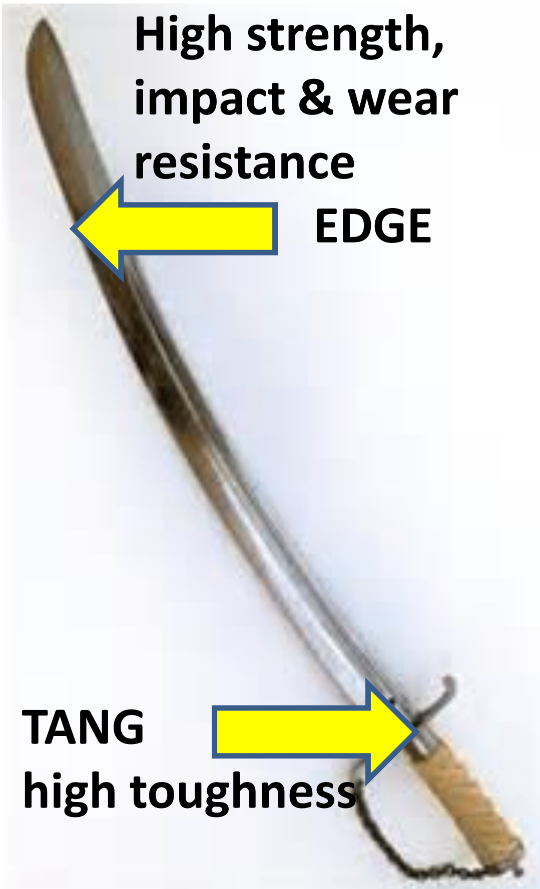
Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

Focus on Steel – Localized Hardening

NEED FOR STEEL PARTS WITH AREAS OF DIFFERENT PROPERTIES



Long reliable service life

Crankshaft - converts reciprocating to rotational motion

Focus on Steel – Localized Hardening

A CENTURIES OLD TECHNOLOGY
INVENTED BY THE OLD CHINESE SWORD BLACKSMITHS

Differential Heat Treatment

a technique used during heat treating
to harden or soften certain areas of a steel part,
creating a difference in hardness between these.

There are two methods:

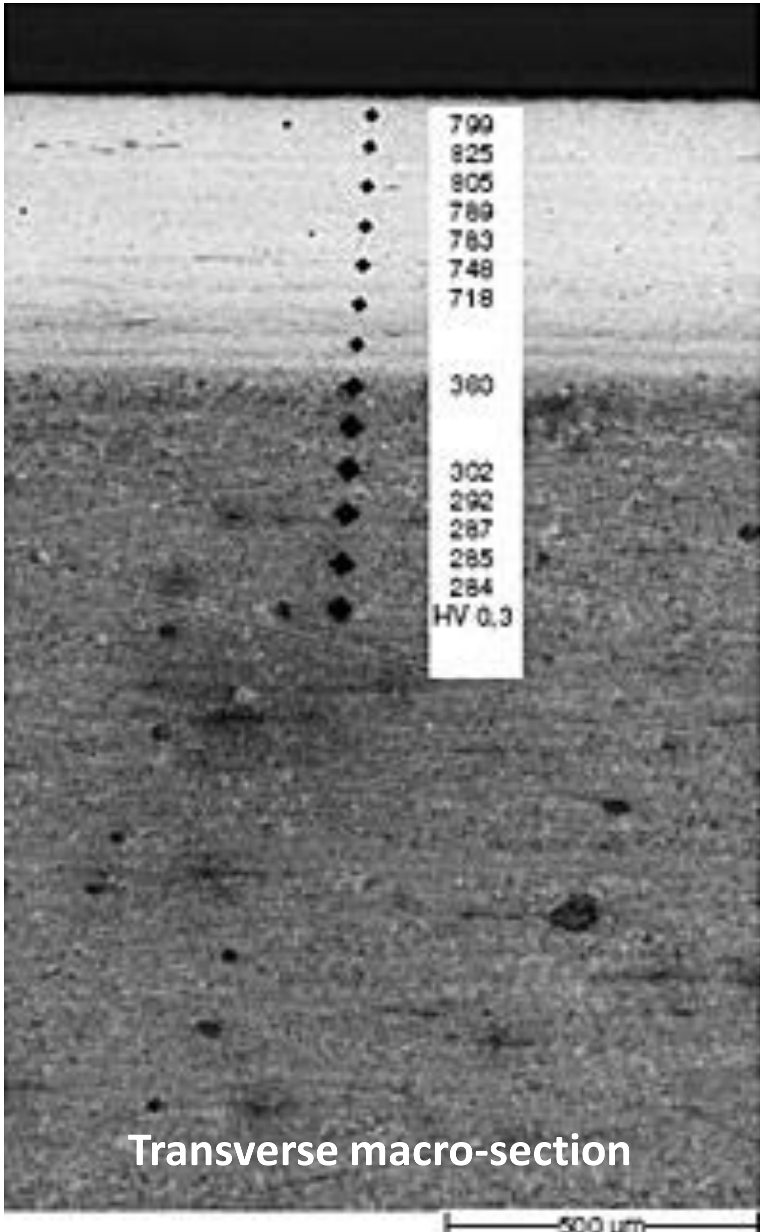
DIFFERENTIAL HARDENING **DIFFERENTIAL TEMPERING**

Hardening

a metallurgical and metalworking process
used to increase the hardness of a metal

Martensitic Transformation
(Quenching & Tempering)

Focus on Steel – Thermal Hardening



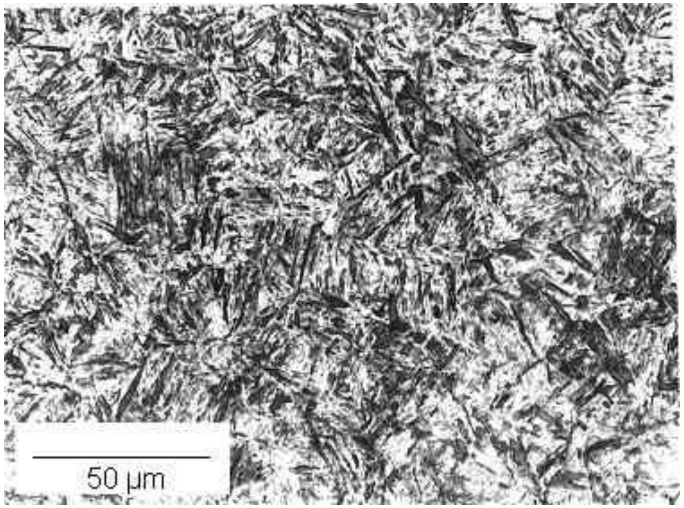
Martensite

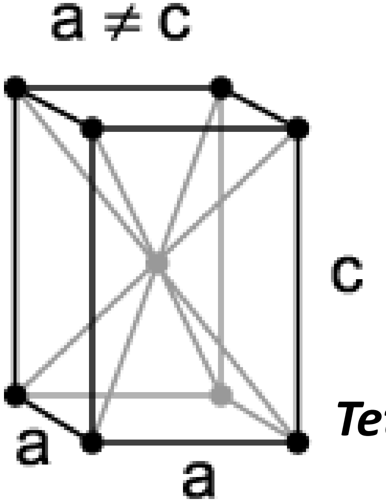
Hardening is characterised as:
heating up steel to the Austenitic temperature followed by rapid quenching –
producing the structural form of Martensite (hardening structure).

Martensite is required in steels
to achieve a considerable increase in hardness.
The achievable (Martensitic) hardness
is directly dependent
on the carbon content of the steel:
The higher the carbon content,
the greater the hardness

Martensite

a body-centered tetragonal form of iron in which some carbon is dissolved.
Martensite forms during quenching,
when the face centered cubic lattice of austenite is distorted
into the body centered tetragonal structure
without the loss of its contained carbon atoms into cementite and ferrite.
Instead, the carbon is retained in the iron crystal structure,
which is stretched slightly so that it is no longer cubic.
Martensite is more or less ferrite supersaturated with carbon.





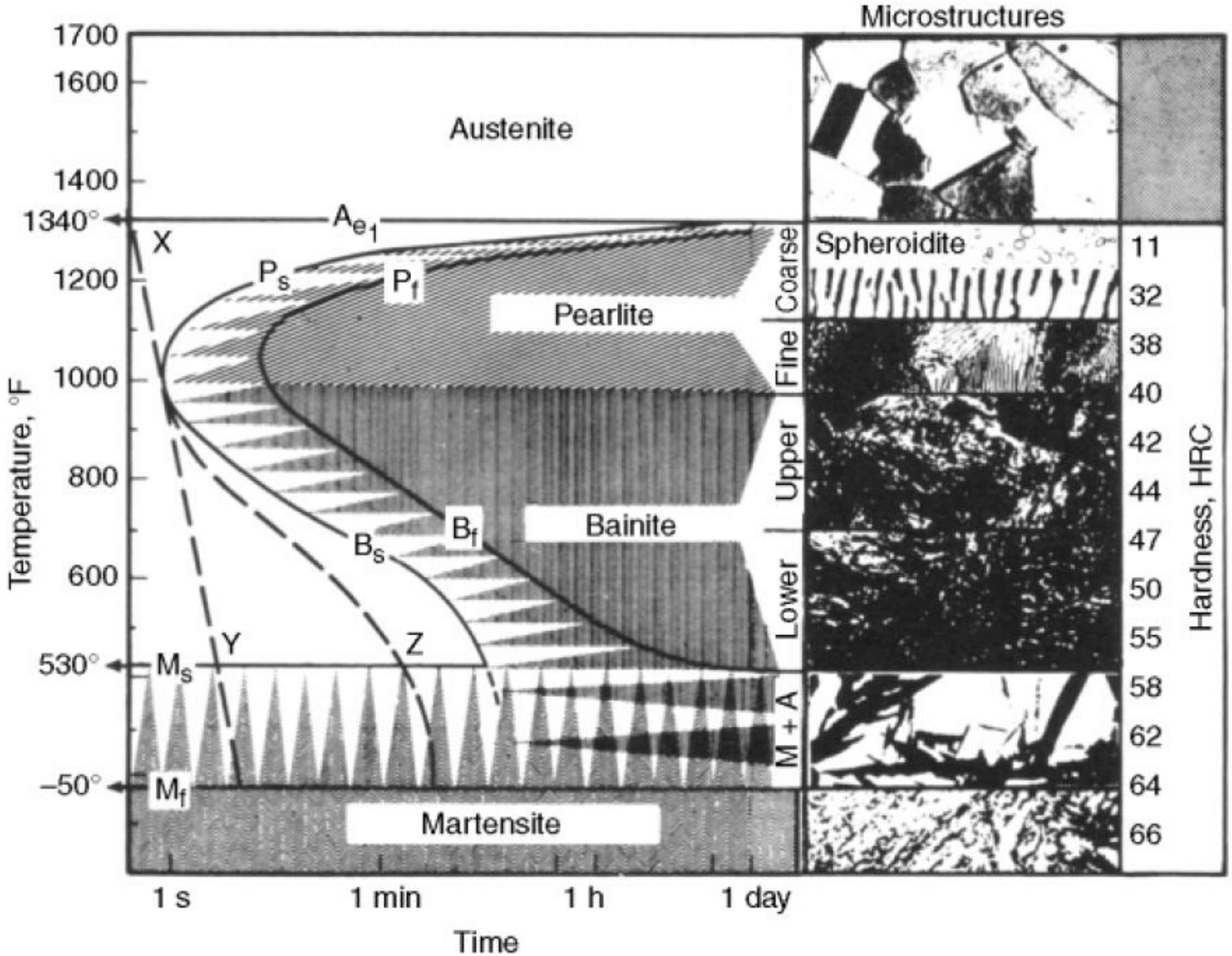
Body Centered Tetragonal Unit Cell

Martensite

a form of steel crystalline structure of utmost hardness formed through the displacive, diffusionless transformation during fast cooling of austenitic phase called quenching.

However:
It is very brittle and must be softened by tempering

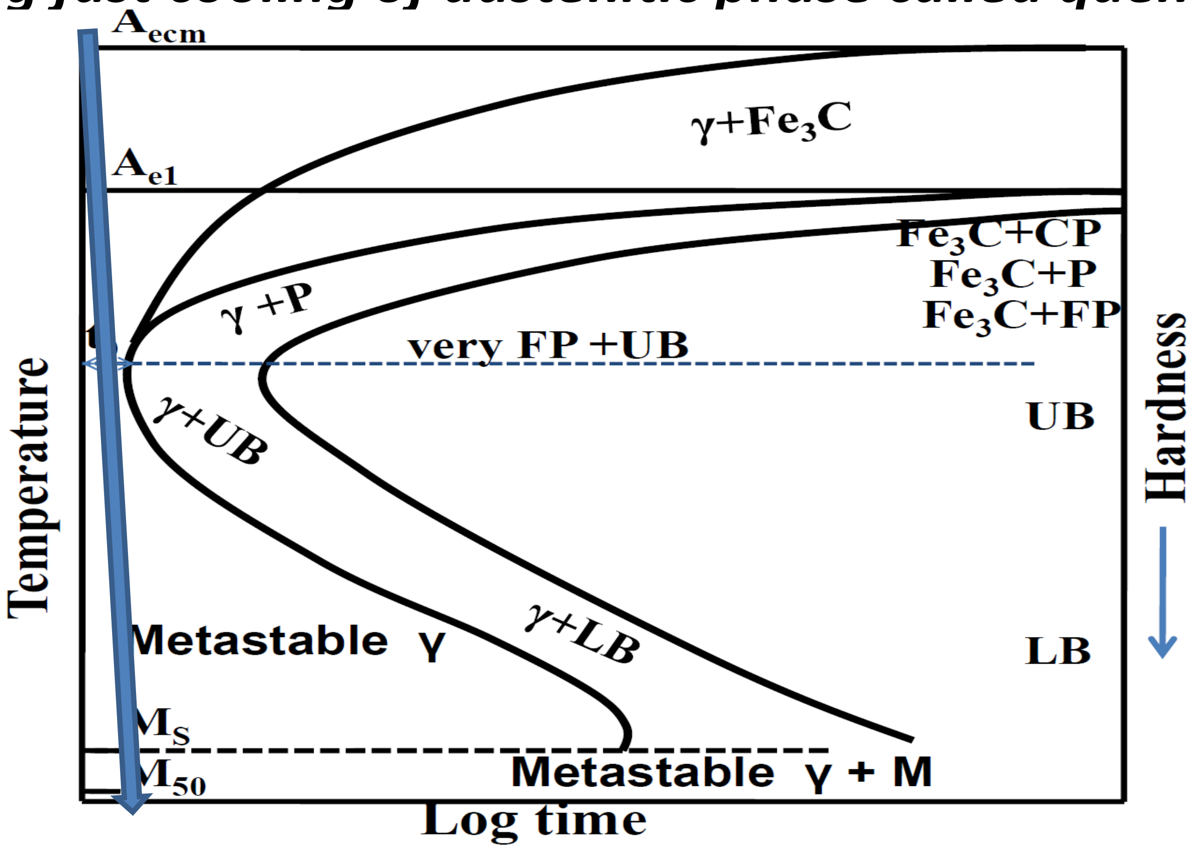
Focus on Steel – Localized Hardening



Time-Temperature Diagram for a Eutectoid (0.77%) Carbon Steel

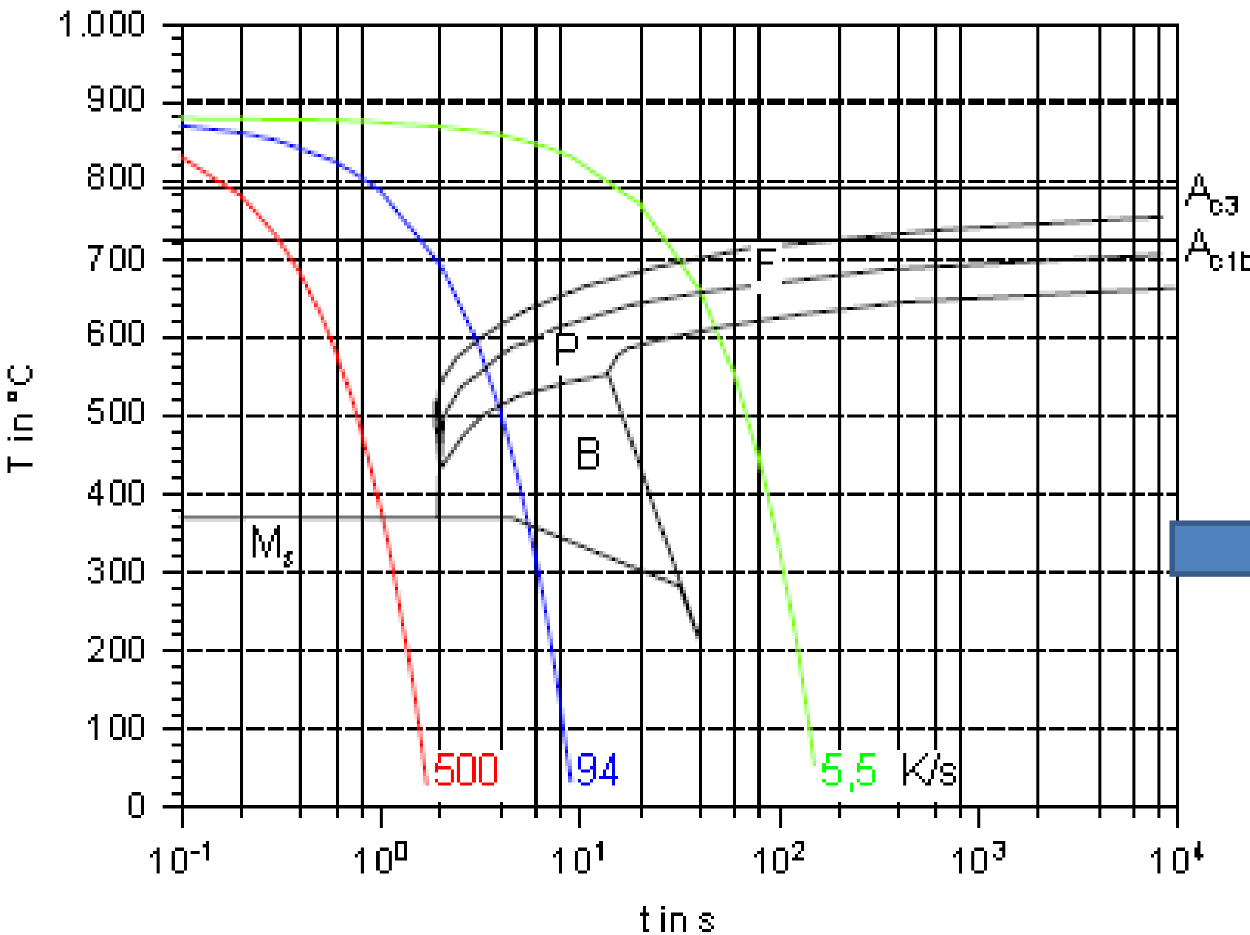
Martensite

a hard form of steel crystalline structure formed through the displacive, diffusionless transformation during fast cooling of austenitic phase called quenching

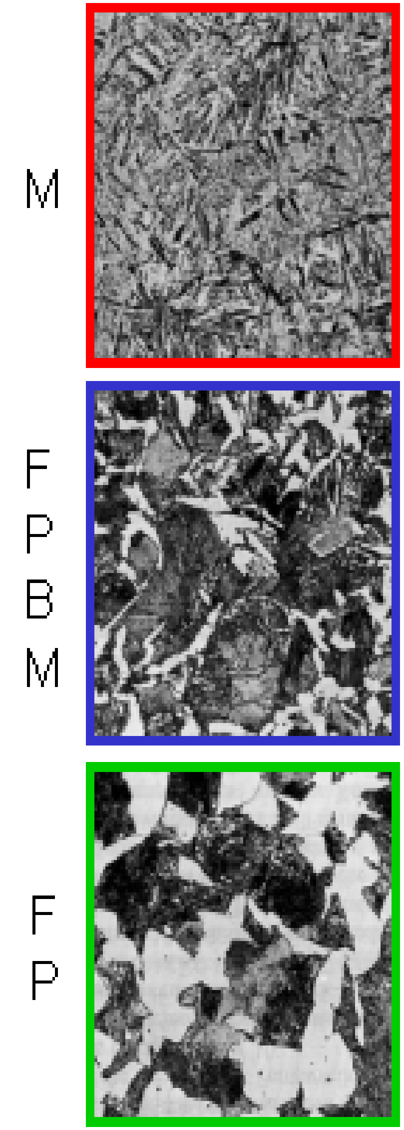


Focus on Steel – Differential Hardening

C45 (1.0503)

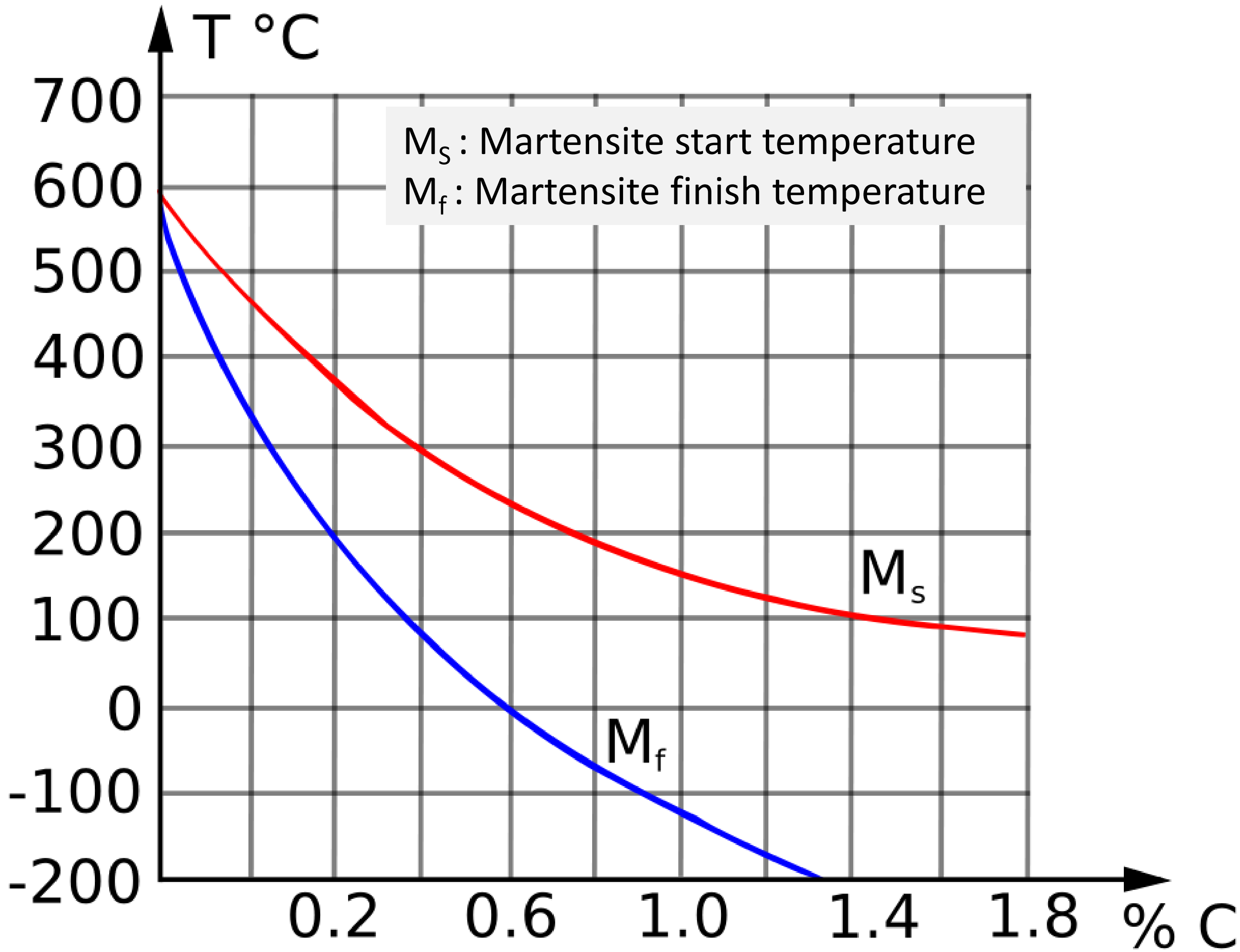


Metallographic Constituents



Microstructures resulting from temperature control (see ttt diagram)

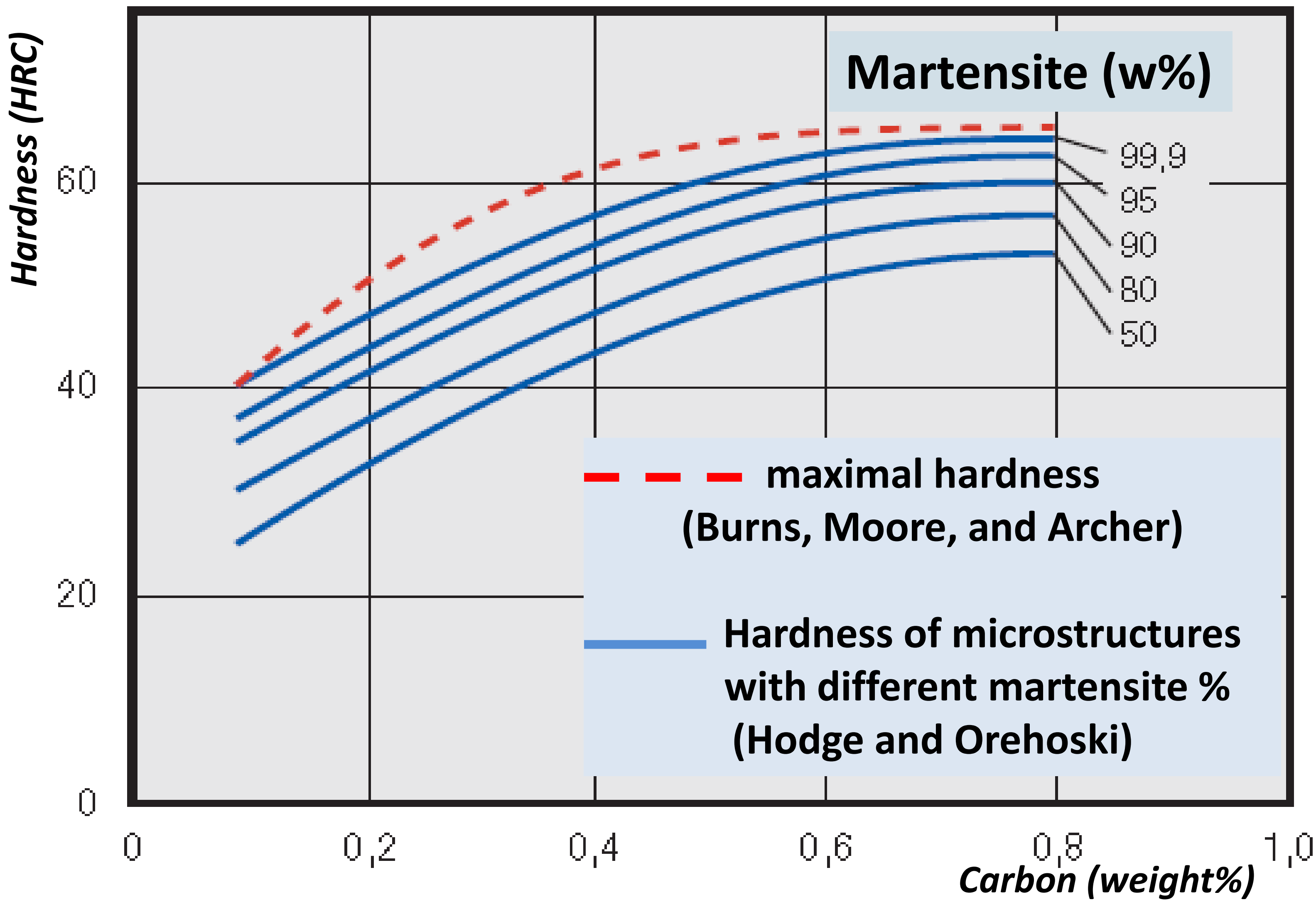
Focus on Steel – Differential Hardening



Relation between Carbon Content and Transformation Temperatures

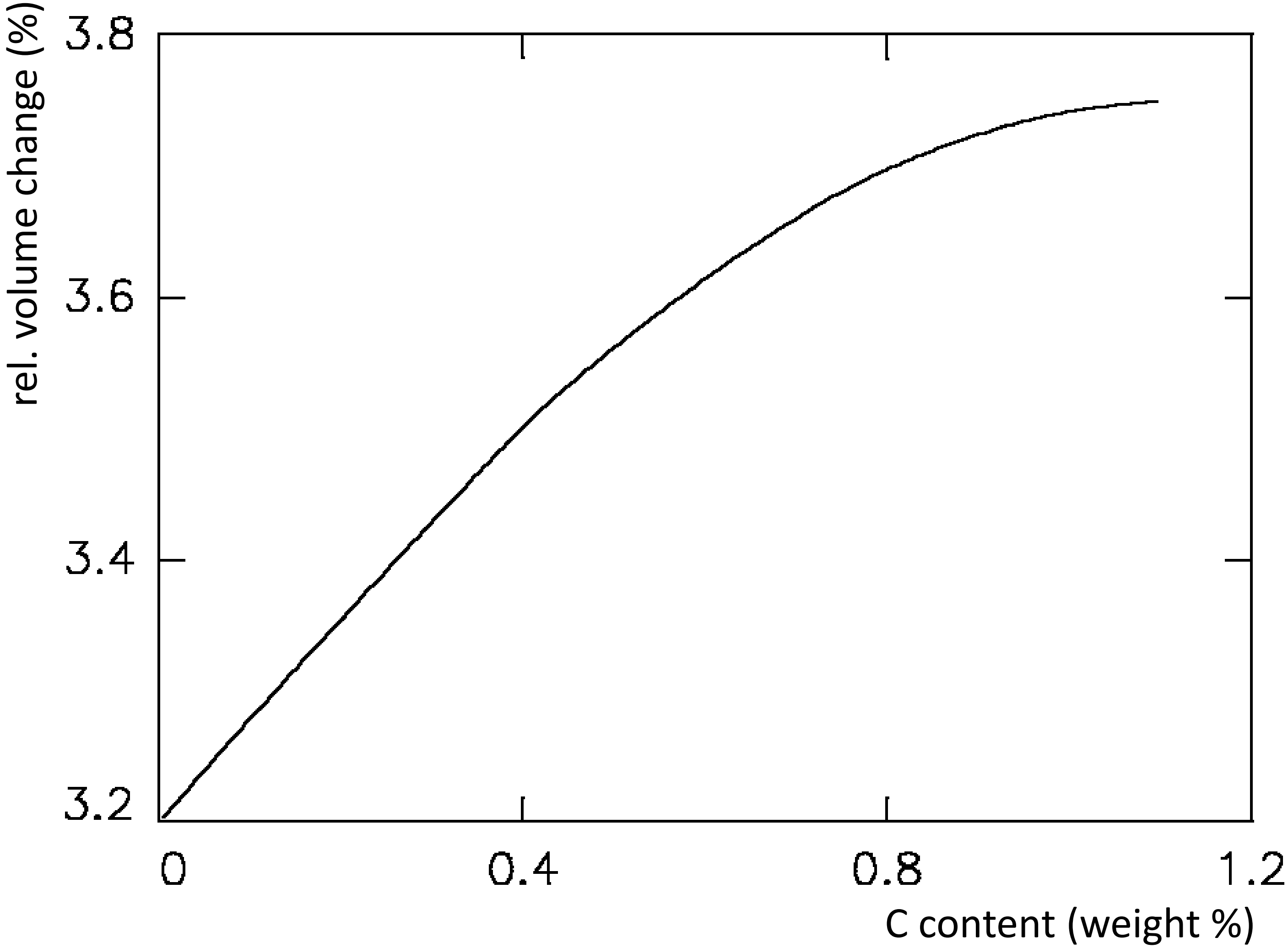
Heat Treatments - Thermal Hardening

Achievable Maximal Hardness linked to the Carbon Content



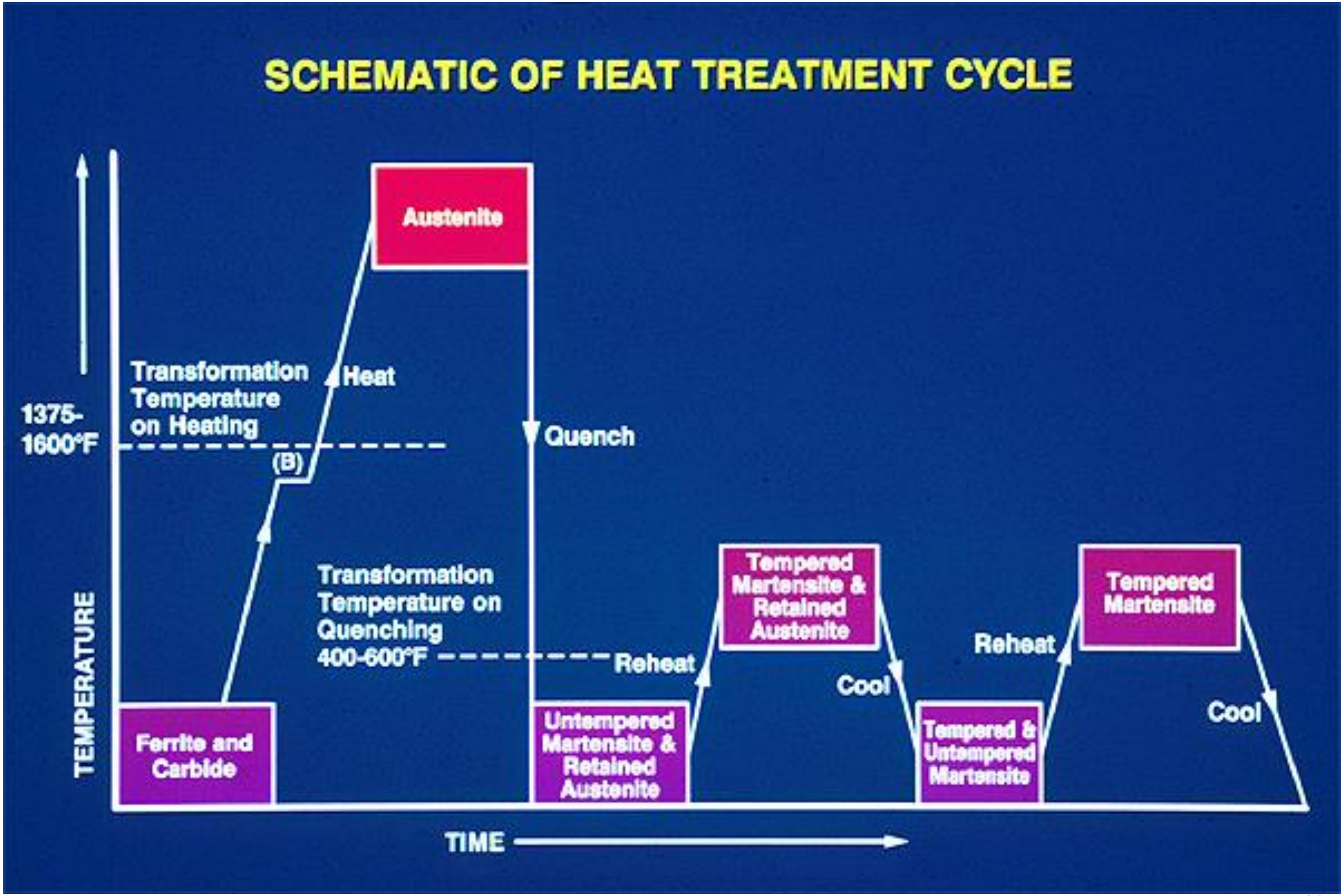
Heat Treatments - Thermal Hardening

SHAPE DISTORTION



Relative Volume Enlargement effected by the Carbon Content

Focus on Steel – Localized Hardening



Differential Hardening

a method commonly used in heat treating swords and knives to increase the hardness of the edge without making the whole blade brittle.

To achieve this, the edge is cooled faster than the spine by adding a heat insulator to the spine before quenching or by carefully pouring water onto the edge of a blade.

Focus on Steel – Localized Hardening

jian **(劍) (7th century BCE)**

Focus on Steel – JIAN, the sword of wisdom

The figure on the lower left,
Lü Dongbin,
one of the Taoist immortals,
wears a jian on his back,
referred to as
the sword of wisdom.

"The Eight Immortals Crossing the Sea."

Differential Tempering

An inverse method,
which originated with the broadswords of Europe.

Differential tempering is obtained
by quenching the part uniformly,
then tempering one part of it.

This is usually done with a directed heat source.
The heated portion of the metal is softened by this process,
leaving the non-heated part at the higher hardness

Focus on Steel – Differential Hardening

In modern times,
we can quickly heat steel to red-hot
in a localized area and then quench.

Common Techniques are:

- **Flame Hardening**
- **Induction Hardening**
- **Laser Hardening**

These techniques are based on pure thermal procedures
However, there are also others

Heat Treatments
Surface (Case) Hardening

Carbon > 0,3 weight %

THERMAL HARDENING

- **Induction hardening**
- **Flame hardening**
- **Laser hardening**
- **Electron beam hardening**

Carbon < 0,3 weight %

THERMO-CHEMICAL HARDENING

- **Carburization**
- **Nitriding**

Heat Treatments - Thermal Hardening

Carbon > 0,3 weight %

Process steps:

- **AUSTENITIZATION**

a) Heating-up the case

T °C > Transition temperature A_{C3} ~ 880°C - 950°C

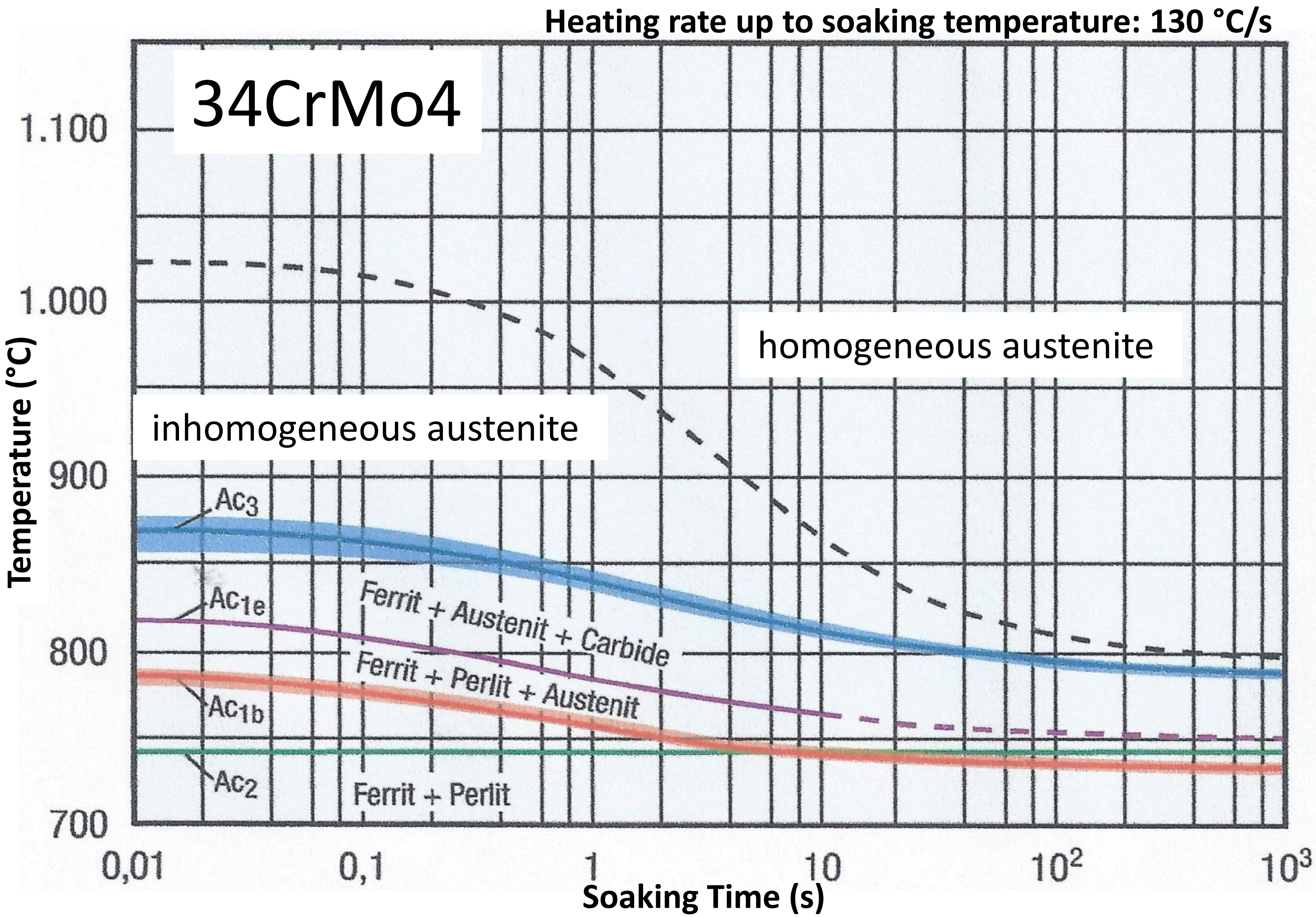
Case hardened depth ~ length of local heating

b) Soaking above transition temperature A_{C3}

Soaking time t ~ diffusion time of C in γ-austenite

~ grain size of austenite

Heat Treatments - Thermal Hardening



Isothermal Time-Temperature-Austenitization TTA-Diagram

Carbon > 0,3 weight %

Process steps:

- **Quenching**

  Formation of martensite hardened by interstitial C

  Parameter: ***Cooling rate ΔT/sec***

  Martensite start temperature M_i

  Martensite finish temperature M_f

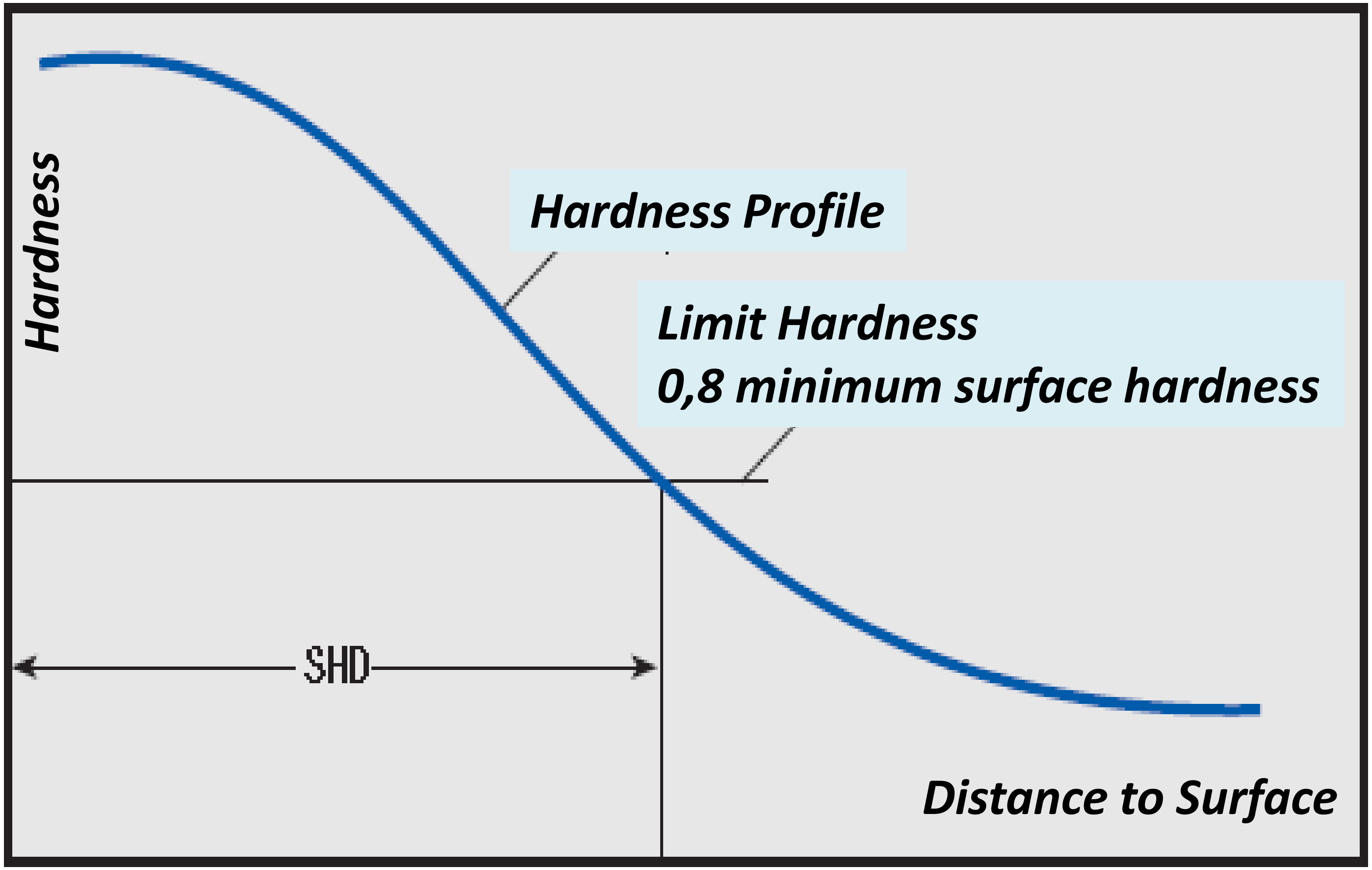
  Base alloy

  Carbon weight%

- **Tempering**

  When indicated, reduction of embrittlement

Heat Treatments - Thermal Hardening



Definition of Surface Hardened Depth SHD

Focus on Steel – Thermal Hardening

Thermal Methods of Hardening by Comparison

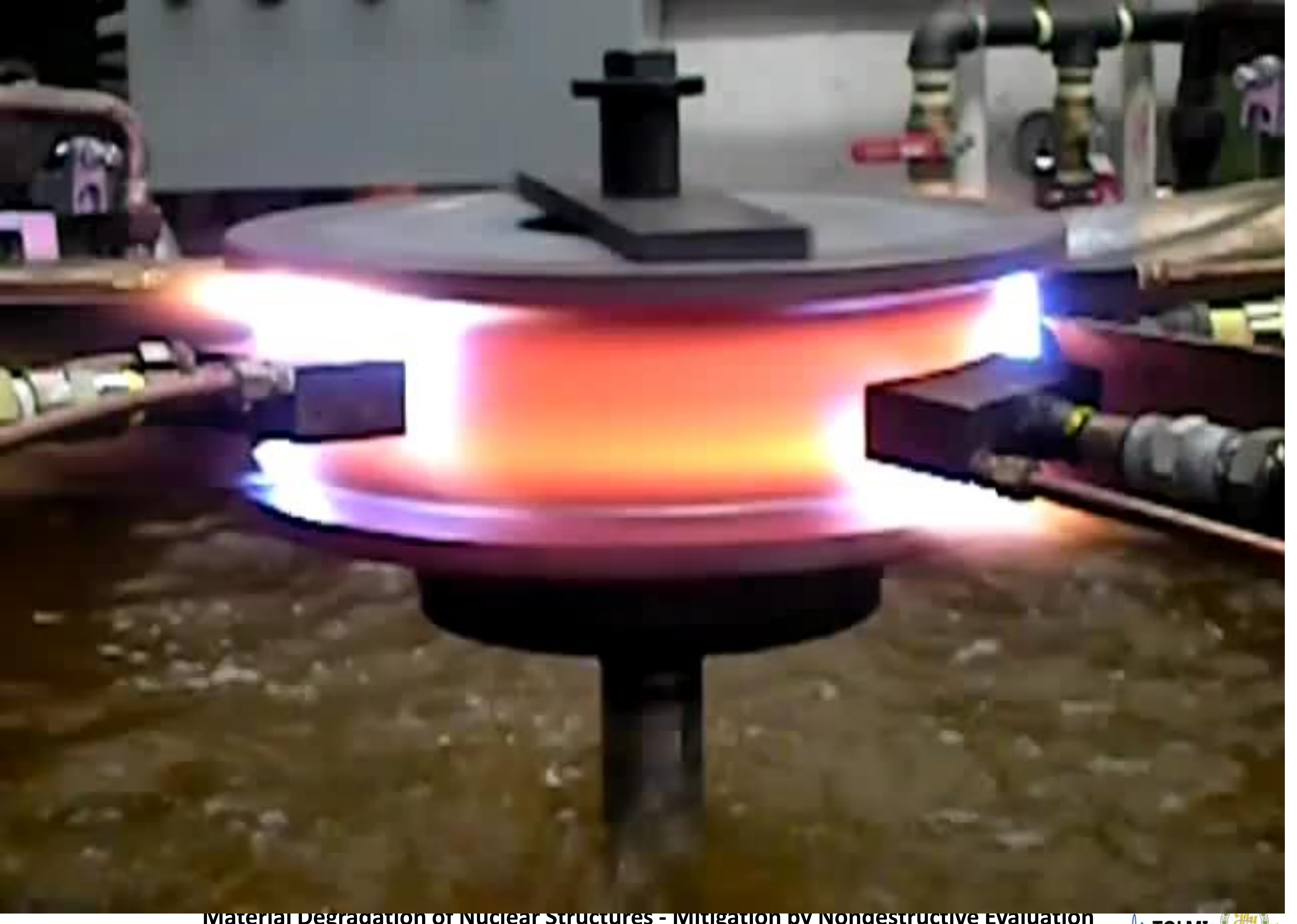
FLAME HARDENING

METHOD	*ADVANTAGES*	*DISADVANTAGES*
0,4% < C < 0,7% (Steel casting) Large parts Wall thickness > 15 mm	Localized hardening of functional surfaces Low technical complexity	Poor reproducibility; Ledeburite hardening at high carbon content
INDUCTIVE HARDENING		
LASER HARDENING		

Focus on Steel – Thermal Hardening

Flame Hardening

(Source: Lingenhöle Technologie GmbH, Feldkirch, Austria)



Focus on Steel – Thermal Hardening

Thermal Methods of Hardening by Comparison

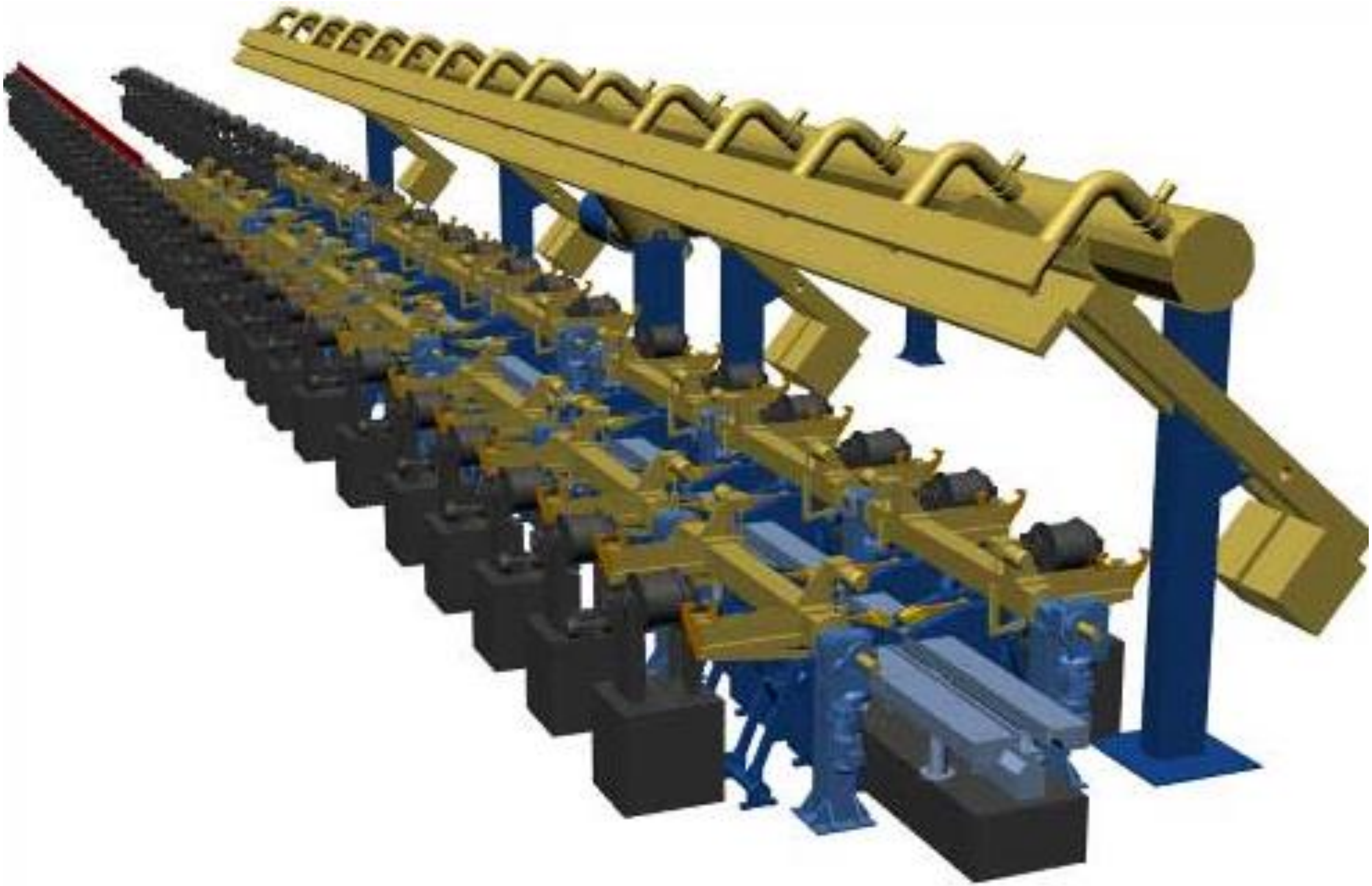
INDUCTIVE HARDENING

METHOD	*ADVANTAGES*	*DISADVANTAGES*
FLAME HARDENING		
Mass Production **C > 0.3%**	**Short Austenitization Times** **High operational capacity** **Automated process** **Low shape distortion**	**Design modification of inductor for the specific part geometry**
LASER HARDENING		

Focus on Steel – Thermal Hardening

System for Inductive Hardening of Crankshafts

Focus on Steel – Thermal Hardening



System for Inductive Hardening of Rails (Source: TEC Tomsk)

Focus on Steel – Thermal Hardening

Inductive Hardening of Rails (Source: TEC Tomsk)

QUALITY AWARENESS

CONTINUING PROCESS MONITORING & FEEDBACK

Fault Conditions

- ***Material State***
  - Coarse grain microstructure of the hardened surface layer with irregular local scatter of hardness
  - Tempered fine grain microstructure of the core material
- ***Interface hardened zone – core***
  - hardening depth too small
  - local variations of hardening depth

QUALITY AWARENESS

CONTINUING PROCESS MONITORING & FEEDBACK

ERROR SOURCES of INDUCTION HARDENING PROCESS

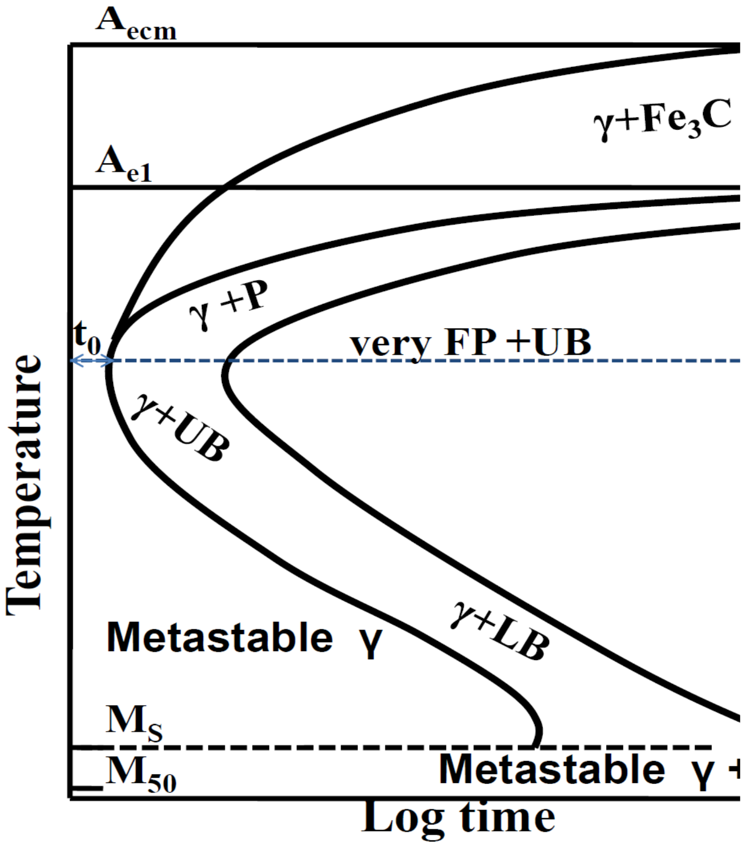
- ***Material state***
  - ***Coarse grain***
- ***Local scatter of heating***
  - ***Lift-off effects***
  - ***Power fluctuations***
  - ***Manipulator caused irregularities***
  - ***Magnetic inhomogeneity (permeability variations)***
- ***Inaccurate temperature control***
  - ***Soaking time too short***
  - ***Austenitization temperature suboptimal***

QUALITY AWARENESS

CONTINUING PROCESS MONITORING & FEEDBACK

ERROR SOURCES (continued)

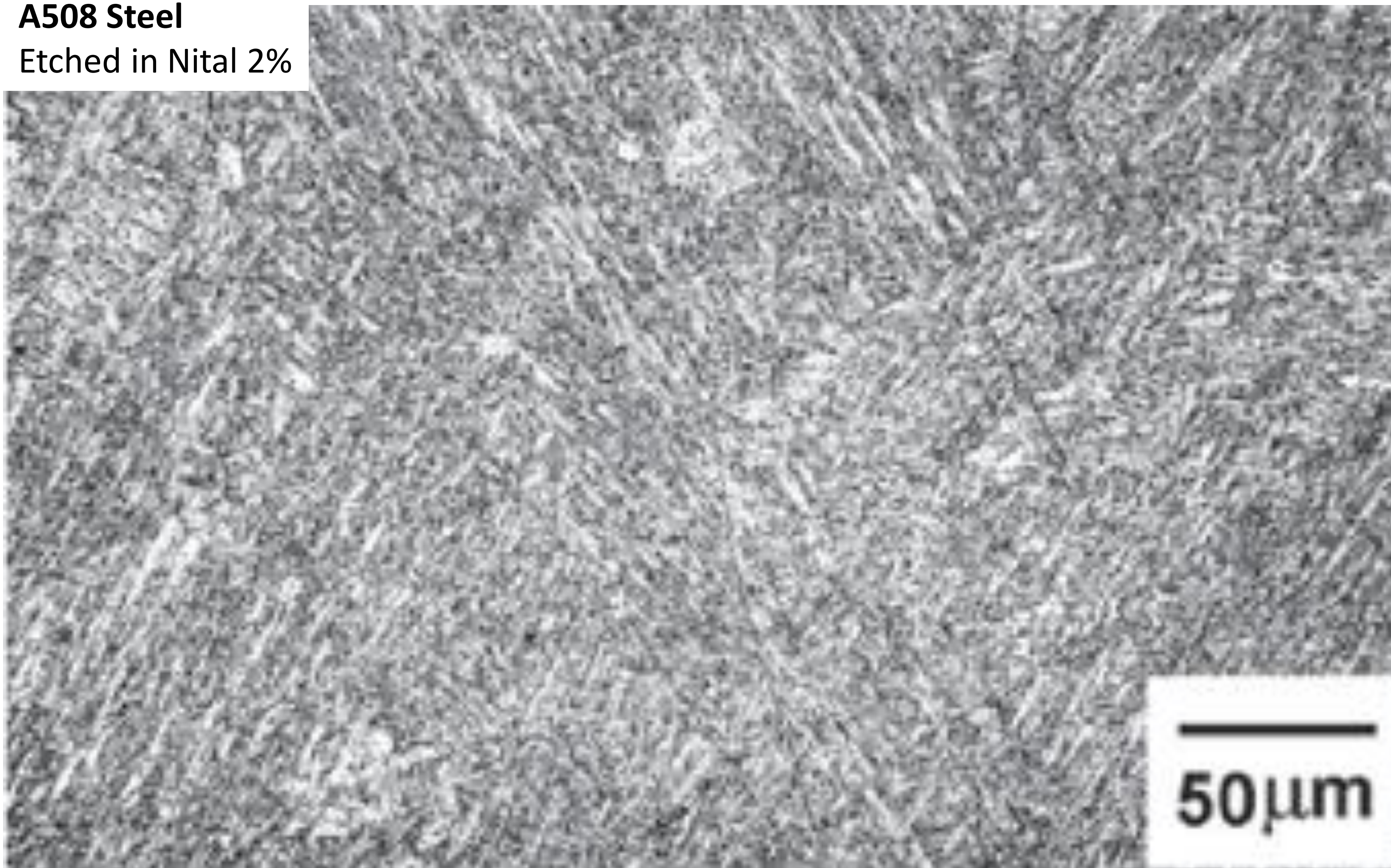
- ***QUENCHING***
  - *- too slow*
  - *- inadequate account of part geometry*
  - *- inadequate self-quenching*



Micrographs of faulty inductive hardened edge layers

MARTENSITE

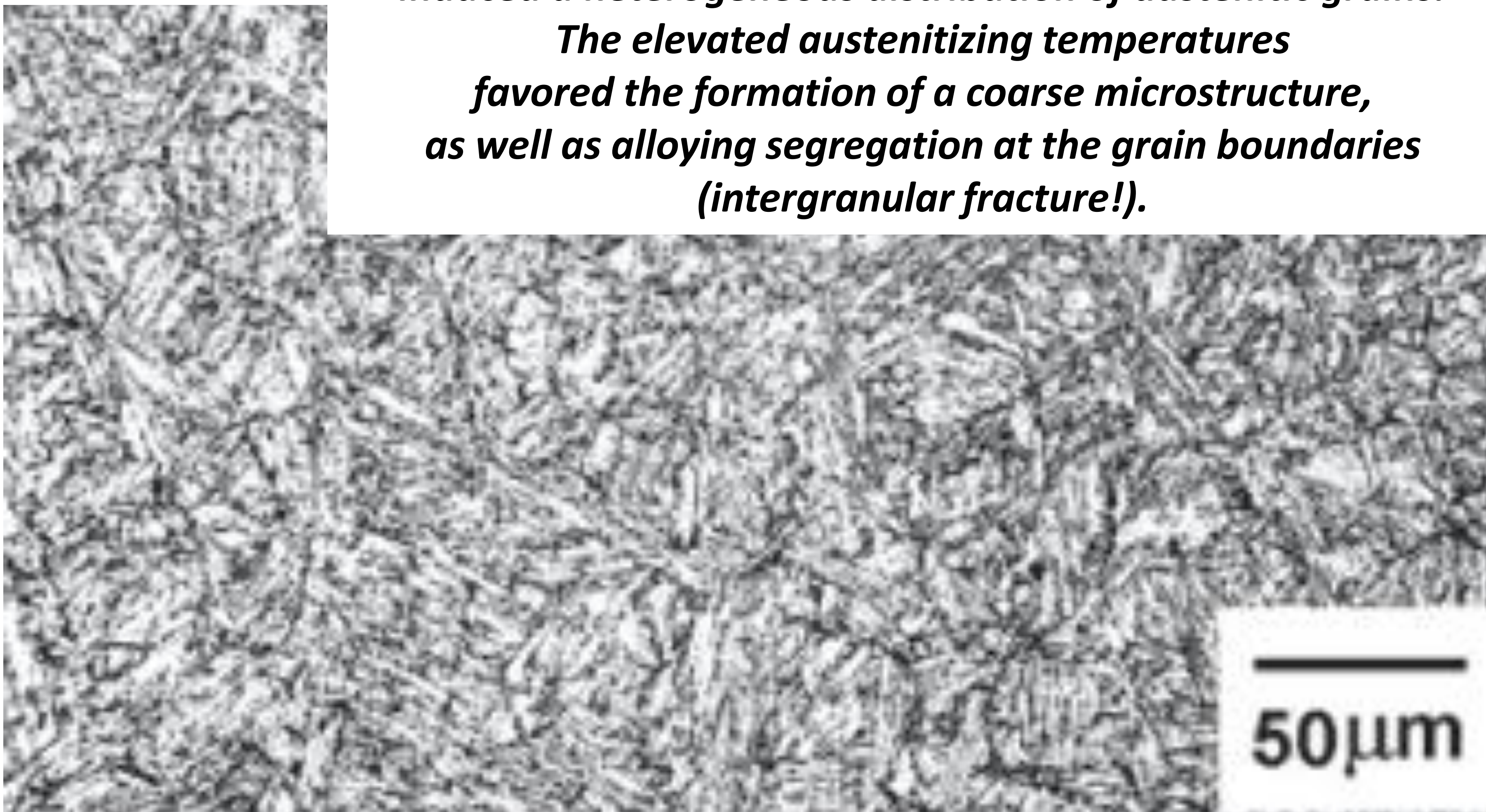
A508 Steel
Etched in Nital 2%



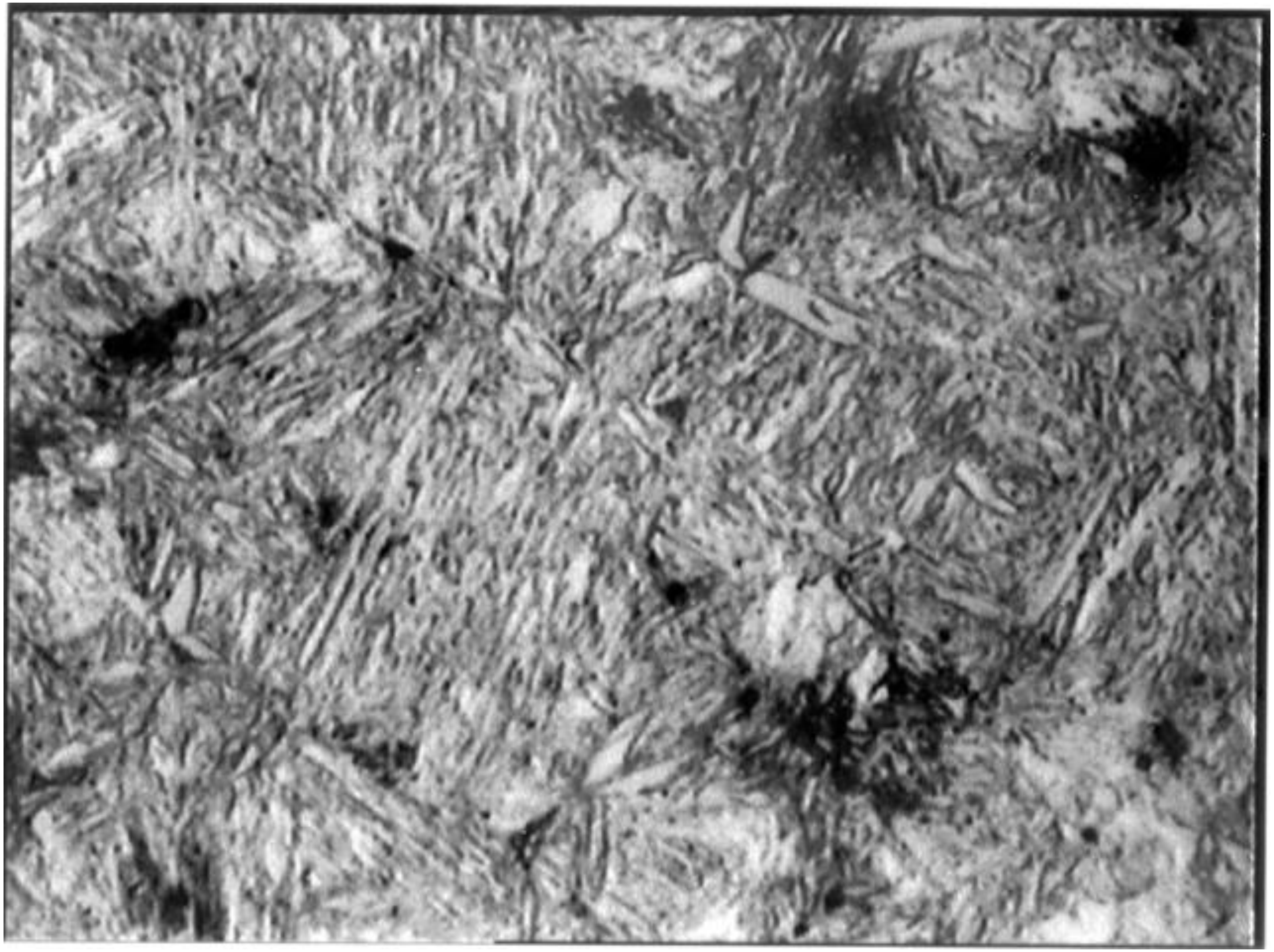
MARTENSITE

A508 Steel
Etched in Nital 2%

Partial recrystallization during discontinuous cooling,
induced a heterogeneous distribution of austenitic grains.
The elevated austenitizing temperatures
favored the formation of a coarse microstructure,
as well as alloying segregation at the grain boundaries
(intergranular fracture!).



MARTENSITE



Steel 0,35 % C, quenched from 870 °C

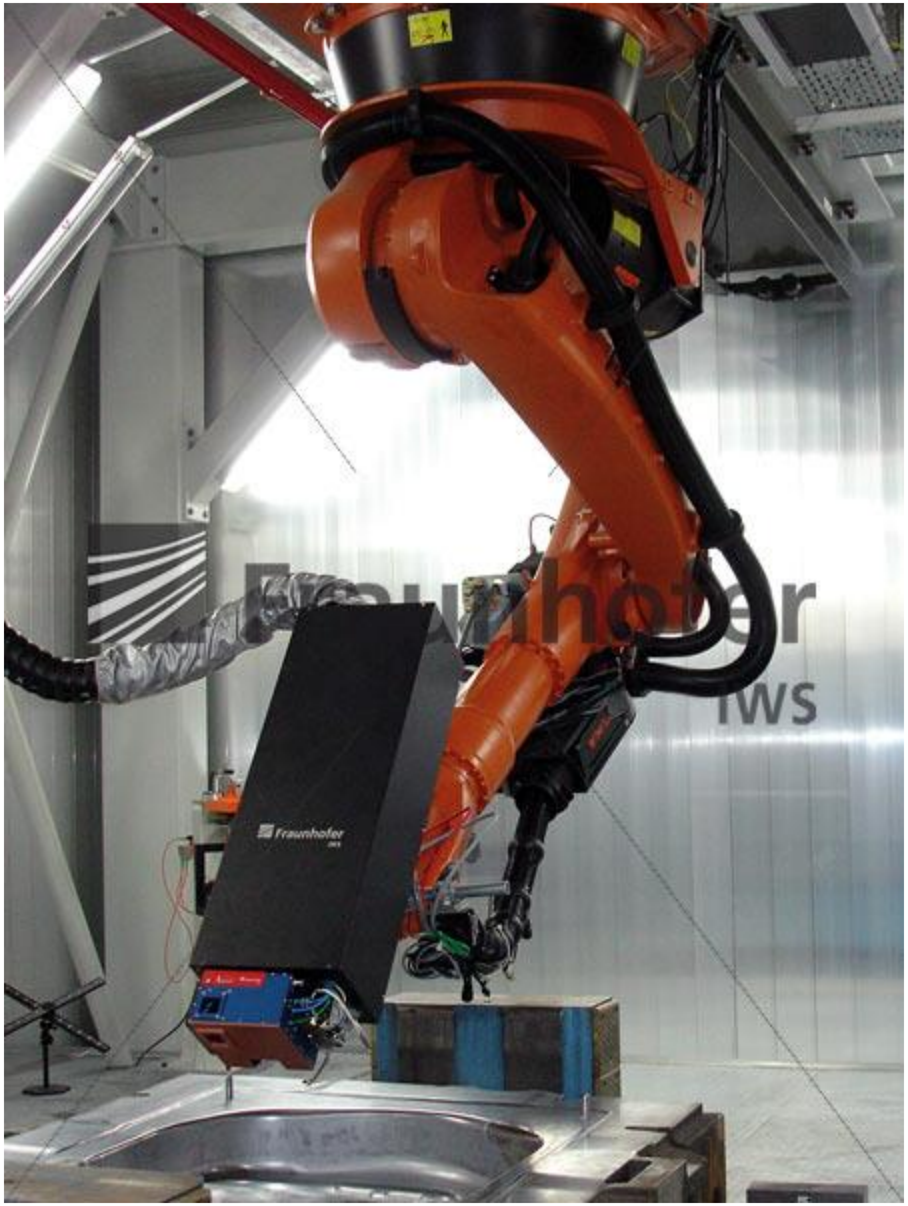
Focus on Steel – Thermal Hardening

Thermal Methods of Hardening by Comparison

LASER HARDENING

Machine parts **Tool making** **Self-Quenching**	**Exact and precisely localized hardening;** **Short process times;** **Almost no deformation;** **Hardening of complex-shaped surfaces;** **Flexible use of tool;** **Temperature controlled process with fine-grain hardened microstructure;** **no risk of contamination**	**Small track width (5mm – 20 mm)**

Focus on Steel – Thermal Hardening



LASER HARDENING TECHNOLOGY

optimized laser spot shapes and intensity profiles

For each contour to be hardened a laser spot can be generated with an appropriate width and intensity profile.

Changes can be made by commands during an ongoing hardening process.

The temperature is measured with an integrated camera system.

60 mm wide hardening tracks are possible with the available 6 kW laser power.

Focus on Steel – Thermal Hardening

TECHNOLOGY

Laser Hardening System with a Hardened Component (ERLAS GMBH)

Thermal Methods of Hardening by Comparison

ELECTRON BEAM HARDENING

METHOD	*ADVANTAGES*	*DISADVANTAGES*
FLAME HARDENING		
INDUCTIVE HARDENING		
LASER HARDENING		
High demand hardening Hardening depth: 0.1 – 1.0 (1.5) mm Main application areas: Automotive Machine construction Medical technology Aerospace	The electron beam is a very efficient tool characterized by its great precision for a controlled hardening process It can be combined with other thermo-chemical hardening processes, such as nitrifying, to increase wear resistance.	Complex and expensive equipment

Thermal Methods of Hardening by Comparison

THE ELECTRON BEAM SURFACE MODIFICATION

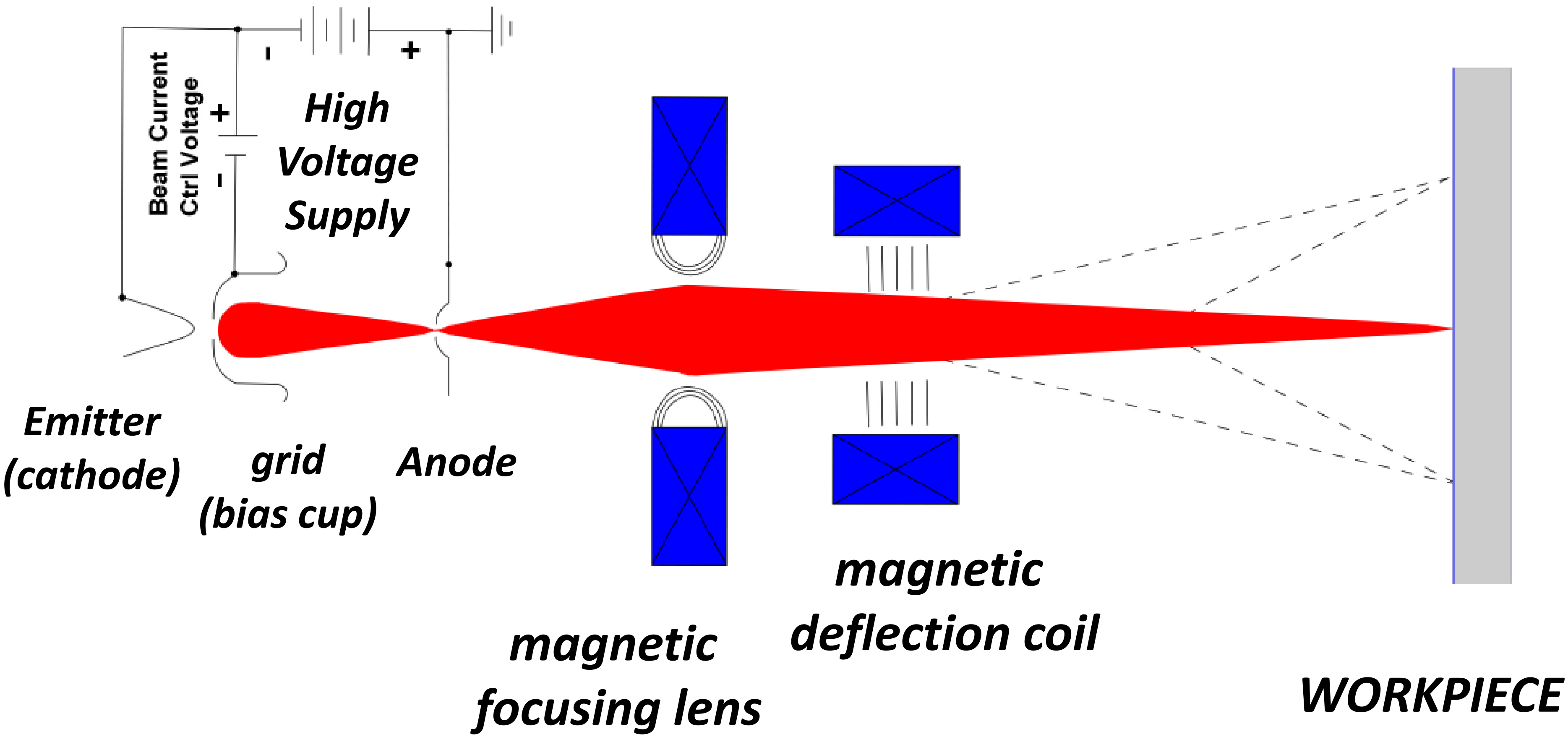
A narrow boundary layer (typically 0.1 – 3 mm) is heated up above the austenitic temperature and rapidly cooled down again. The process of rapid heat absorption into the surrounding cold mass is referred to as self quenching. This self quenching requires no other medium for cooling, in comparison to other procedures. High temperature gradients are achieved because of the very high power-density of the electron beam. The heat is applied locally in a very short time – typically in milliseconds. Very little heat flows away into boundary zone; therefore the body of the work-piece remains relatively cold. Electron beam hardening produces less deformation when compared to other methods. A fine Pearlite or hardening structure is of an advantage for the complete diffusion of carbon material due to the short time required for the formation of Austenite.

PTR PRÄZISIONSTECHNIK GMBH

ELECTRON BEAM HARDENING TECHNOLOGY

- The thickness of the energy absorption layer is proportional of square of the acceleration voltage and inversely proportional to density of material
- Typical acceleration voltages of the beam range from 60 to 150 kV and typical electron range values are 10 to 50 μm
- By accurately controlling acceleration voltage, depth of hardening can be precisely controlled throughout the process
- Beam focusing and guidance is done by electromagnetic coils
- Precise application of the energy with respect to workpiece location is thus possible

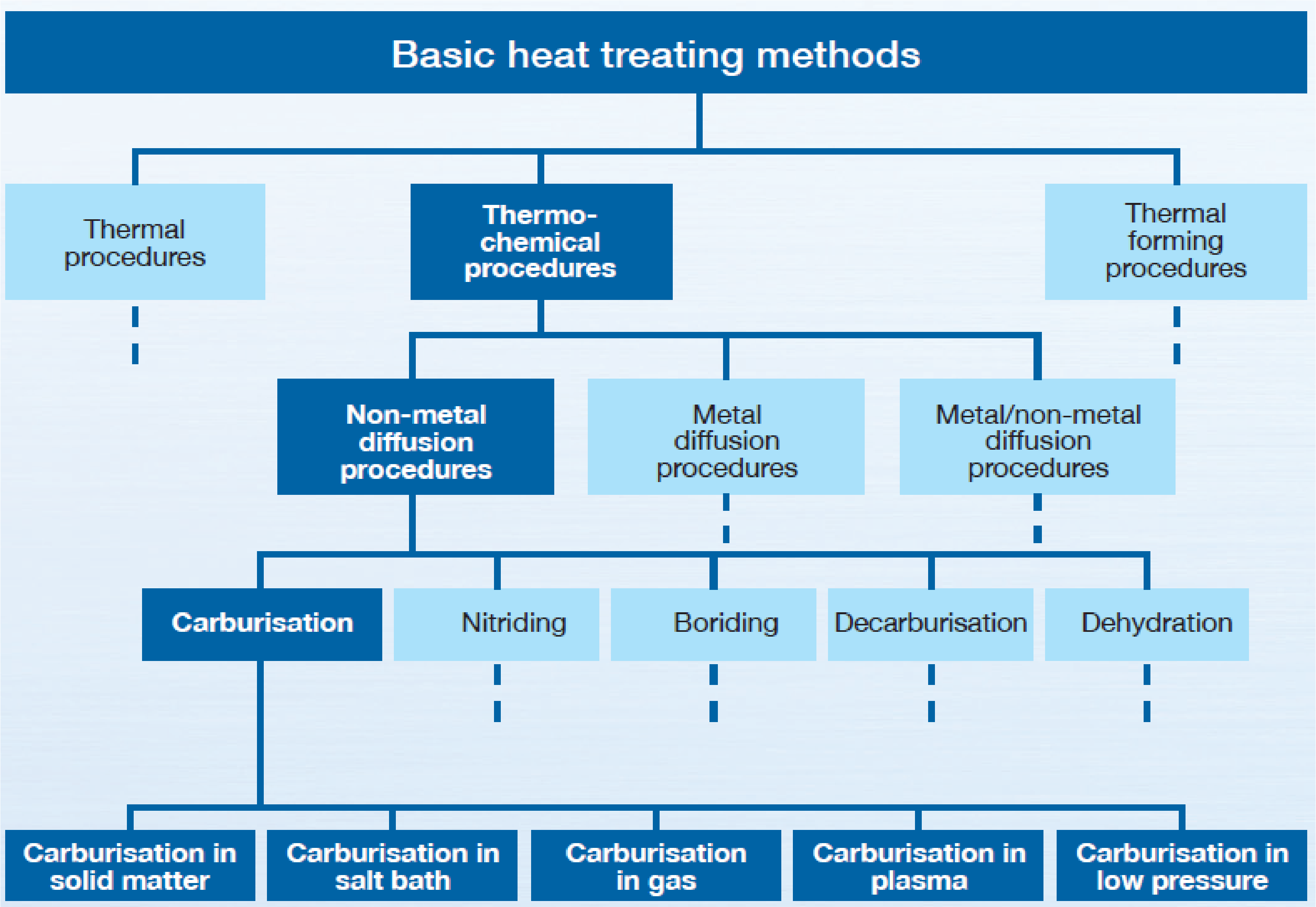
Focus on Steel – Electron Beam Hardening
TECHNOLOGY



Focus on Steel – Thermal Hardening

ELECTRON BEAM HARDENED PARTS

Heat Treatments
Surface Hardening



CASE HARDENING OBJECTIVES

Edge Hardening of Tough Steels with Low Carbon Content (<0.3 weight%)

Parts with ductile core and wear-resistant surface (drive parts and toothed wheels)

- ✓ Increasing the wear resistance with enhanced surface hardness
- ✓ Raising the load carrying capacity
- ✓ Improving the bending strength and the excessive load allowance with tough core material
- ✓ Improving the fatigue strength

Rule of thumbs: Case hardening depth is a function of time to the second

Steels with Carbon Content < 0,3 weight%

Process Steps

- **CARBURIZING**

  At temperatures of 880°C < T < 950°C (Austenite)

  Diffusion process → Carbon content gradient at the surface

- **HARDENING**

  Quenching;

  typical case hardening depth range: 0,1 mm < CHD < 4,0 mm
  The enlarged volume of martensitic edge case cause (desirable) residual compressive stress

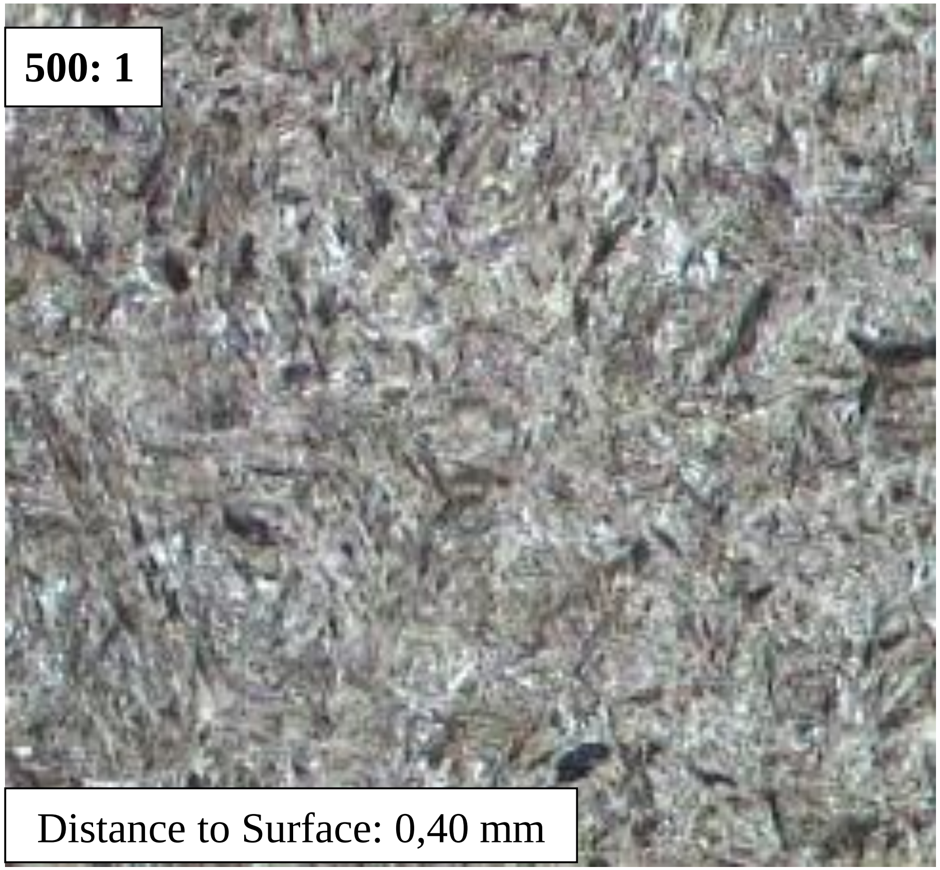
- **RAISING DUCTILITY**

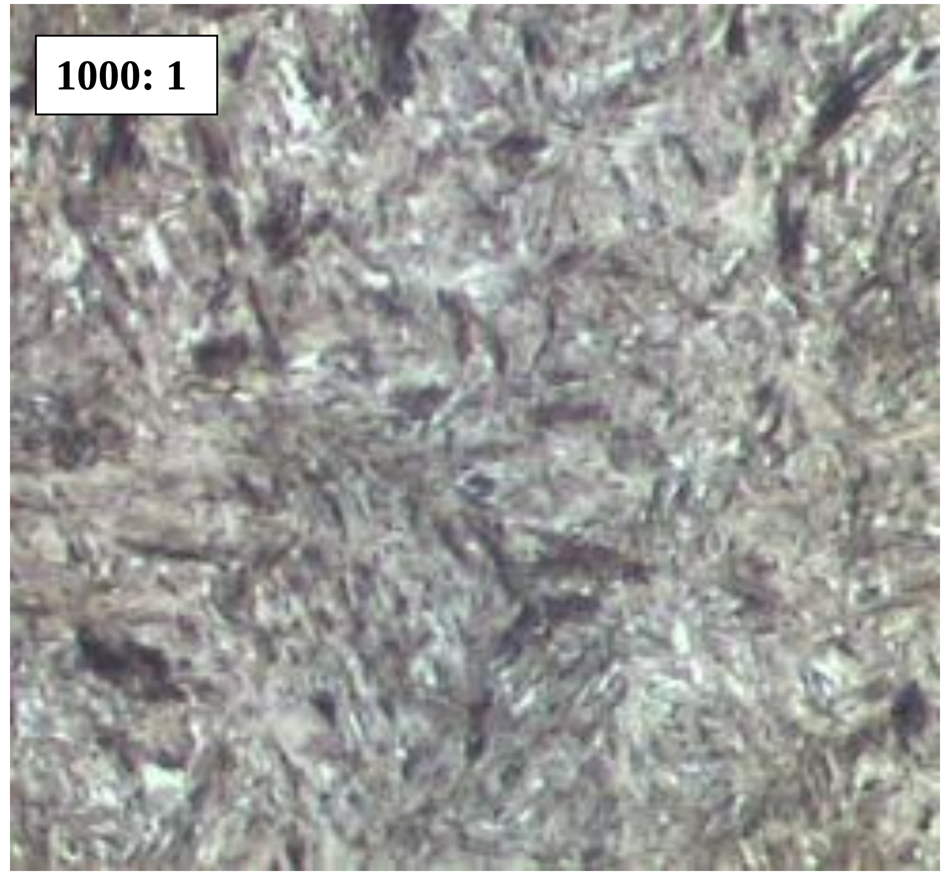
  Tempering improve ductility of

  extremely hard and brittle edge martensitic microstructures

CASE HARDENING

Martensite with low amount of residual austenite (about 2%)





Typical Case Hardened Carburized Edge Microstructure

Process Steps

- **ANNEALING**

below tempering temperature at about 500°C
in nitrogen releasing environment (salt bath, nitriding furnace)

- **HARDENING**

Nitrogen diffuses into the edge zone (a few tenth of mm thick)
Formation of extremely hard metal nitrides

Achievable hardness up to 1,200 HV
(highest achievable hardness for steels)

Nitriding

a heat treating process that diffuses nitrogen
into the surface of a metal to create a case hardened surface

The significant advantage of nitriding is
that the case hardness is developed without quenching
and the attendant distortion problems.
Finishing operations can be eliminated
or held to a minimum.

Nitriding is most commonly used on
low-carbon, low-alloy steels,

HARDENING BY FORMATION OF METAL NITRIDES

*Literature on Nitrogen in Steels: www.keyto**metals**.com/page.aspx?ID...site=kts...*

Nitriding - Advantages

Surfaces are highly wear resistant with anti-galling properties,
Surface hardness is resistant to softening by temperature (< process T)
Improved fatigue life and corrosion resistance
The nitrogen diffusion takes place at relatively low temperatures
(typical process temperature is 975 F),
the hardening occurs without quenching.

Core properties are not affected by the nitriding process
provided the final tempering temperature for the product
was higher than the nitriding process temperature.

*Literature on Nitrogen in Steels: www.keyto**metals**.com/page.aspx?ID...site=kts...*

Heat Treatments - Thermal Chemical Hardening
NITRIDE HARDENING OF NITRIDING STEELS

(EN 10085)
Heat-treatable Steels with Nitride Forming Alloy Elements
(Chromium, Molybdenum, Aluminum)

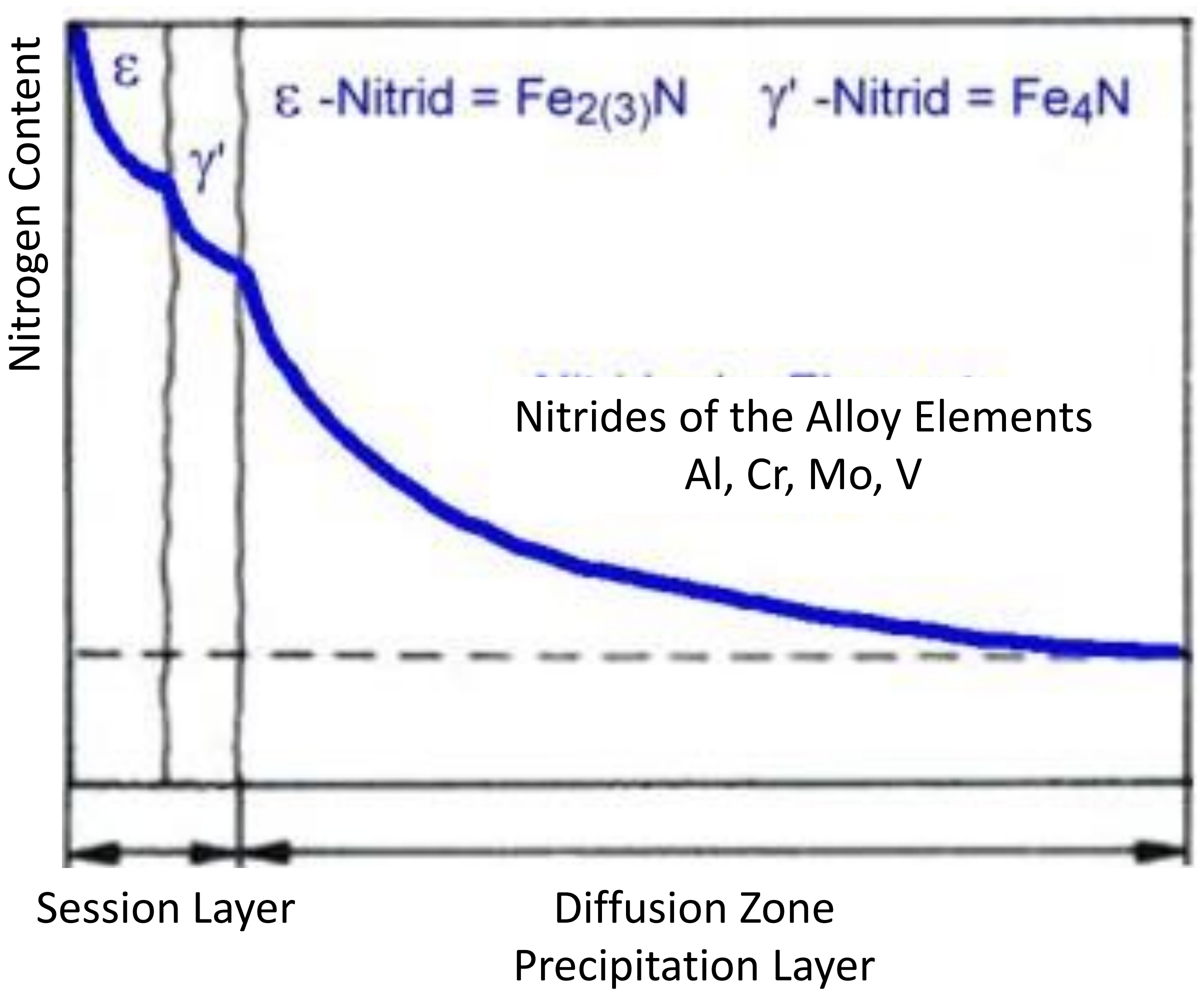
Work pieces with ductile core and wear resistant surface

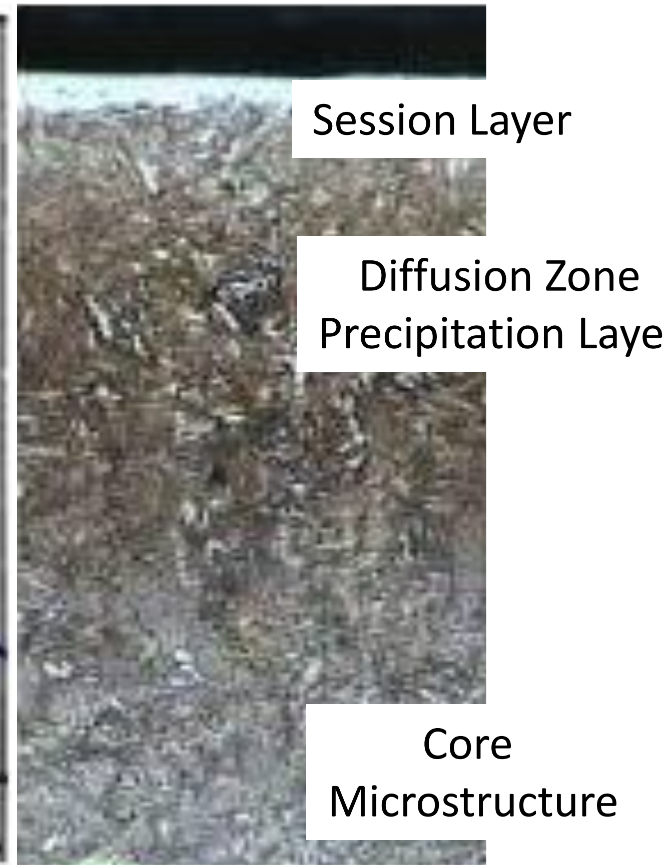
- ✓ **Extremely high case hardness**
- ✓ **Highly resistant against wear**
- ✓ **Low coefficient of friction**
- ✓ **High loading capacity**
- ✓ **Tough core Improves bending fatigue strength and excessive load tolerance**
- ✓ **Highly corrosion resistant**
- ✓ **Improved fatigue strength**
- ✓ **Use at elevated temperatures**
  (thermal stability of nitrides: tempering temperature > 400°C)

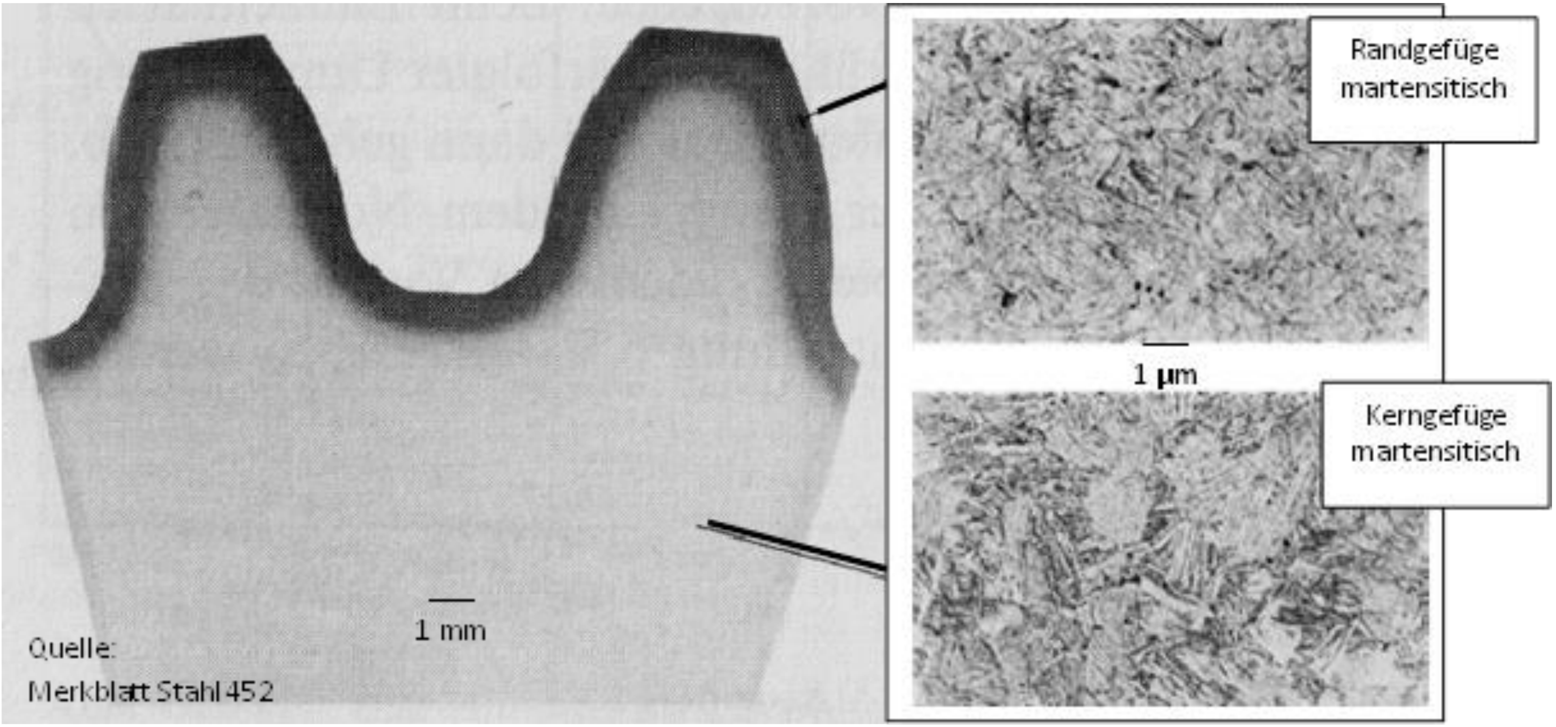
Expensive Production of Nitriding Steels

Heat Treatments - Thermal Chemical Hardening
Nitriding Hardening

STRUCTURE OF NITRIDE LAYER

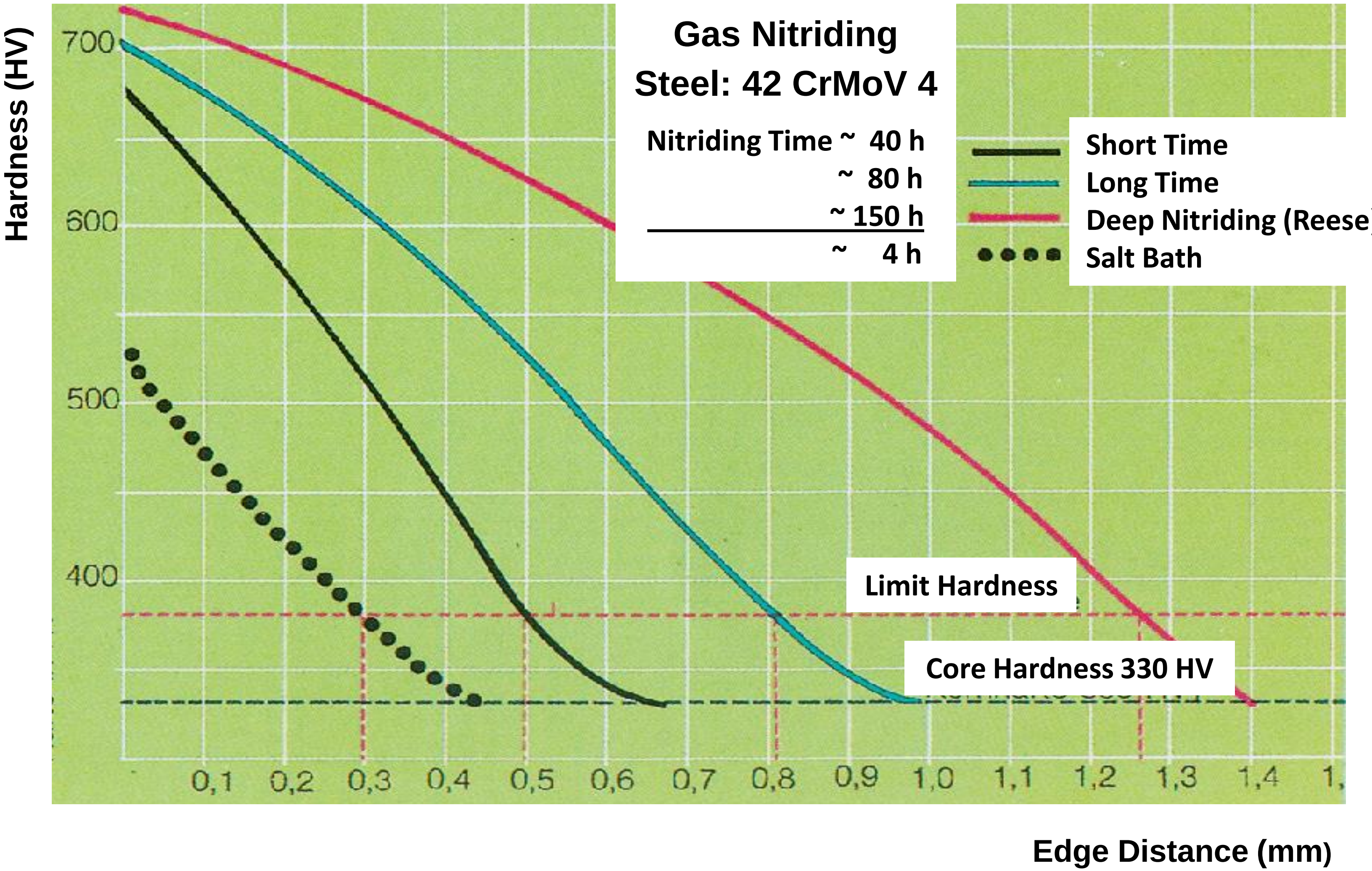






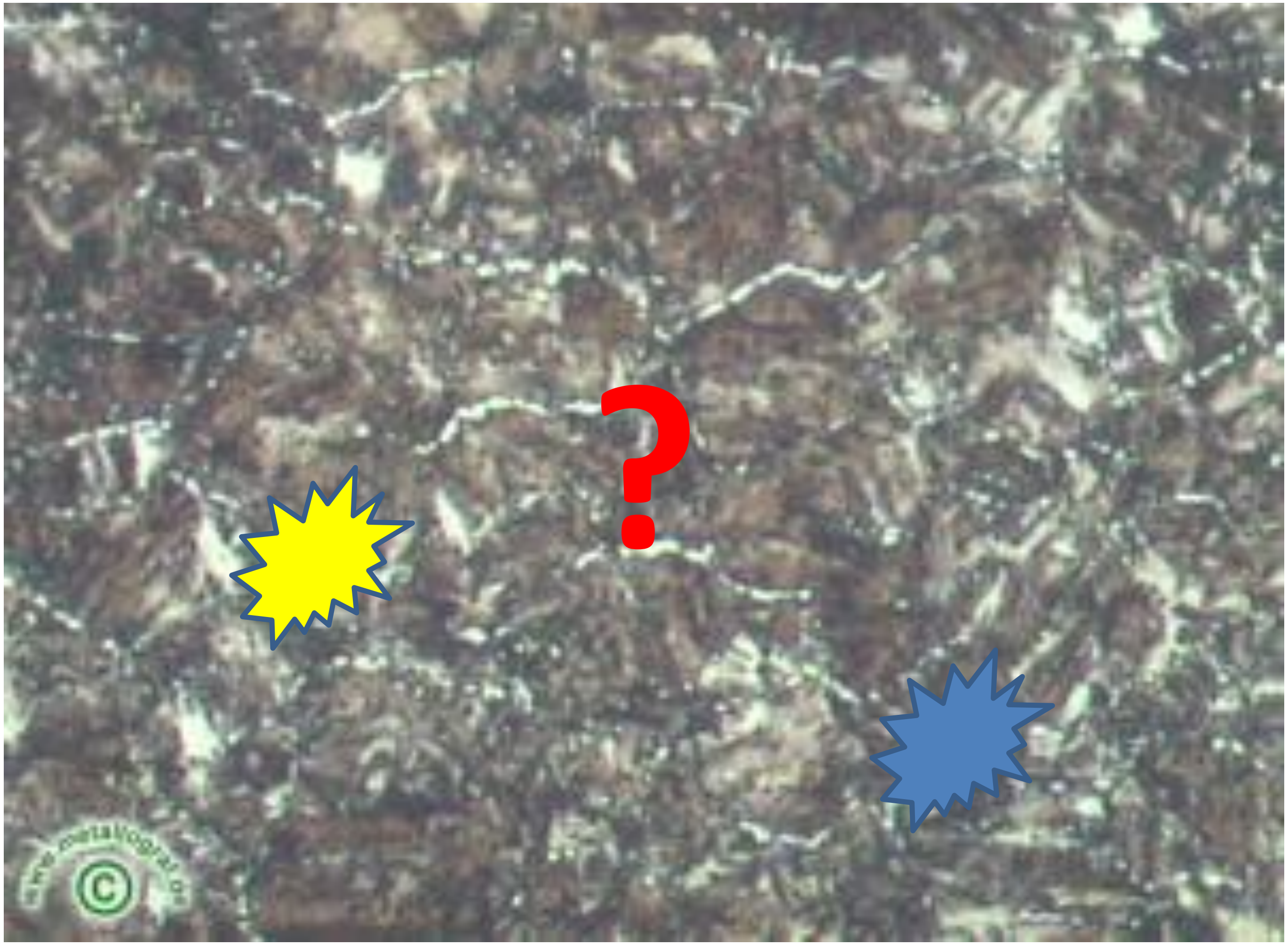
Gefüge von einem randschichtgehärteten Zahnrad

NITRIERHÄRTEN



Effect of Nitriding Time on Surface Hardness and Hardness Depth
(Source: Merkblatt Stahl 447)

NITRIERHÄRTEN



Diffusionszone mit Karbidausscheidungen

Focus on Steel – Localized Hardening

Differential tempered steel

Focus on Steel – Localized Hardening

P 3121

Ultrasonic testing instrument for non-destructive
hardness depth testing of heat-treated parts