength as compared to normalized / toughened ductile iron, nearing those of steel at times, especially for the lower tensile grades.

**Table 1:** British Standards Specification for ADI EN 1564: 1997

| Mechanical Properties measured on test pieces from separately cast samples. | | | | |
|---|---|---|---|---|
| Material Symbol | Number | Tensile Strength N/mm2 (min) | 0.2% Proof Stress N/mm2 (min) | Elongation % (min) |
| EN-GJS-800-8 | EN-JS1100 | 800 | 500 | 8 |
| EN-GJS-1000-5 | EN-JS1110 | 1000 | 700 | 5 |
| EN-GJS-1200-2 | EN-JS1120 | 1200 | 850 | 2 |
| EN-GJS-1400-1 | EN-JS1130 | 1400 | 1100 | 1 |
| Refer to relevant Standard for full details | | | | |

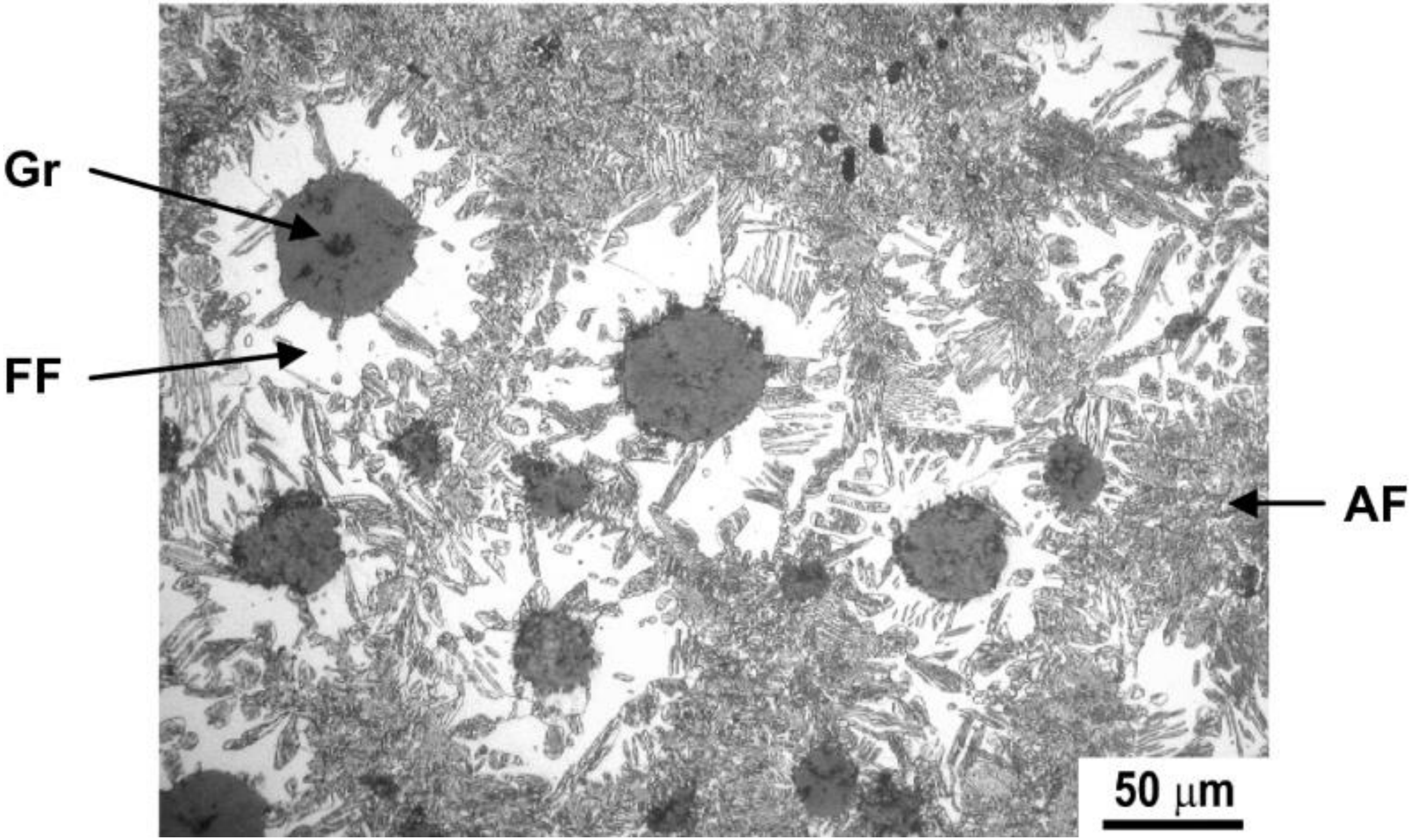
**Table 2:** Standard ADI Grades (USA) ASTM 897-90 (ASTM 897M-90)

| Grade | Tensile Strength (min) | | Yeild Strength (min) | | Elongation % | Impact Energy * | | Typical Hardness BHN |
|---|---|---|---|---|---|---|---|---|
| | Ksi | Nmm2 | Ksi | Nmm2 | | Ft-lbs | Joules | |
| 1 | 125 | 850 | 80 | 550 | 10 | 75 | 100 | 269-321 |
| 2 | 150 | 1050 | 100 | 700 | 7 | 60 | 80 | 302-363 |
| 3 | 175 | 1200 | 125 | 850 | 4 | 45 | 60 | 341-444 |
| 4 | 200 | 1400 | 155 | 1100 | 1 | 25 | 35 | 388-477 |
| 5 | 230 | 1600 | 185 | 1300 | - | - | - | 444-555 |

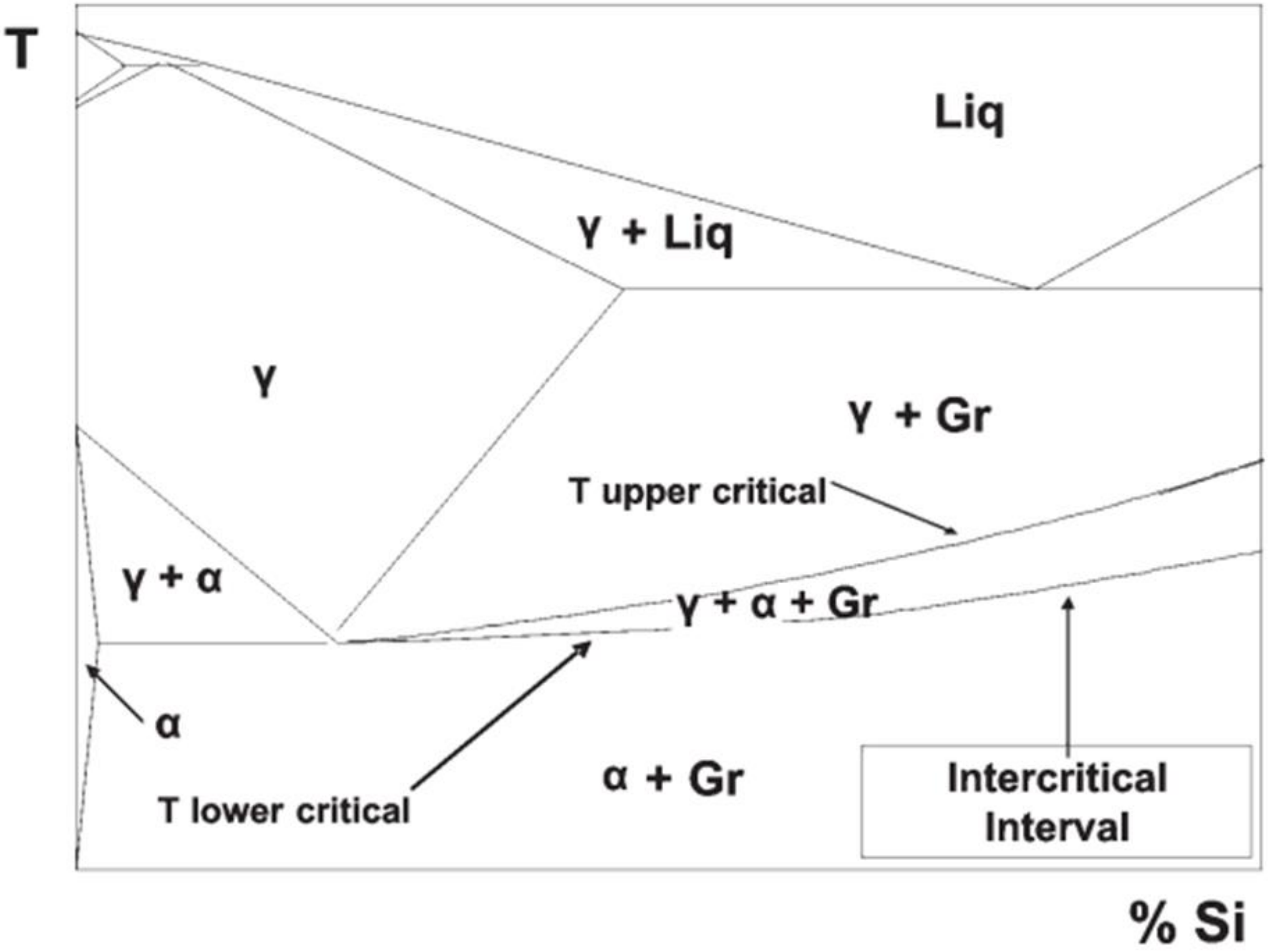
# Dual Phase Ductile Iron

# IntercrItical Heat Treatment in Dual Phase Ductile Iron

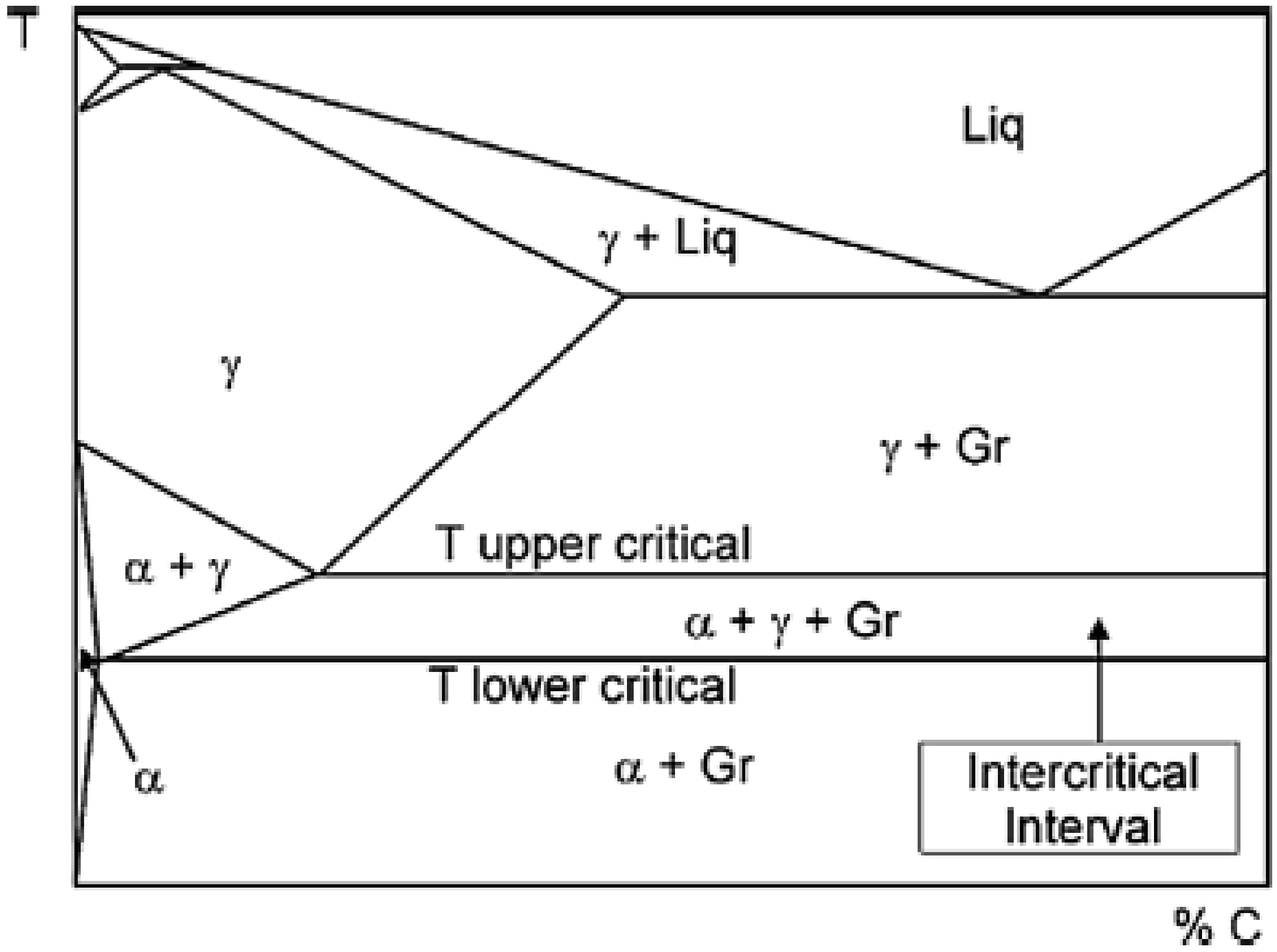
- The simplest method to obtain dual phase microstructure in ADI, could be achieved by **incomplete austenization** at temperatures within the intercritical interval (apx.**750–860 °C**), where austenite (γ), ferrite (α) and graphite (Gr) exist (as given in the phase diagram).
- **This region is called intercritical interval**, and it is limited by the upper and lower critical temperatures. Such temperatures define the starting point at which ferrite transforms into austenite and austenite into ferrite in heating and cooling processes, respectively.
- The intercritical austenitization is followed by an **austempering stage (apx 250–400 °C) in a salt bath**, which is carried out to transform the austenite into ausferrite.
- This heat treatment **yields microstructures with different morphologies and amounts of free ferrite and ausferrite, depending on the intercritical austenitizing temperature.**



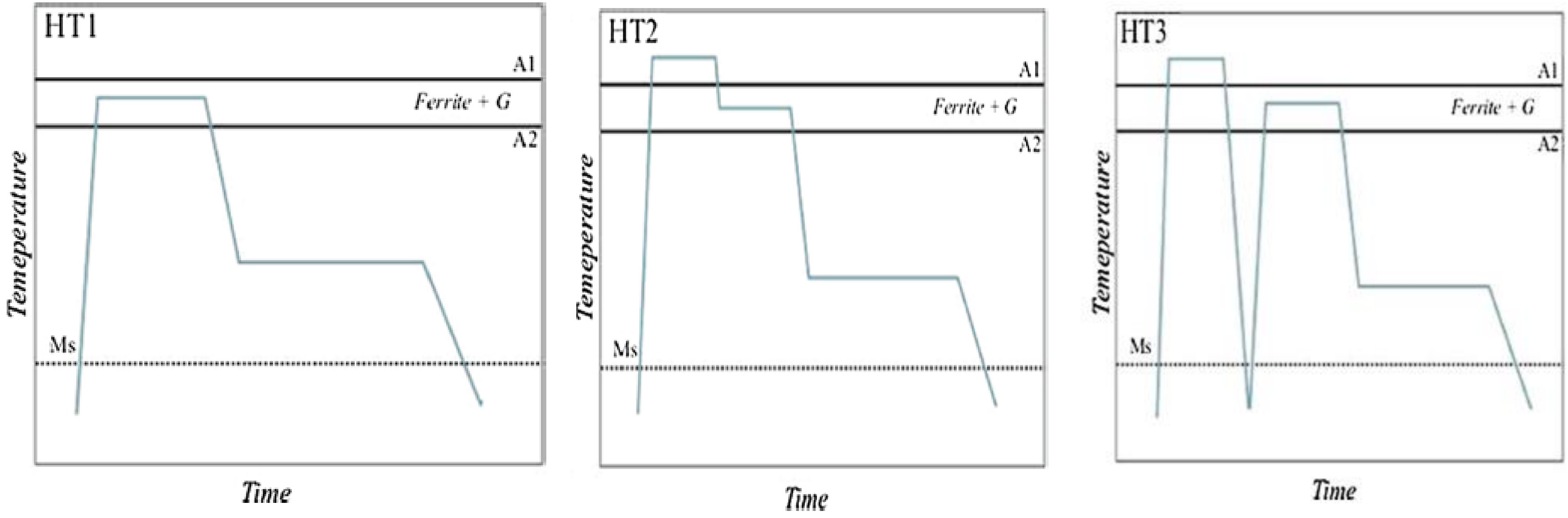

- Microstructure (light microscope) of a DP-ADI obtained after austenitization at 820 °C within intercritical interval; and austempering at 400 °C (AF – ausferrite*, FF – free ferrite, Gr – graphite nodules)
- *In Austempered Ductile Iron and Austempered Gray Iron, the structure is Ausferrite while Bainite forms in steel (consisting of acicular ferrite in carbon -enriched austenite).



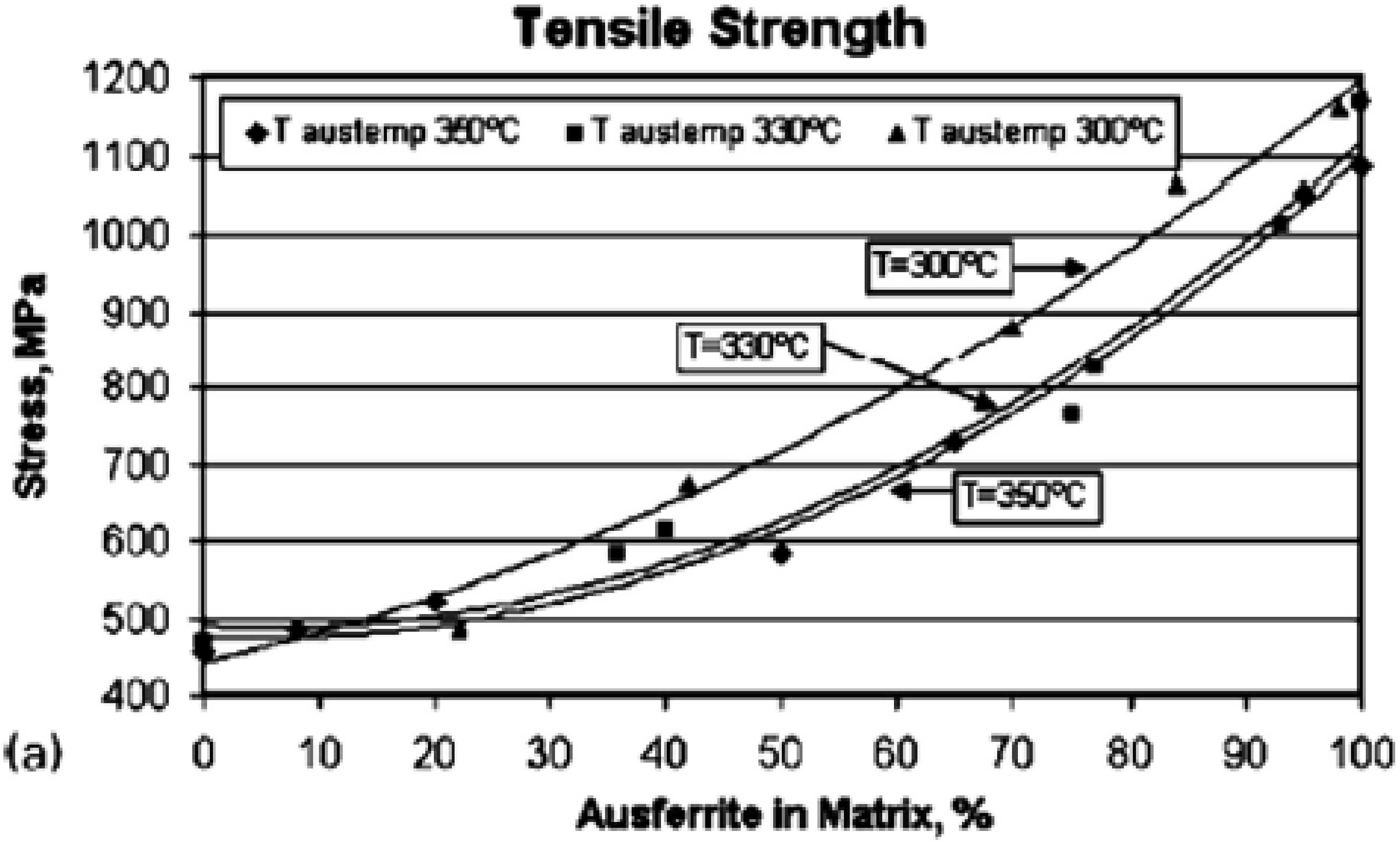

Influence of Si content on the intercortical interval position.

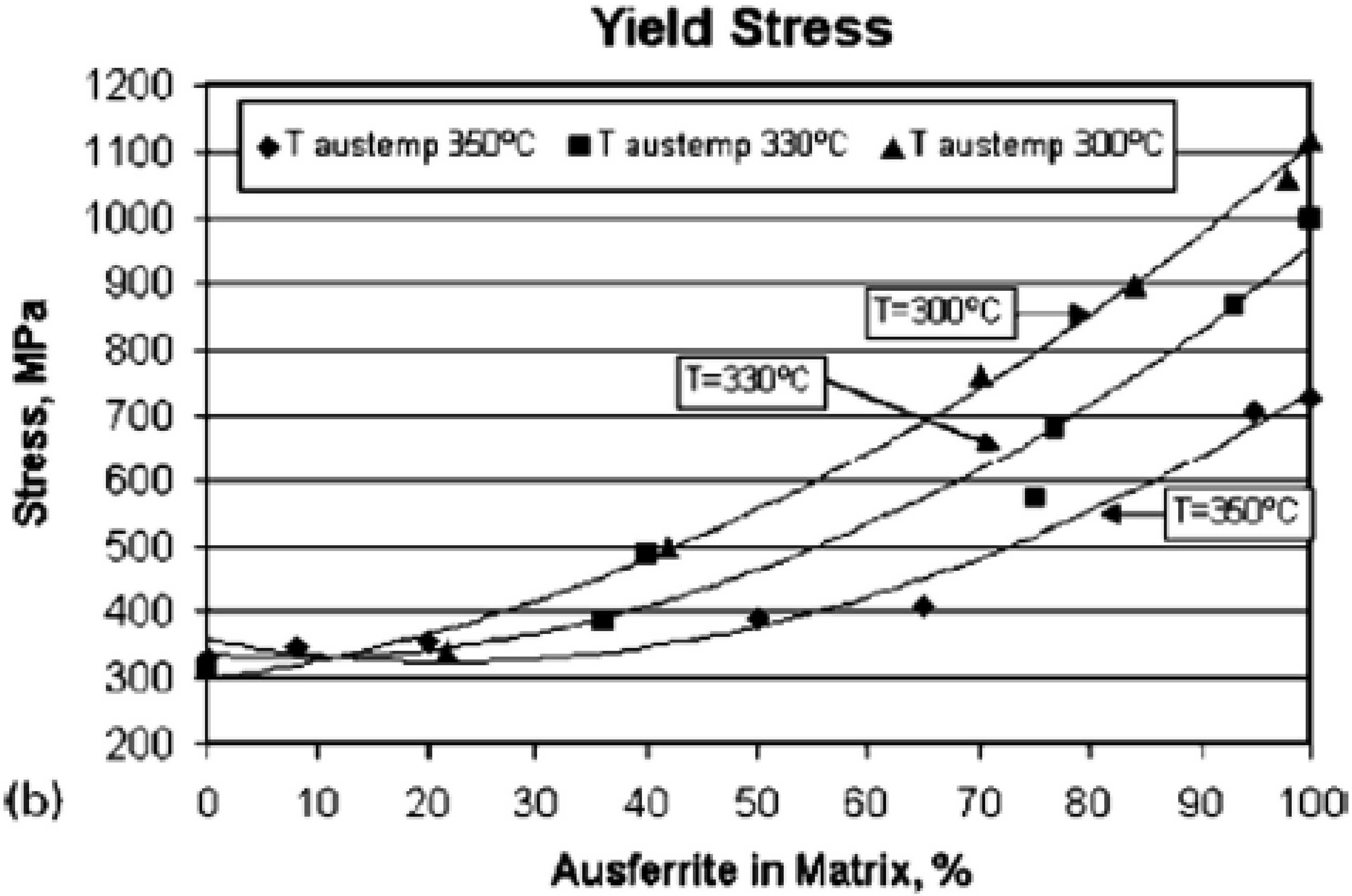


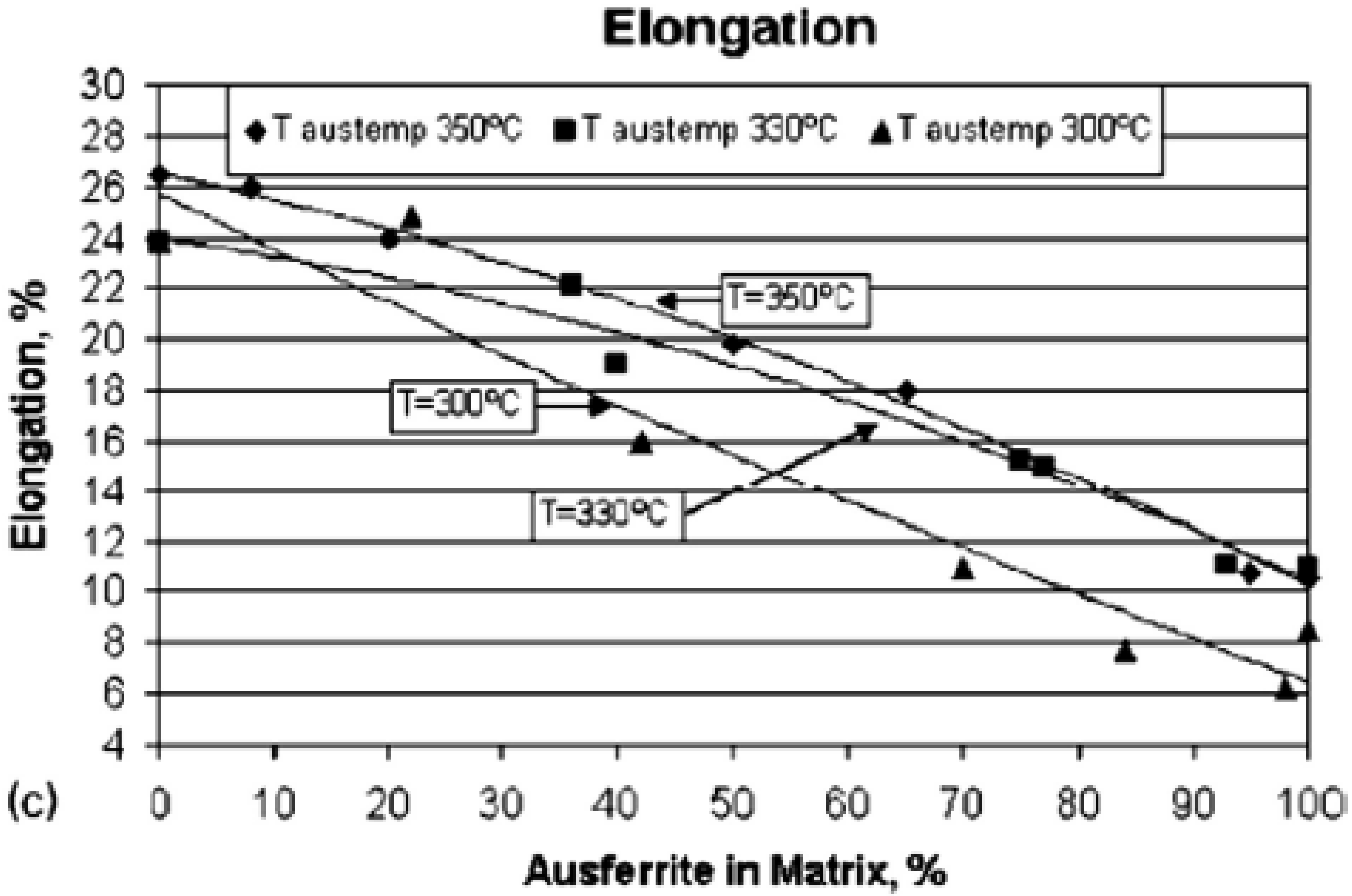

Schematic pseudo binary Fe-C phase diagram at a constant amount of Si (2.5%)



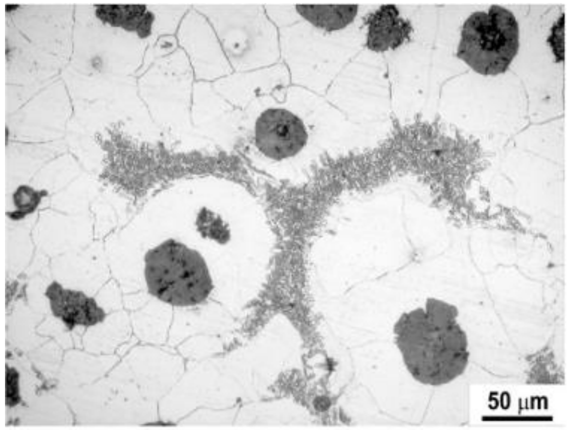

a. HT1: partial austenitization
b. HT2: complete austenitization, second partial austenitization
c. HT3: a typical austenitization-quench cycle


Tensile Strength
T austemp 350°C
T austemp 330°C
T austemp 300°C
T=300°C
T=330°C
T=350°C
Stress, MPa
1200
1100
1000
900
800
700
600
500
400
(a)
0
10
20
30
40
50
60
70
80
90
100
Ausferrite in Matrix, %

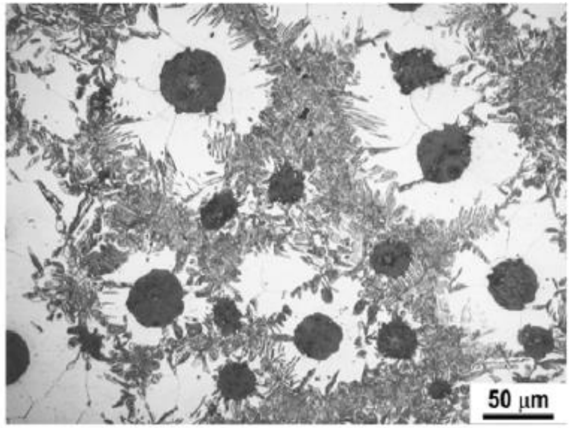

Yield Stress
T austemp 350°C
T austemp 330°C
T austemp 300°C
T=300°C
T=330°C
T=350°C
Stress, MPa
1200
1100
1000
900
800
700
600
500
400
300
200
(b)
0
10
20
30
40
50
60
70
80
90
100
Ausferrite in Matrix, %



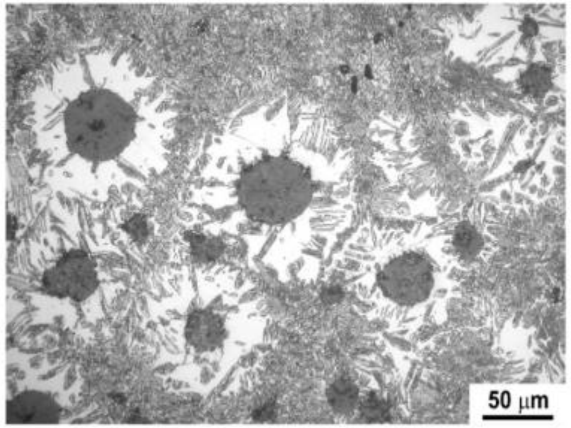

**Relationship between mechanical properties and amounts of ausferrite in the matrix**



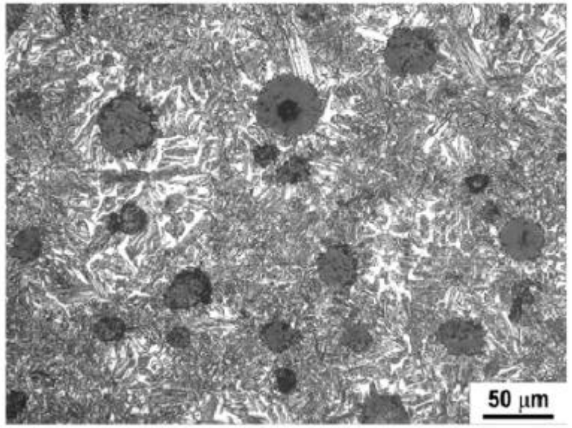

a) $T_\gamma$= 780°C; 78.8FF +9.2%AF+12%Gr



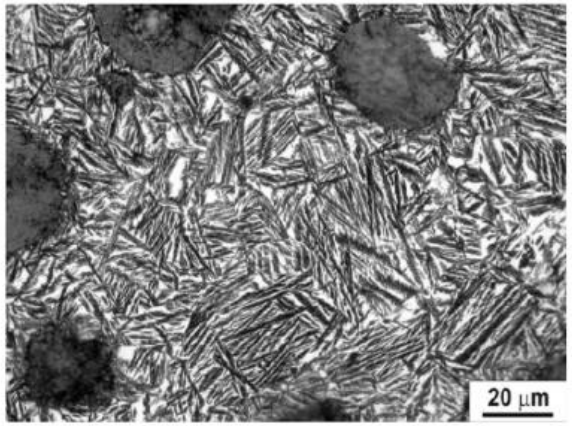

b) $T_\gamma$= 800°C; 39.2%FF +50.8%AF+10%Gr




c) $T\gamma$= 820°C; 20.4%FF 67.6%AF+12%Gr



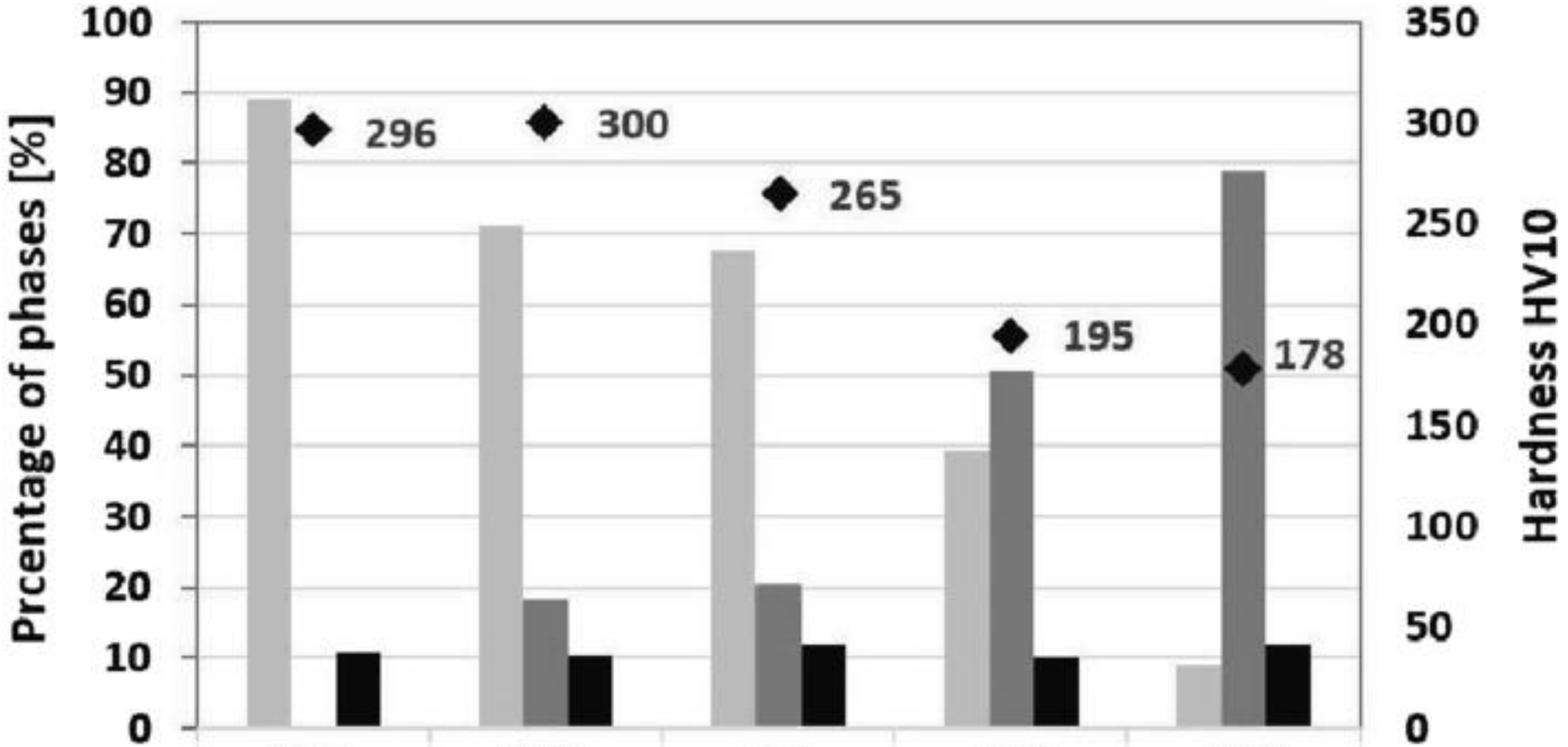

d)$T_\gamma$= 840°C; 18.4%FF +71.2%AF+10.4%Gr




e) $T\gamma$=900°C; 89.1% AF + 10.9% Gr

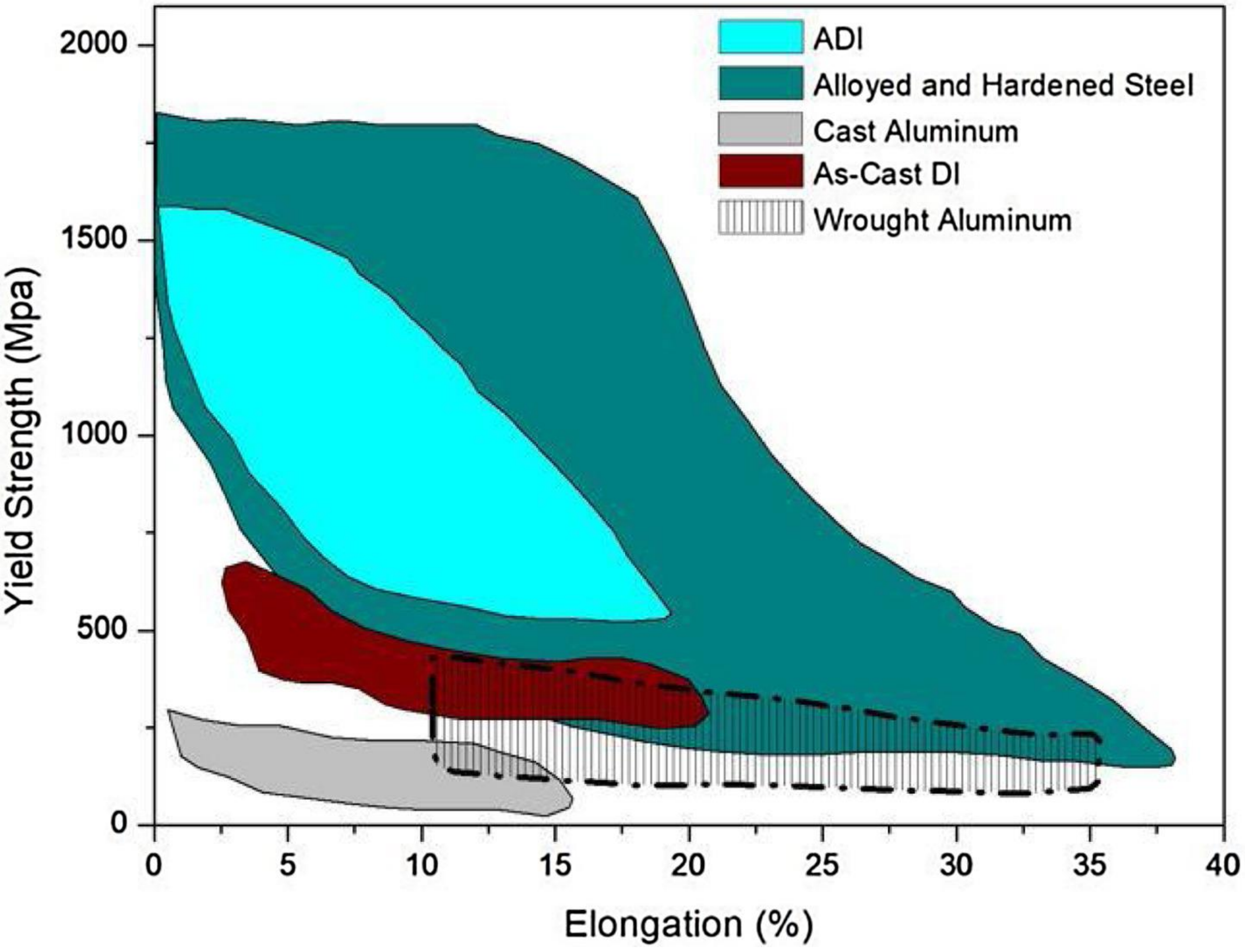
**Microstructure obtained for samples austenitized at different austenitization temperatures Tγ within intercritical interval; austempering temperature 400 °C/1 h in all cases.**

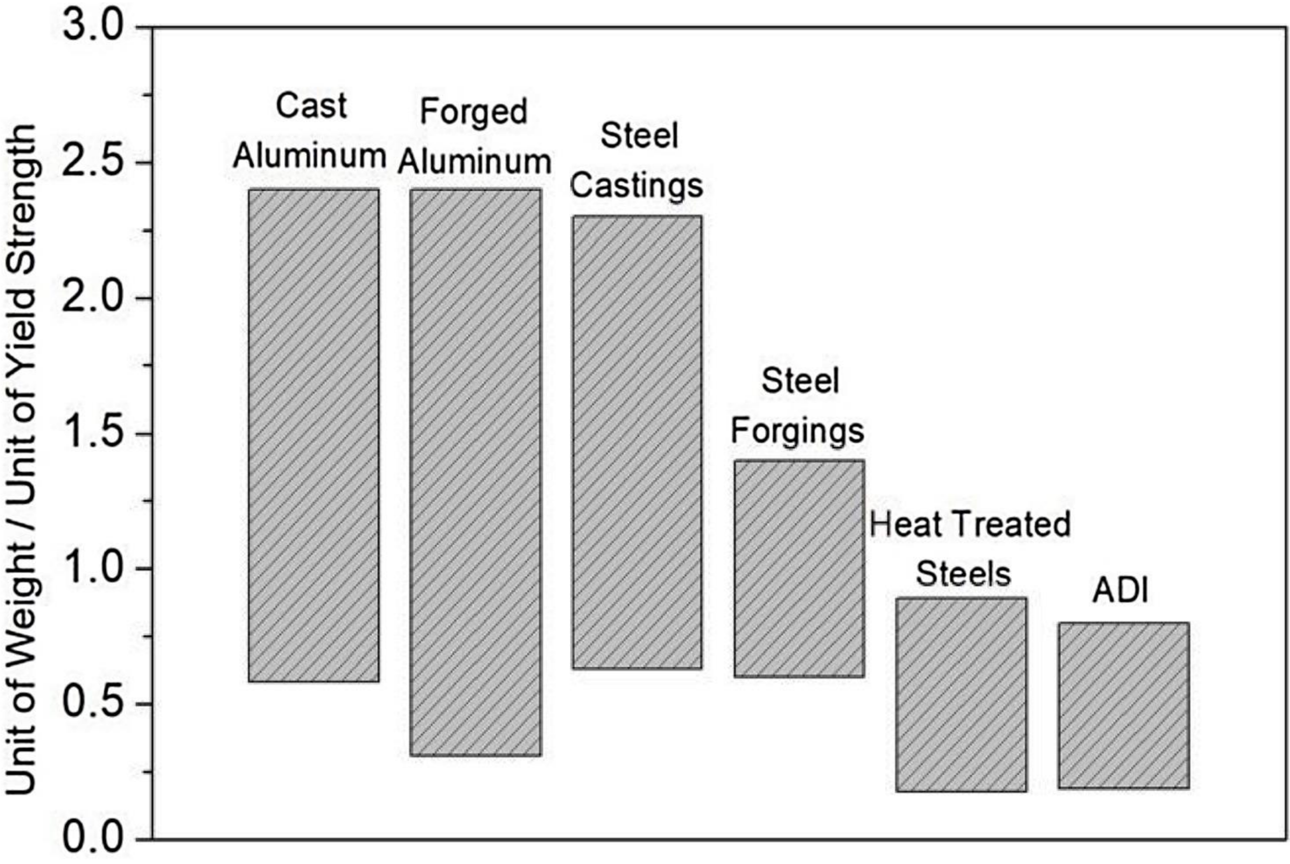
**Austenitization temperatures: 780, 800, 820, 840, and 900$^o$C**




| | 900 | 840 | 820 | 800 | 780 |
|---|---|---|---|---|---|
| Ausferrite [%] | 89.1 | 71.2 | 67.6 | 39.2 | 9.2 |
| Free ferrite [%] | 0.0 | 18.4 | 20.4 | 50.8 | 78.8 |
| Graphite [%] | 10.9 | 10.4 | 12.0 | 10.0 | 12.0 |
| Hardness HV10 | 296 | 300 | 265 | 195 | 178 |

Effect of microconstituents percentages on the values hardness of dual phase austempered ductile iron

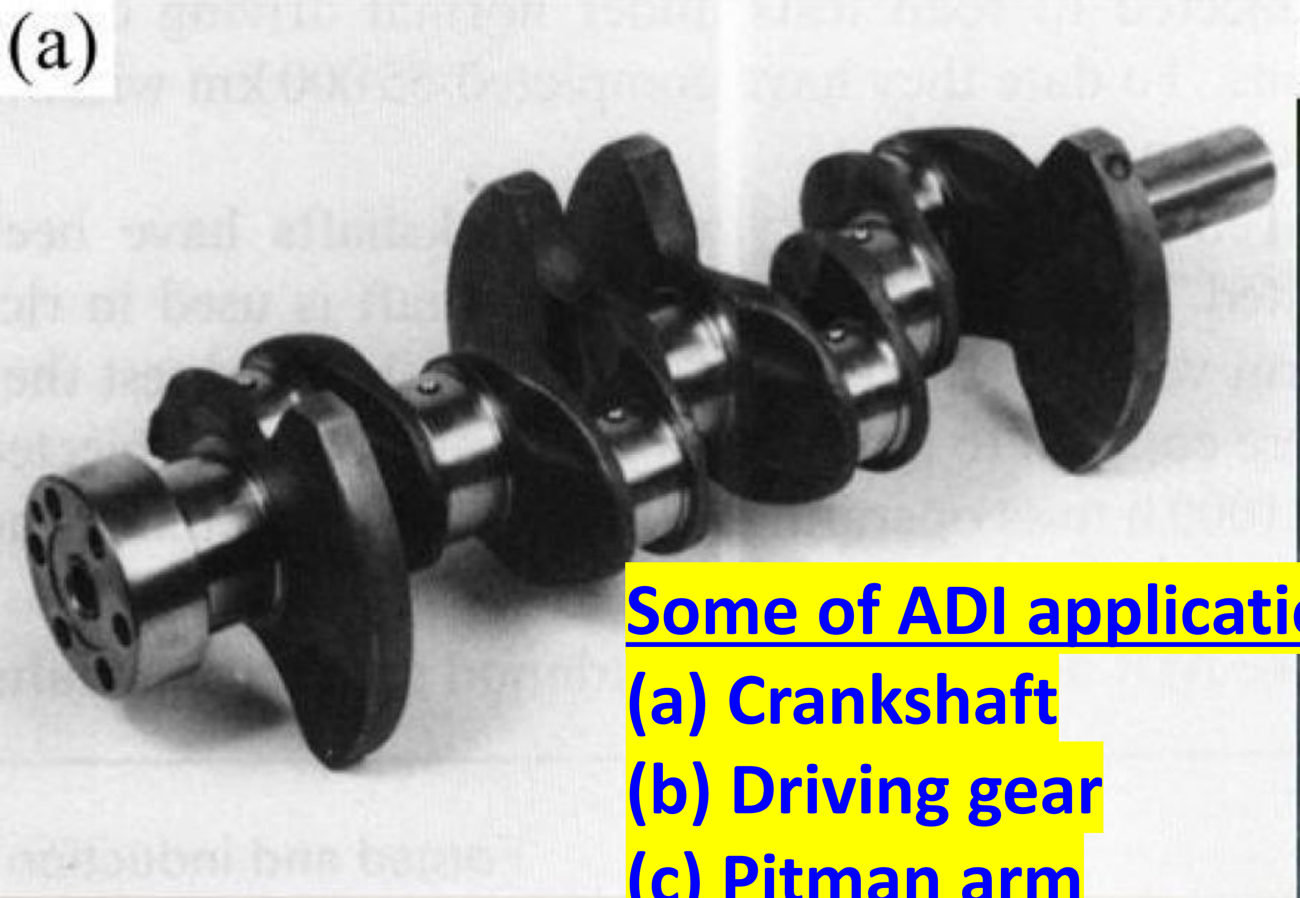



**Comparison of yield strength, elongation, unit weight and unit cost of ADI with other engineering materials.**

## Applications & Examples

- The properties of ADI coupled with the cost and flexibility benefits of ductile iron castings means the potential for ADI applications is vast:
- Agriculture - excellent resistance to soil wear
- Digger/Grab teeth - high strength and wear resistance
- Industrial - wear components, pumps, etc.
- Gears - for wear resistance and better vibration damping than steel
- Construction - crushing, grading and wear components etc.
- Food & feed milling - grinding, mixing, pelletizing etc.






## Some of ADI applications

**(a) Crankshaft**

**(b) Driving gear**

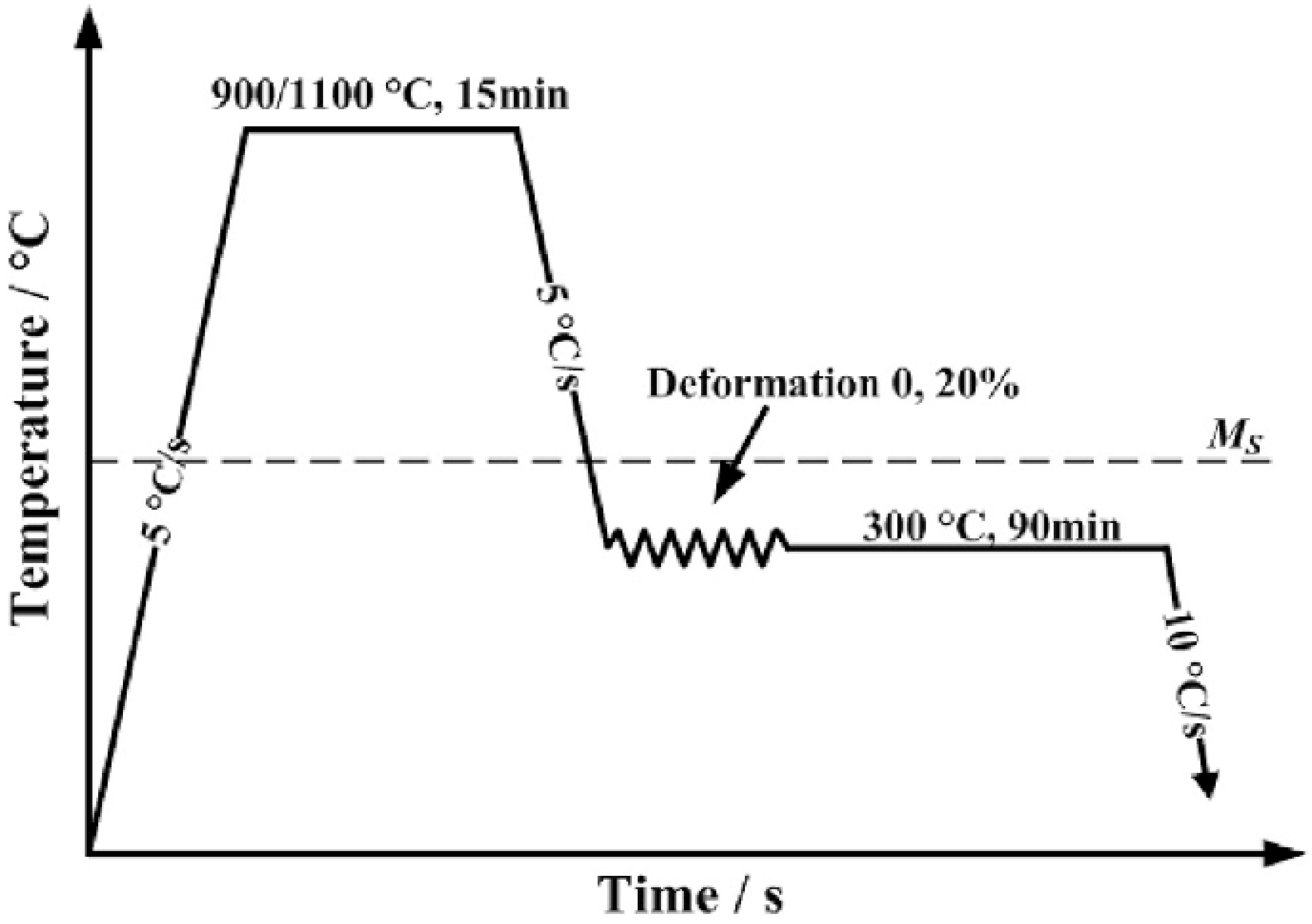
**(c) Pitman arm**

- The best combinations of mechanical properties for these new mixed structures were found when using high austempering temperatures, around 350$^{o}$C).
- In particular, dual phase ADI microstructures containing approximately **20% of ausferrite** in their microstructures have widely superseded the mechanical and **fatigue properties** of fully ferritic DI, at the same time, preserving a high ductility.
- This combination of properties is appreciated in automobile safety parts.

- **Quenching Media**
- Quenching solutions act only through their ability to cool the steeL They have no beneficial chemical action on the quenched steel and in themselves impart no unusual properties.
- Most requirements for quenching media are met satisfactorily by **water** or **aqueous solutions** of **inorganic salts such as table salt or caustic soda, or by some type of oil**. The rate of cooling is relatively rapid during quenching in brine, somewhat less rapid in water, and slow in oil.
- **Brine usually is made of a 5- to 10-percent solution of salt (sodium chloride) in water.** In addition to its greater cooling speed, brine has the ability to "throw" the scale from steel during quenching.

# *Thermomechanical Treatment of ADI (Ausformed ADI)*

***Strain induced austenite transformation***


900/1100 °C, 15min
5 °C/s
5 °C/s
Deformation 0, 20%
$M_S$
300 °C, 90min
10 °C/s
Temperature / °C
Time / s

# *Ausforming process*

- Ausforming of DI is a subdivision of the above-mentioned austempering processing method.
- The deformation in the ausforming processes introduced into the austempering schedule ***just after quenching but before any substantial transformation of austenite***. ***It is shown that ausforming could provide mechanical driving force in the form of strain defects in addition to the chemical thermodynamic driving force***.
- This can be used to ***accelerate the rate of stage I*** of austempering.
- The ***enhanced nucleation rate*** of ausferrite and C-enriched austenite ***leads to finer and more homogeneous*** aus-ferrite, which in turn, results in a ***dramatic increase in strength, hardness and wear resistance.***

- In ausformed austempered ductile iron (AADI), mechanical deformation is utilized to affect the microstructure and, consequently, the mechanical properties of ductile iron due to acceleration of ausferrite reaction, ***refining the microstructure and increase of the structural homogeneity***.
- Ductile iron will be ***subjected to plastic deformation either by applying compressive stresses in the austenite region (800-900C) before quenching to austempering temperature or at quenching temperature 300-400C.***

- Transformation of austenite to martensite by deformation has been extensively studied in **TRIP steels**, whereas very little has been reported on the martensite transformation induced by cold rolling and its effect on microstructure and hardness of low alloy ADI.
- In the course of fracture toughness tests of ADI in the upper bainite region, containing high volume fraction of retained austenite, $\gamma r \rightarrow \alpha'$ (martensite) **transformation induced plasticity** TRIP has been reported to occur, leading to superior toughness compared to conventional cast iron.
- **TRIP Steels** (Transformation Induced Plasticity Steel) are part of the Advanced High-Strength Steel (AHSS) family. The microstructure of TRIP steels consists of at least five-volume percent of retained austenite, which is embedded in a primary ferrite matrix. The microstructure also contains hard phases like bainite and martensite in varying amounts.

# The effects of strain-induced austenite transformation on the microstructure evolution and phase transformation characteristics

- By applying strain, the rate of the β-to-α phase transformation increased significantly during deformation as well as during slow cooling following deformation. This increase in the kinetics of the β-to-α transformation can be ascribed to strain-induced phase transformation.
- Thermomechanical treatment of ductile iron: Particularly interesting is thermomechanical treatment (OCP) of spheroidal cast iron which undergoes isothermal treatment to obtain the AADI cast iron (Ausforming Austempered Ductile Iron).

- **Cryogenic Processing**
- Many cast irons are cryogenically treated **(-195˚C) to stabilize the microstructure and enhance properties** (e.g., **dampening and wear characteristics**). A typical cycle consists of:

➢ - **slowly reducing temperature** over a period of **6-8 hours**,

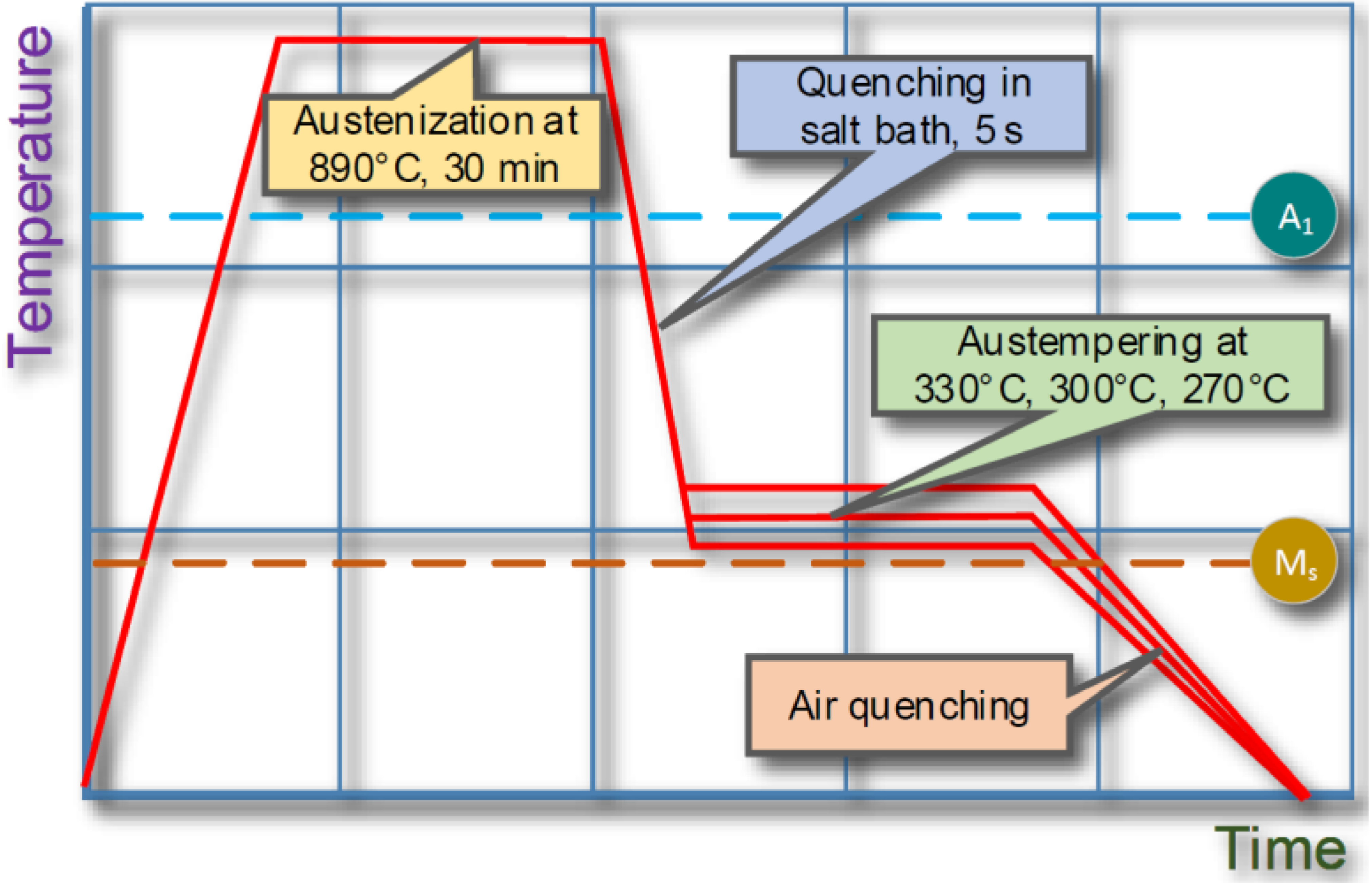
➢ - **stabilizing** at temperature (typically **8-12 hours**) and

➢ - **slowly raising** the temperature **back to room temperature again** over a period of **6-8 hours.**

- Cryogenically treated gray cast-iron **brake rotors** in automotive applications have been shown to **improve service life**. In police cars, where a combination of high speeds and frequent braking translates to brake-component replacement around 12,875 km (8,000 miles), cryogenic processors report having extended the time between replacement of these components consistently up to 38,625 km (24,000 miles).

# Cryogenic treatment

- **Cryogenics** is one of the freezing technologies that **can improve the mechanical properties** of the metal. This method of freezing (cooling) uses liquid nitrogen with temperatures **below 0 °C**. The process for obtaining **liquid nitrogen** involves compressing gas into a liquid form (e. g. nitrogen [N2] and carbon dioxide [CO2]). Liquid nitrogen has long been used to freeze organic materials for the storage and extraction of research materials in applied biology. Liquid carbon dioxide, in comparison, is used to fill fire extinguisher tubes.
- **Liquid nitrogen has a boiling point of –195.8 °C, whereas liquid carbon dioxide boils at –57 °C**. At higher temperatures than these, nitrogen and carbon dioxide are volatile gases, so generally liquid nitrogen and liquid carbon dioxide are at temperatures lower than their boiling points. With such cold temperatures, both liquid nitrogen and liquid carbon dioxide have the ability to freeze organic matter and are relatively more effective than ammonia or Freon coolants.


Temperature
Austenization at
890° C, 30 min
Quenching in
salt bath, 5 s
A1
Austempering at
330° C, 300°C, 270°C
Ms
Air quenching
Time

# End

# ADI (heat treatment regime):

I. ***Austenitizing:*** During the austempering process, the ductile cast iron is heated up to austenitizing temperature range (***850–950 C)*** for complete homogenization of austenite and then

II. ***Rapid quenching***: Quenched rapidly to an austempering temperature range (250–400 C).

III. ***Austempering*** (Holding isothermally): It is then isothermally heat-treated at that temperature range (***250–400 C***) for the transformation of austenite.