ADI – The New Prospective Material for Designer and mechanical Engineers

Adel Nofal

Department of Foundry Technology,

Central Metallurgical R&D Institute (CMRDI),

Cairo, Egypt

CONTENTS

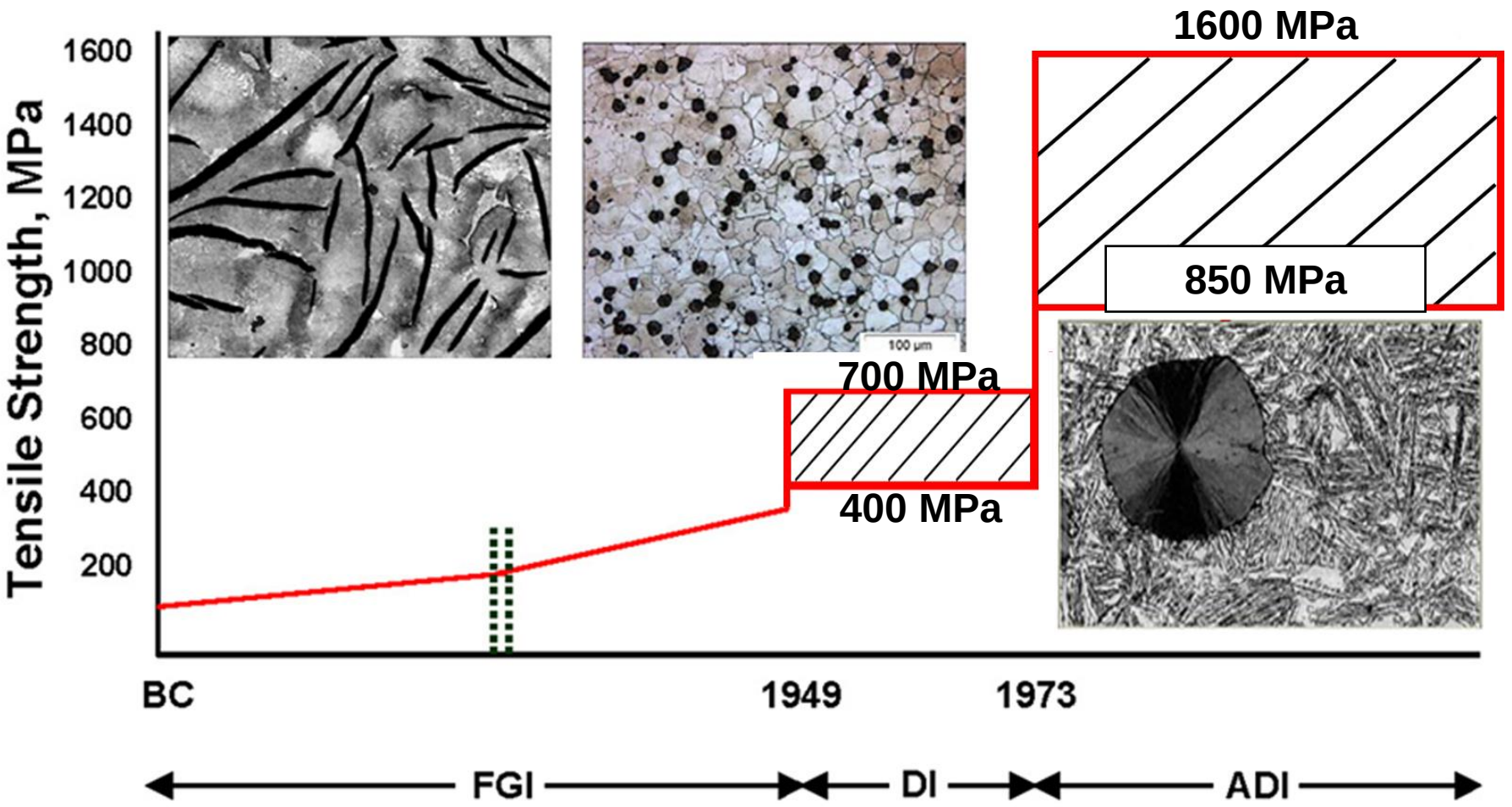
1. Introduction
2. Strengthening Mechanisms: (The Mystery of ADI)
3. Enhancement of Strength properties
4. Abrasion Resistance Enhancement Techniques
5. Machining and Machinability of ADI
6. High – Strain Dynamic Deformation of ADI

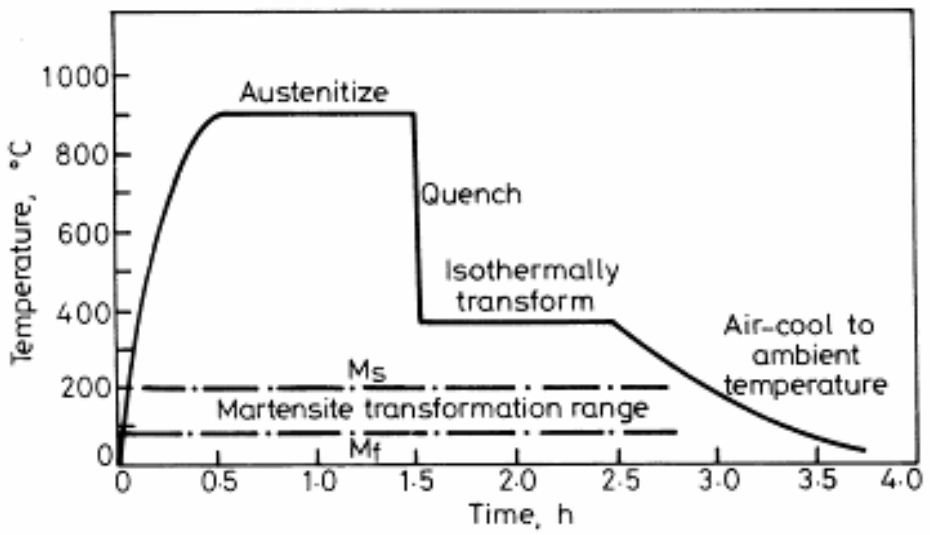
   (ADI and Ballistic Performance)
7. Corrosion Resistance of ADI
8. Weldability of ADI – a problem still to be solved

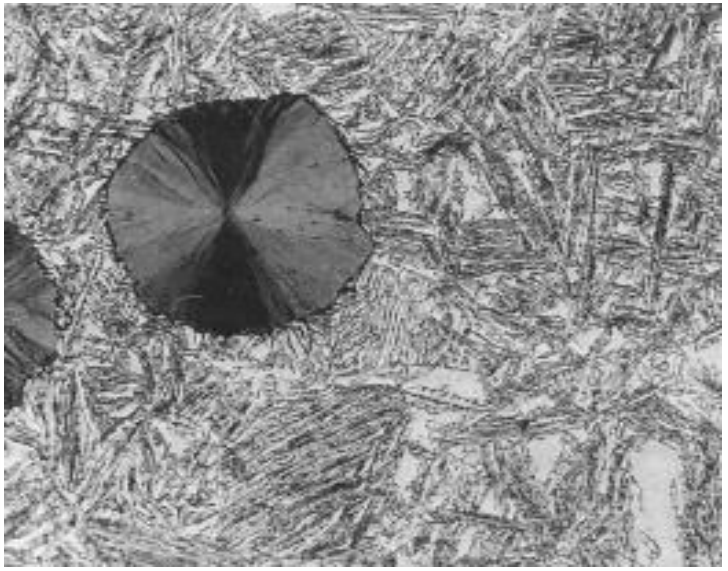
1

INTRODUCTION

Cast Iron – The New Dynamic Material

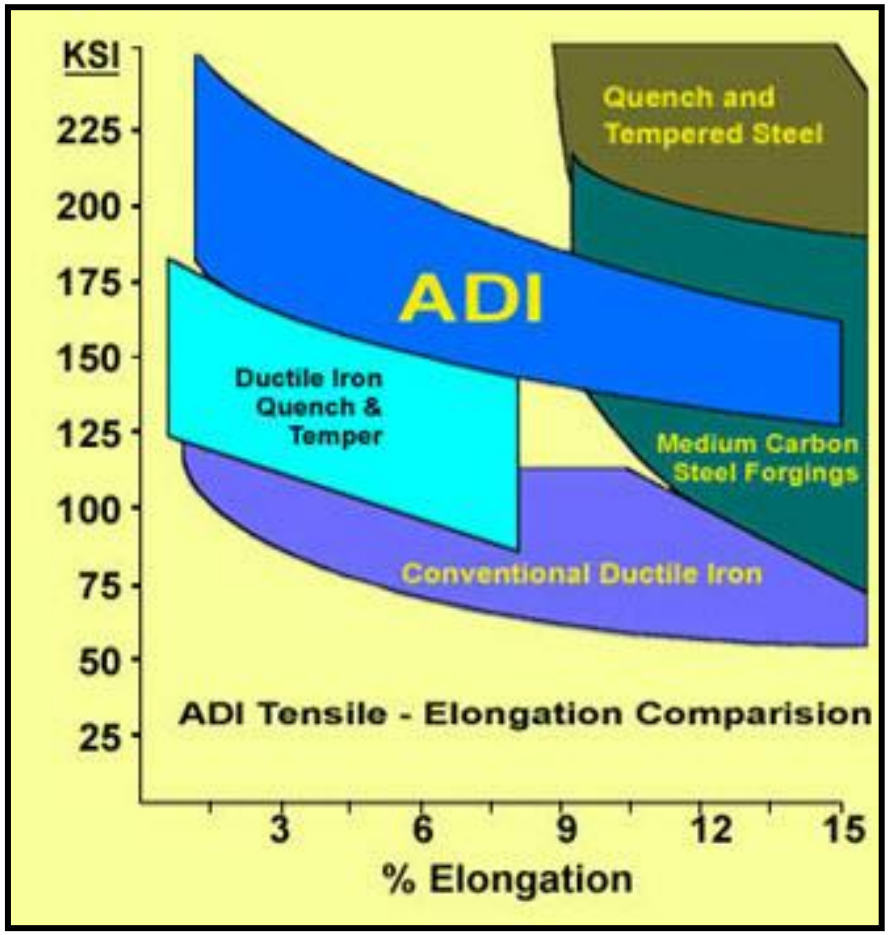






- Austempered ductile iron ADI is a relatively new engineering material with exceptional combination of mechanical properties and marked potential for numerous applications.
- The attractive properties of ADI return to its distinct and unique microstructure, which consists of fine acicular ferrite within 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)



- ADI can be twice as strong as commercial SG iron at the same level of elongation.
- ADI approaches the properties of a structural low alloy steels
- ADI exhibits excellent fatigue strength and wear resistance.

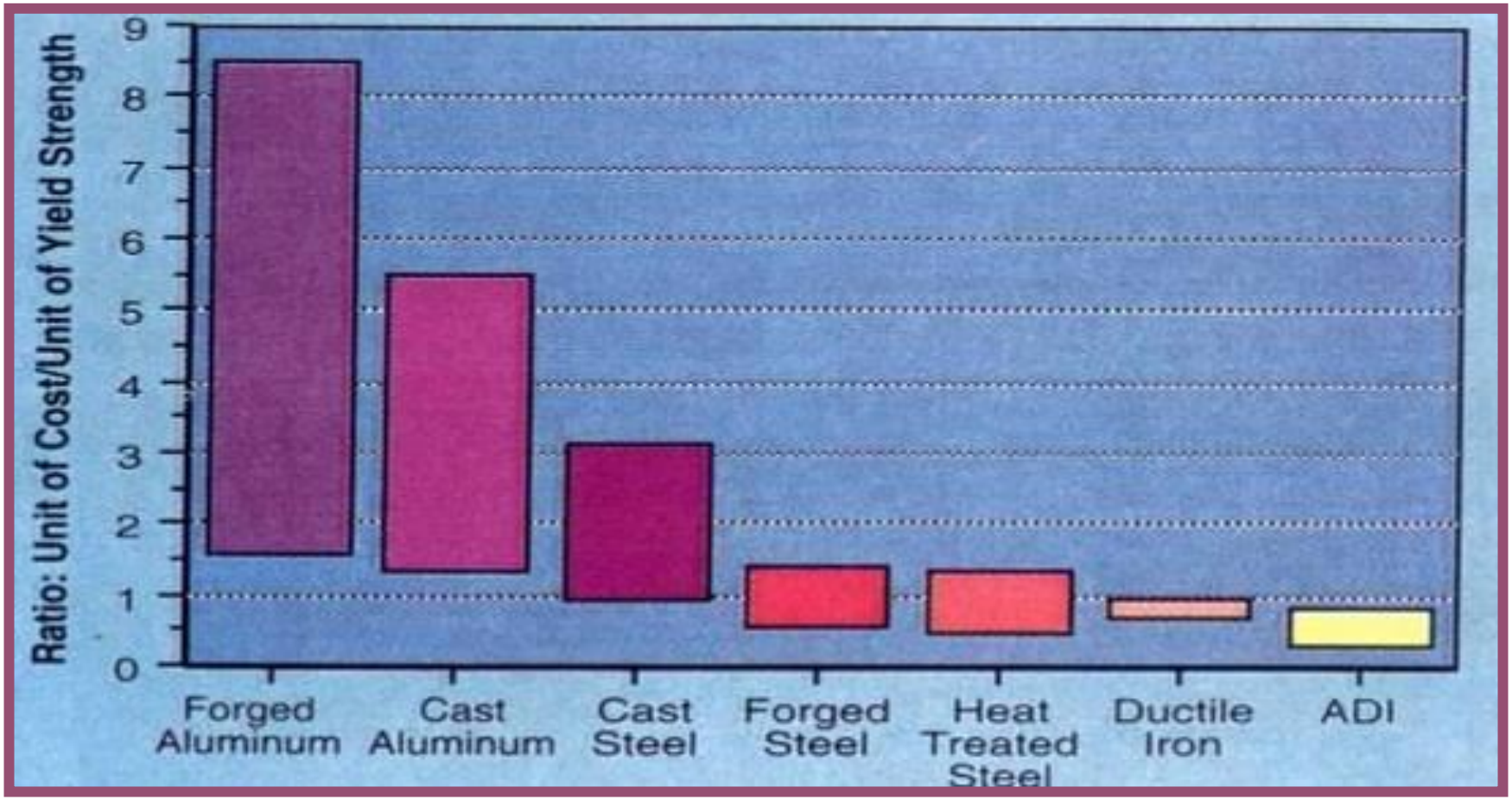
ASTM 897 Property table for ADI

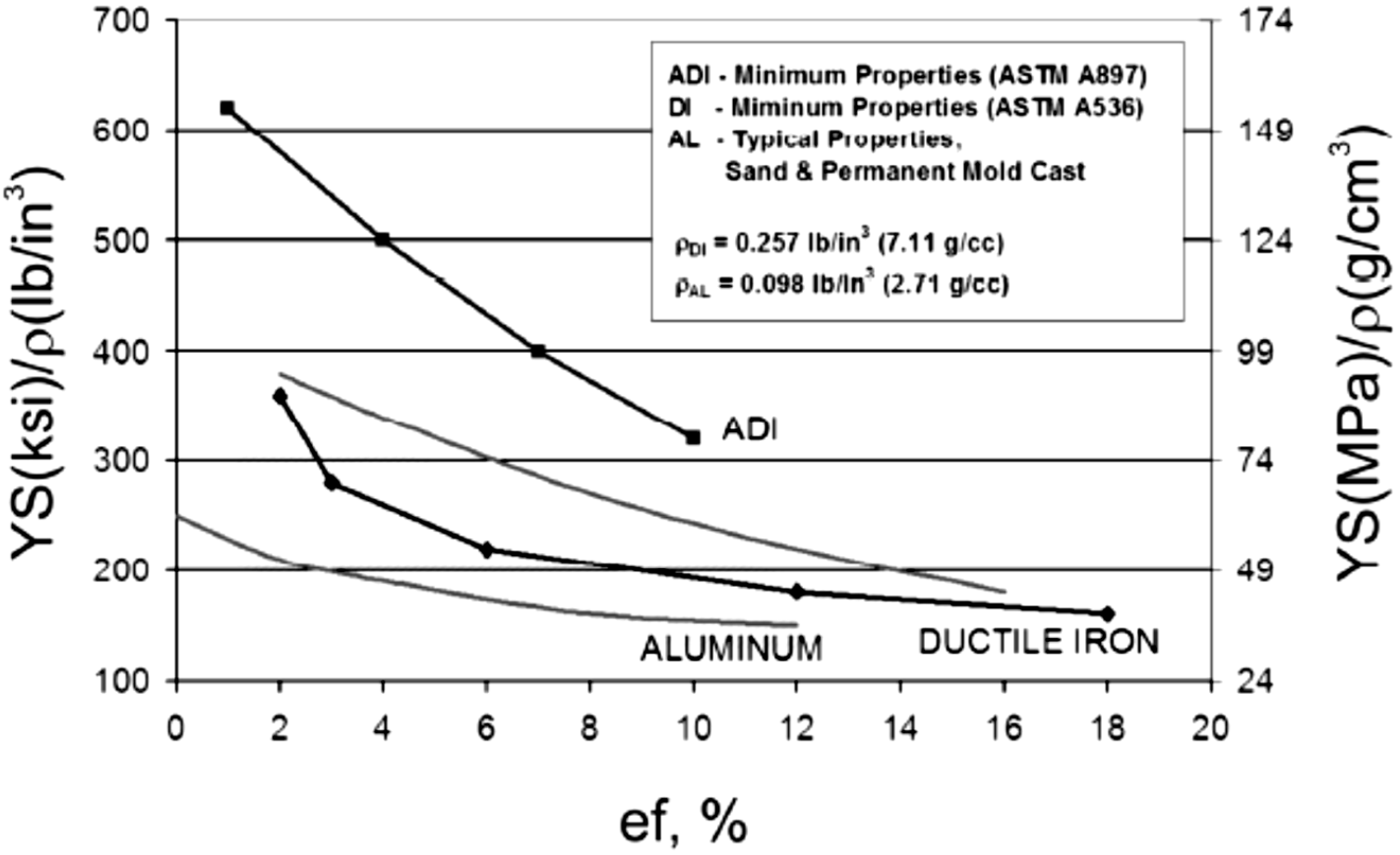
Grade	Tensile Strength (MPa/Ksi)	Yield Strength (MPa/Ksi)	Elong. (%)	Impact Energy (J/lb-ft)	Typical Hardness (BHN)
1	850/125	550/80	10	100/75	269-321
2	1050/150	700/100	7	80/60	302-363
3	1200/175	850/125	4	60/45	341-444
4	1400/200	1100/155	1	35/25	366-477
5	1600/230	1300/185	N/A	N/A	444-555

THE COMPETITIVE EDGE OF ADI



THE COMPETITIVE EDGE OF ADI



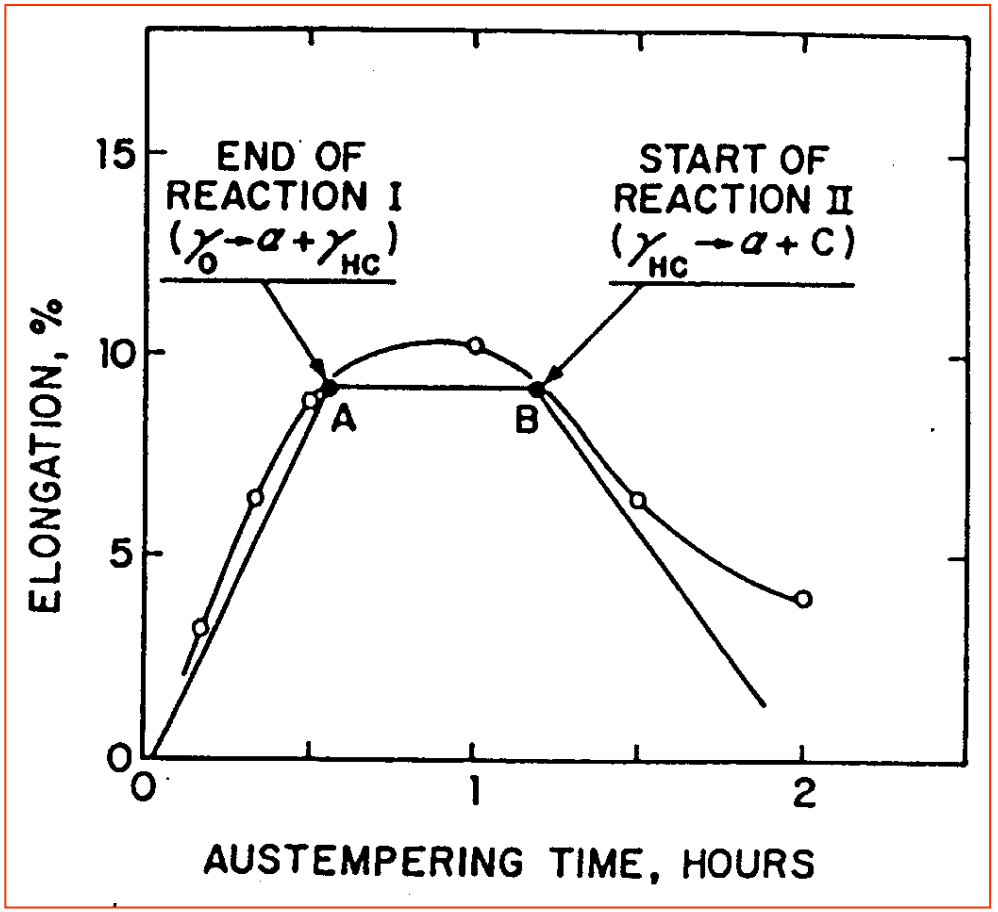


Specific yield strength – elongation relationships for typical cast aluminum alloys, ASTM A536 grades of ductile iron, and ASTM A897 grades of austempered ductile irons: a) specific yield strength(YS/ρ) to elongation, b) specific yield strength(YS/E) to elongation.

- As the austempering time is extended, the Stage II reaction eventually occurs in which the austenite decomposes to form more ferrite and carbides are precipitated: $\gamma_{HC} \rightarrow \alpha$ + carbides.

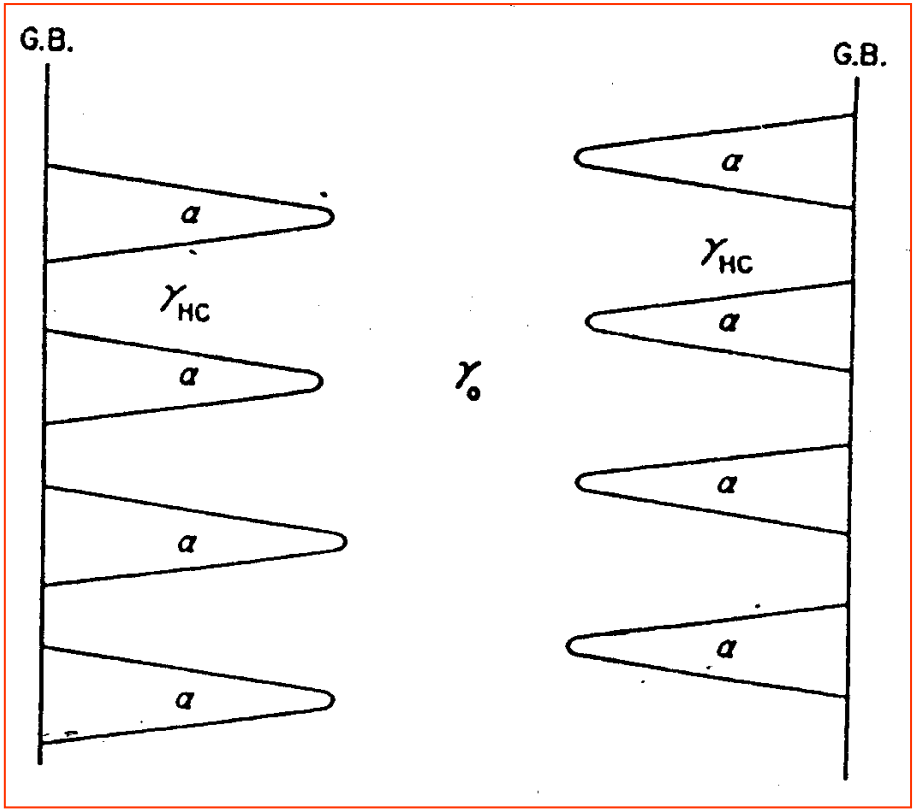
- This results in a deterioration in the mechanical properties. The period between the end of Stage I (t_1) and the start of Stage II (t_2) is known as the 'processing window' and has been the subject of extensive research.

- The optimum combination of mechanical properties is achieved between two values.



Idealized characterization of the influence of the two bainite reactions on toughness during austempering. Original austenite (γ_o), bainitic ferrite (α), high-carbon austenite (γ_{HC}), carbide (c)

- Once austenitized, castings are quenched to the austempering temperature.
- This is below that for transformation to pearlite and above that for transformation to martensite (Ms) and usually in the range 235-400°C.
- It is important to miss the pearlite ‘nose’ by ensuring that the castings are appropriately alloyed and transferred rapidly into a quench medium having a high heat extraction capability.
- During isothermal holding at the austempering temperature, ferrite platelets nucleate and grow into the austenite and the excess carbon (arising from the different solid solubilities of C in ferrite and austenite) diffuses into the untransformed austenite.
- Whereas in steels the carbon precipitates as carbides to form ‘bainite’, the higher Si content of ductile iron delays carbide precipitation.

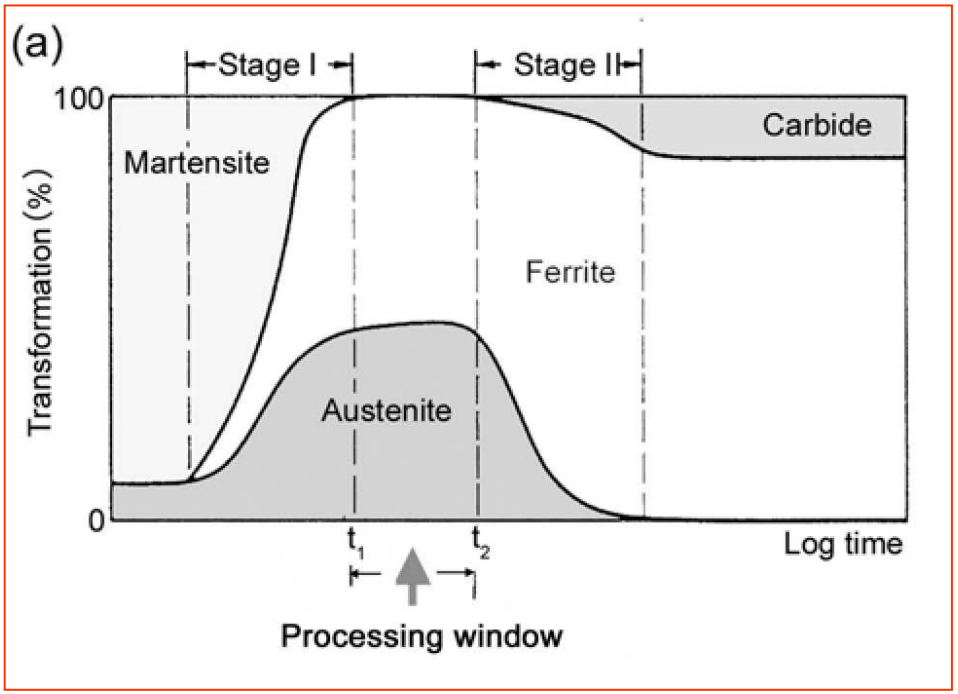


Schematic illustration of bainitic ferrite (α) platelets growing from a grain boundary (GB) into the original austenite (γ_o) and creating zones of high-carbon austenite (γ_{HC})

- Hence the austenite carbon content is progressively increased, reducing its Ms temperature.

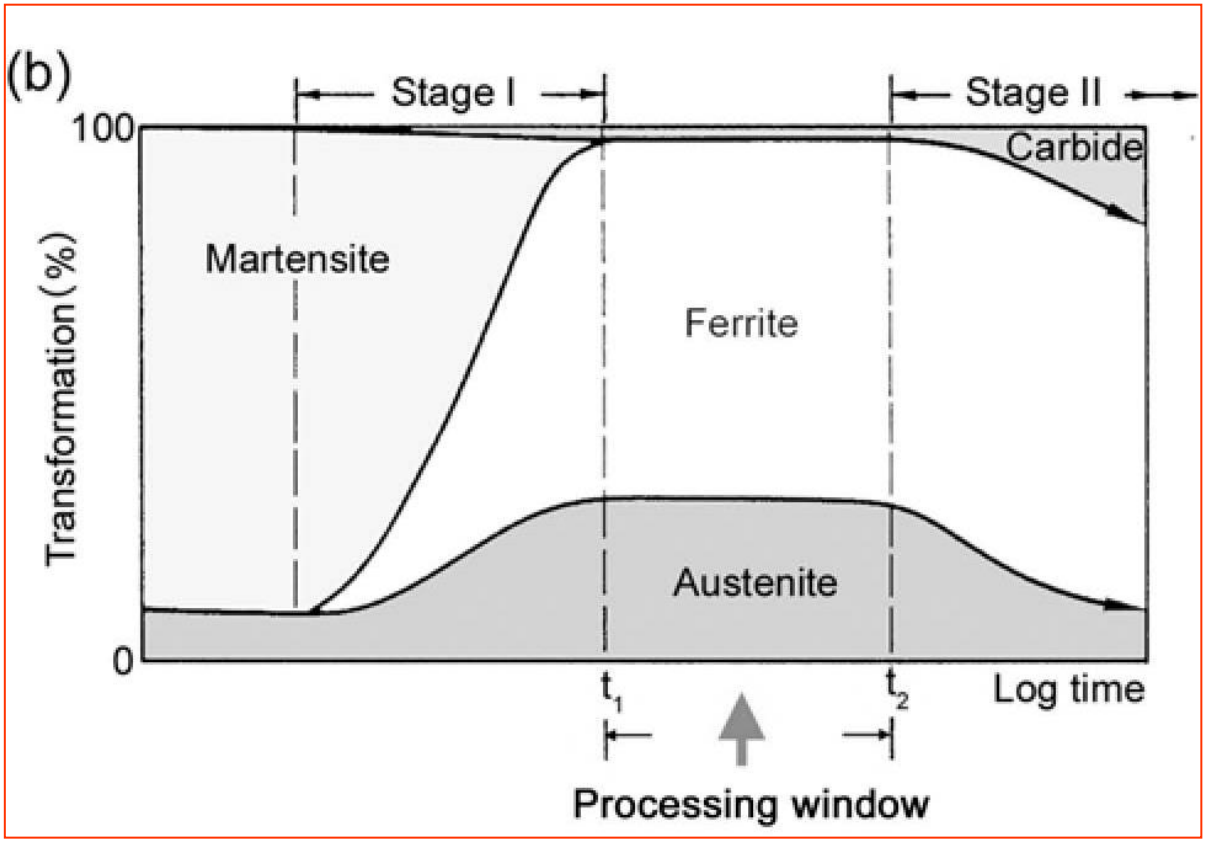
- If castings are held for long enough, the Ms temperature is depressed to below room temperature and the final matrix structure will consist of bundles of ferrite platelets set in a matrix of retained austenite which has been stabilized by a high carbon content (γ_{HC}); this is called ‘ausferrite’.

- The reaction is known as the Stage I reaction: $\gamma \rightarrow \alpha + \gamma_{HC}$. The end of Stage I is defined as that time when no martensite is present in the room temperature structure.

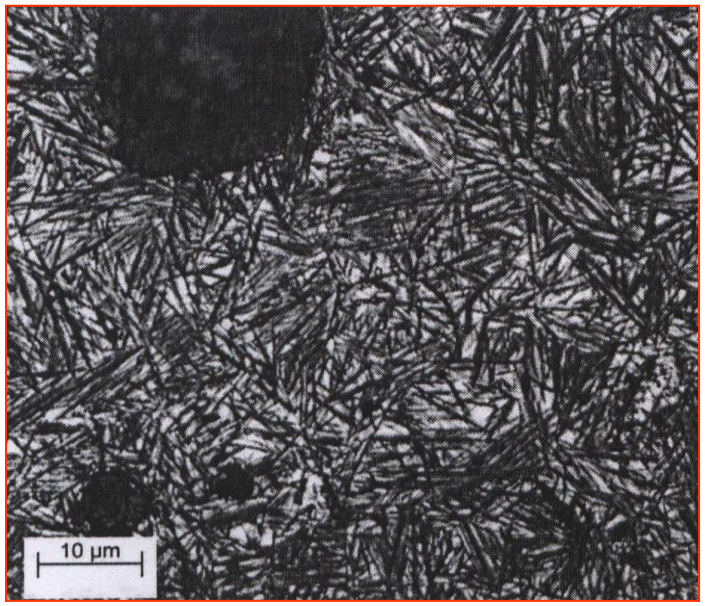


Developments in the microstructure when austempering ductile iron at (a) high temperatures, (b) low temperatures.

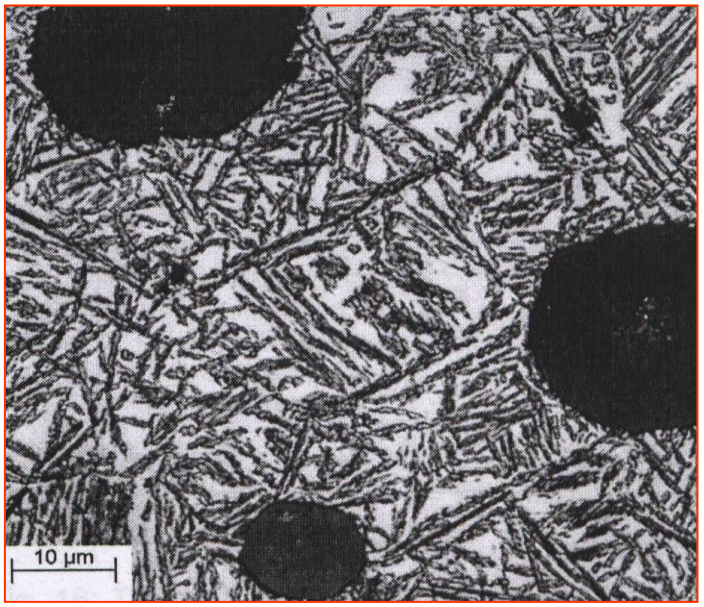
- As the austempering temperature is reduced, the driving force for the formation of ferrite increases and the diffusion rate of carbon decreases.
- This can result in the excess carbon remaining trapped in the ferrite and the precipitation of silico-carbides at the same time as the ausferrite.
- This is analogous to the lower bainite formed in steels and produces a hard grade of ADI having relatively low ductility and toughness.



Developments in the microstructure when austempering ductile iron at (a) high temperatures, (b) low temperatures.



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



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

- 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.

ADI at CMRDI



Experimental Foundry at CMRDI



Austempering Plant

2

STRENGTHENING MECHANISMS

Strengthening Mechanisms of ADI

(a) ***The strengthening mechanism of ferrite***

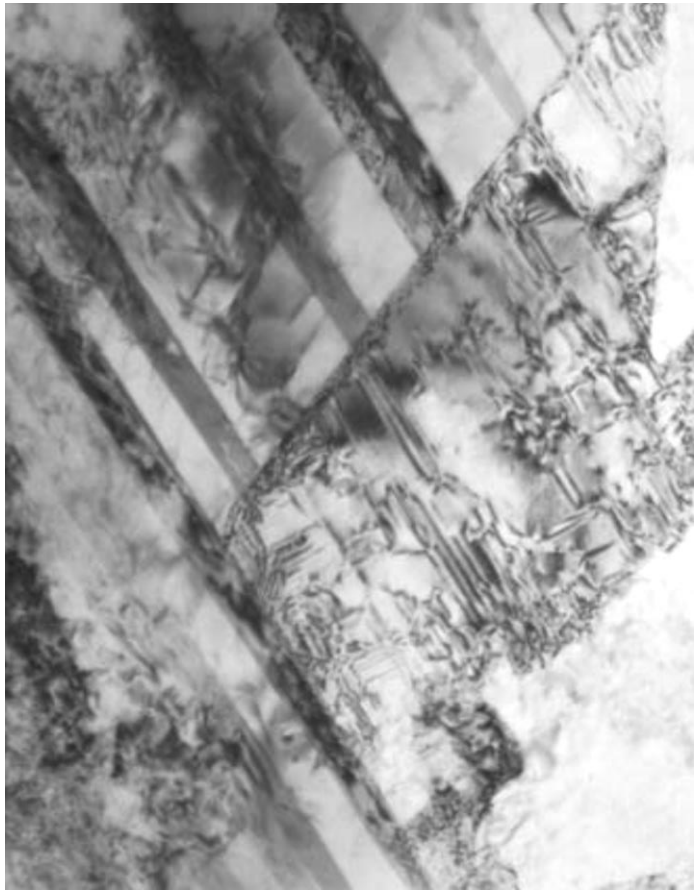
hardening caused by very high dislocation density, accompanied by high density very small dislocation loops.



Strengthening Mechanisms of ADI

(b) ***Austenite strengthening***

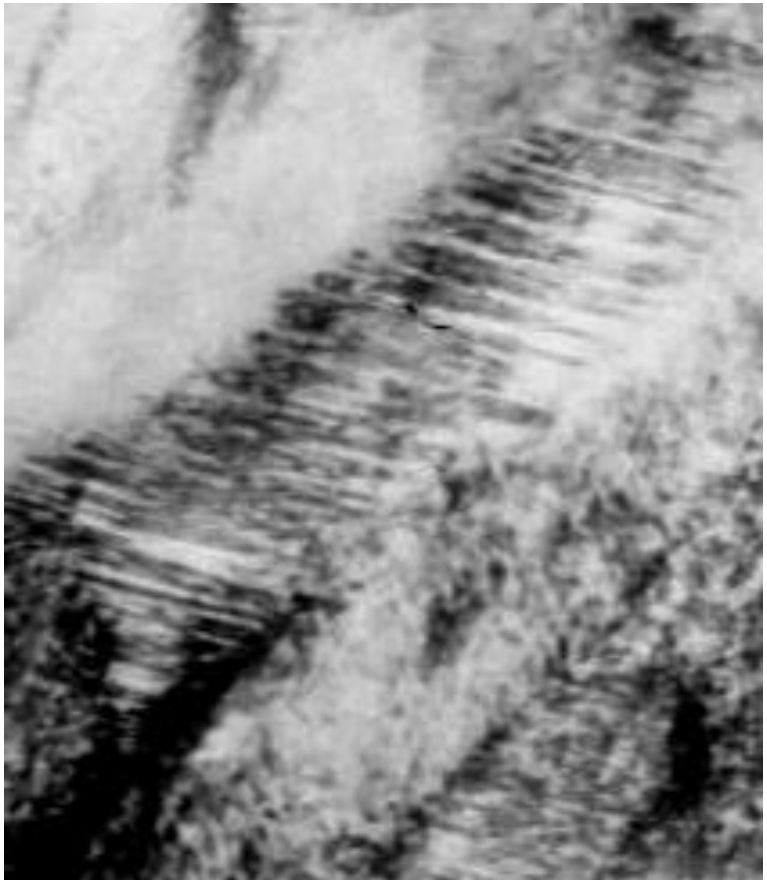
by solution hardening mechanism supported by grain refining due to twinning, which results in some extra coherent grain boundaries. Moreover, stacking faults representing obstacles for dislocation movement may play some strengthening role.



Strengthening Mechanisms of ADI

(c) ***The austenite to martensite transformation***

temperature is accompanied with high lattice distortion and consequently high strain energy. The martensite grains would be divided into a very large number of ultra thin microtwins. The resulting huge amount of coherent grain boundaries will impede the dislocation movement.



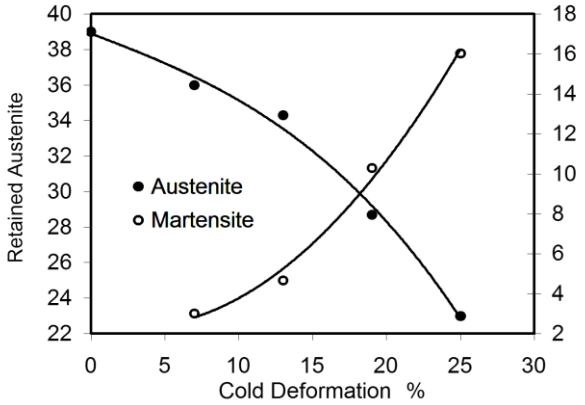
3

ENHANCEMENT OF STRENGTH PROPERTIES

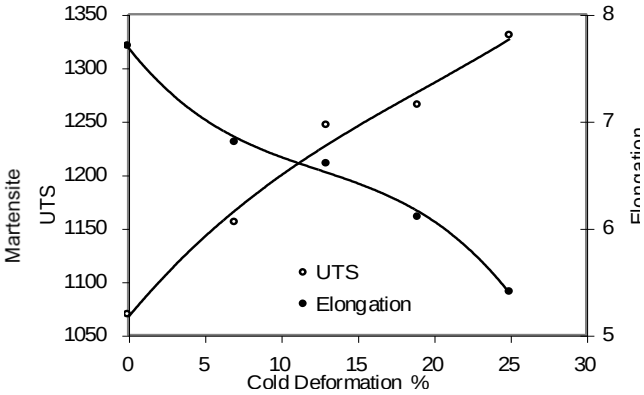
ADI WITH ENHANCED STRENGTH AND TOUGHNESS PROPERTIES

1. Cold Rolled ADI
2. Ausformed ADI (AADI)
3. Two-Step ADI
4. Squeeze Cast ADI
5. Intercritically austempered (IADI)
6. Nano-Structured ADI
7. Thin Wall ADI

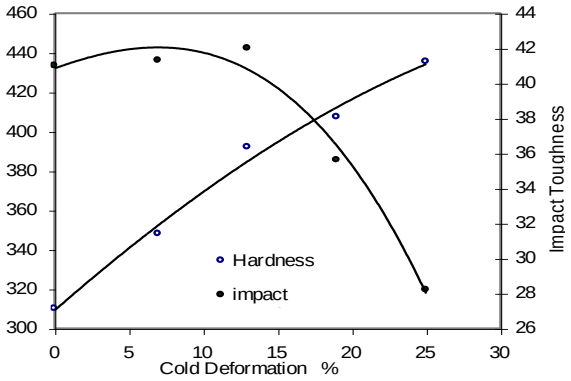
3.1. Cold Rolling of ADI



(a)



(b)

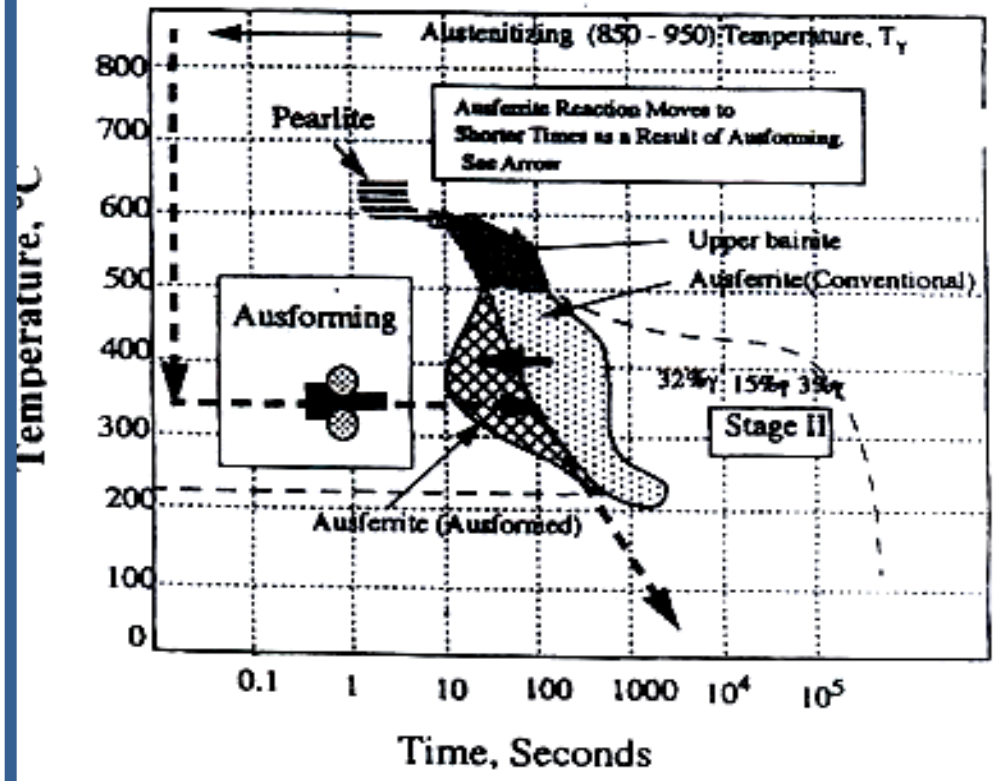


(c)

- ADI was subjected to cold rolling (CR) at different reduction percentages to produce as thin as 3 mm sheets without showing any evidence of cracking.
- With increasing CR reduction: Ultimate tensile strength and hardness increase whereas elongation and impact toughness decrease.
- This is attributed to increase of the hardening of the investigated ADI with cold deformation processes (deformation bands and twins) and deformation – induced martensite.
- The observed changes in the mechanical properties at light cold deformation (7% reduction) are mainly attributed to the hardening of this alloy by plastic deformation concentrated in γ_r. At this light deformation the amount of mechanically formed martensite is very small.

3.2. Ausforming of ADI (AADI)

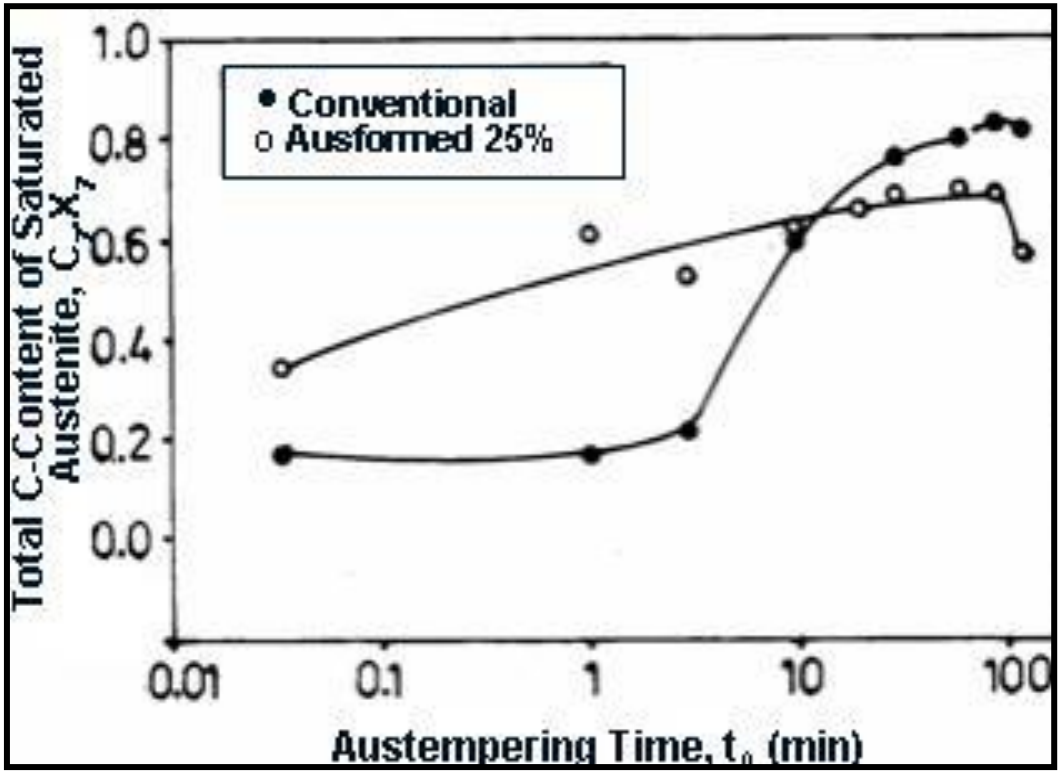
❖Ausforming is introduced into the austempering schedule just after the quench but before any substantial transformation of austenite.



❖ The mechanical deformation step could provide a mechanical driving force in the form of strain defects in addition to the chemical thermo-dynamic driving force in order to accelerate the rate of stage I of austempering.

❖ The finer scale and more homogeneous ausferrite results in a dramatic increase in strength, hardness and wear resistance.

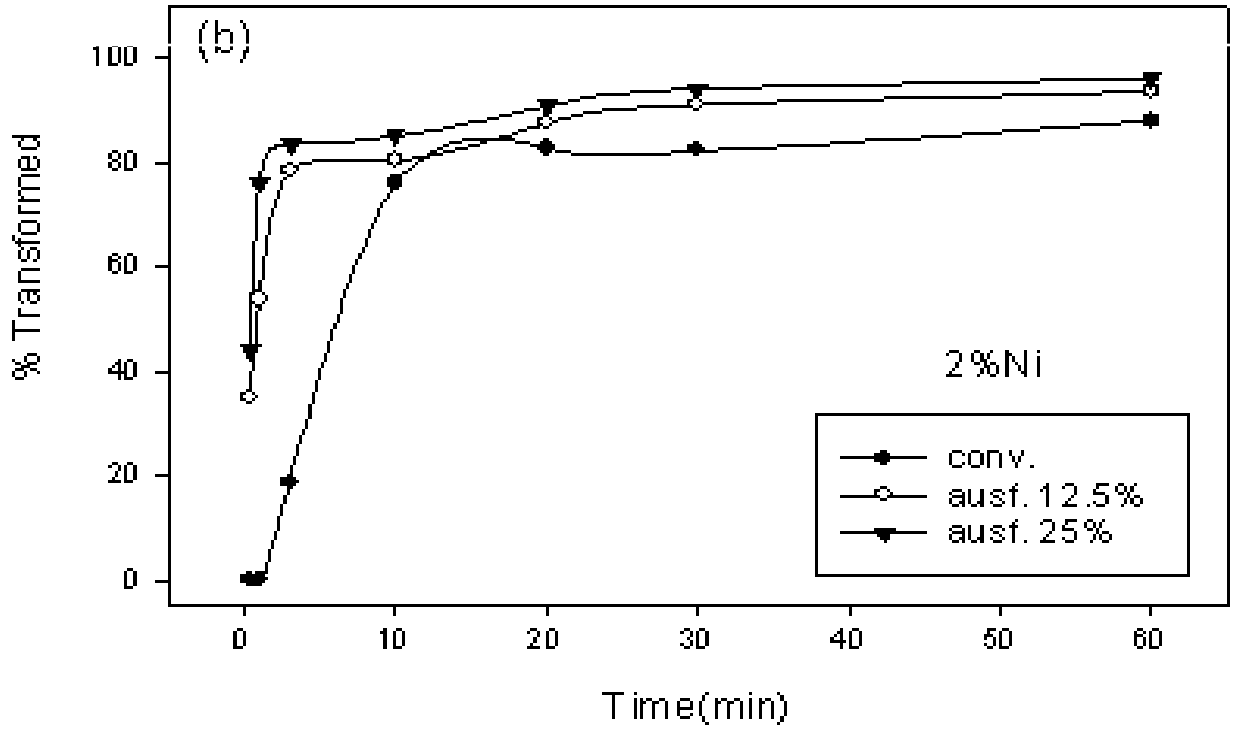
Transformation Kinetics

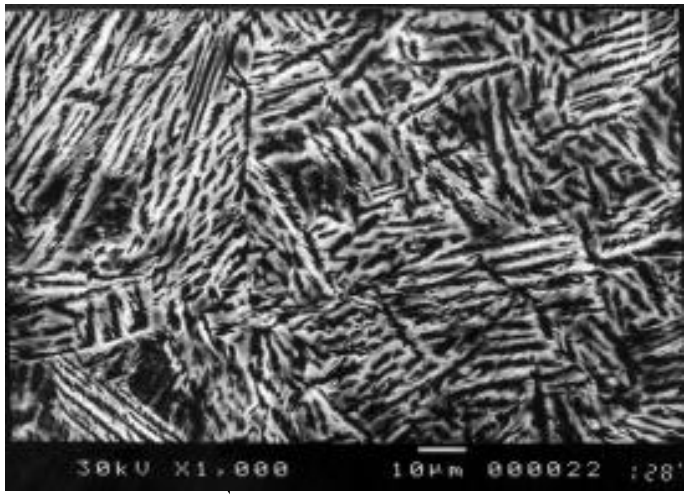


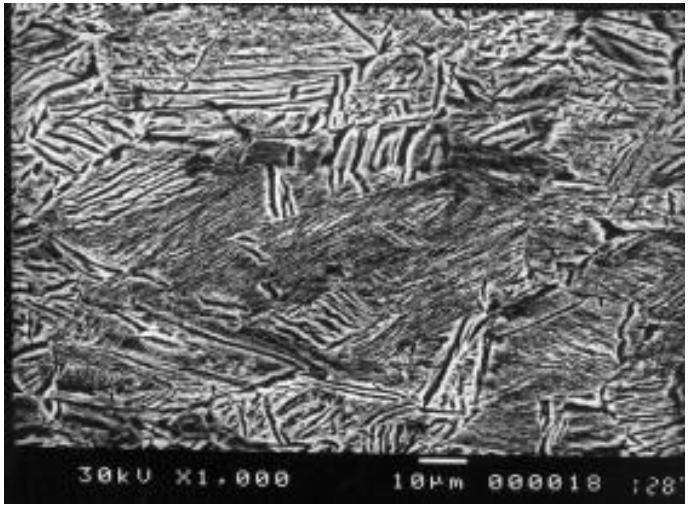
- In the conventionally processed irons, the saturated austenite total carbon content $C_\gamma.X_\gamma$ remarkably increases only after 10 minutes austempering.
- Ausforming results in faster progress of stage I reaction at short austempering times.
- Total C-content of saturated austenite $C_\gamma.X_\gamma$ undergoes a slight decrease after about 100 minutes austempering which may indicate the onset of stage II austempering transformation.

Transformation Kinetics

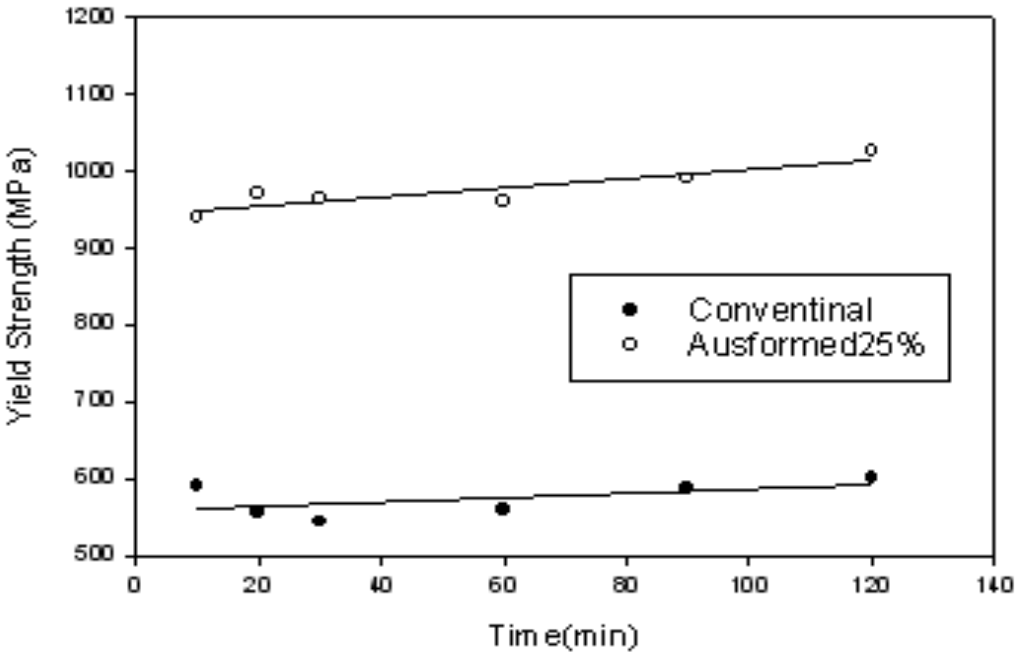
- The rate of stage I transformation was higher in the unalloyed ADI compared to the Ni-alloyed irons.
- For a given short austempering time, the ausferrite transformation was markedly accelerated due to the driving force introduced by deformation.
- Ausforming to 25% reduction followed by austempering for one minute resulted in extremely high volume fraction of ausferrite of more than 80%.







SEM micrographs of ADI alloyed with 2% Ni austempered at 375°C for 1 minute. (a) Conventionally processed; (b) Ausformed to 25% reduction arrows indicate the brittle martensite formed in many zones in the conventionally processed ADI.



Yield strength vs austempering time and ausforming reduction for ADI's alloyed with 2% Ni.

- 25% height reduction during rolling contributed to add a mechanical processing component to conventional ADI heat treatment, thus increasing the rate of ausferrite formation and leading to much finer and more homogeneous microstructure.

- 70% and 50% increase in the yield and ultimate strength respectively – mechanism involves both:

  - Refined microstructural scale due to enhanced ferrite nucleation

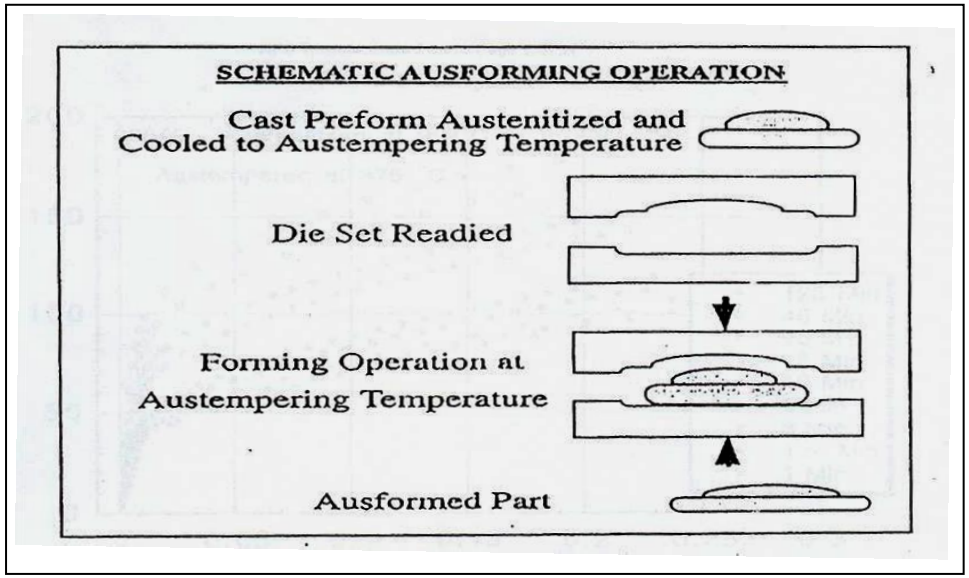
  - Elevated dislocation density

- Ausforming helps to alleviate the deleterious effects of hardenability elements segregation on ductility

Applications of Ausformed ADI

- It is more practical that the advantage of ausforming would be taken by forging rather than by rolling. The forging process may be performed on cast preforms, following the following steps:

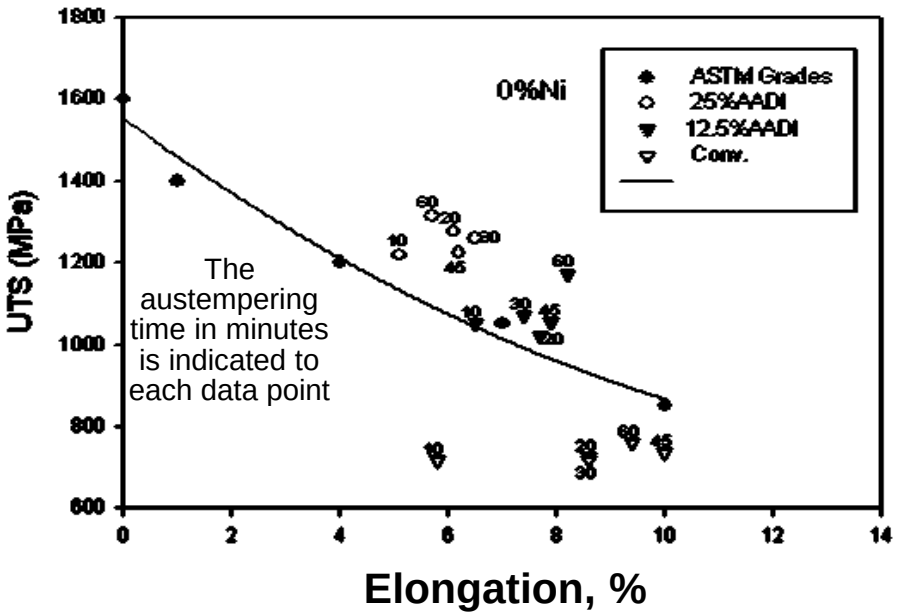
  1. Austenitized
  2. Quenched to the austempering temperature
  3. Inserted into a die
  4. Pressed or forged to the final shape
  5. Returned back into the austempering bath to complete the accelerated transformation



- In situations, where very severe deformation occurs, the work-piece may not need to be returned to the austempering bath to complete the transformation to ausferrite – transformation will have been completed by the time the work-piece is extracted from the die.

- Ultimate tensile strength is plotted against ductility and a curve generated from the minimum specifications for ADI (ASTM Standard A897-90) is superimposed on the plot for comparison.

- Both UTS and ductilities of AADIs are superior to those of conventionally processed ones, regardless of the austempering times.



- The idea of creating preforms in ductile iron and then ausforming them to final shape could be quite effective for relatively simple shaped castings that must meet high demanding strength and ductility requirements, e.g. connoting rods for automotive applications.

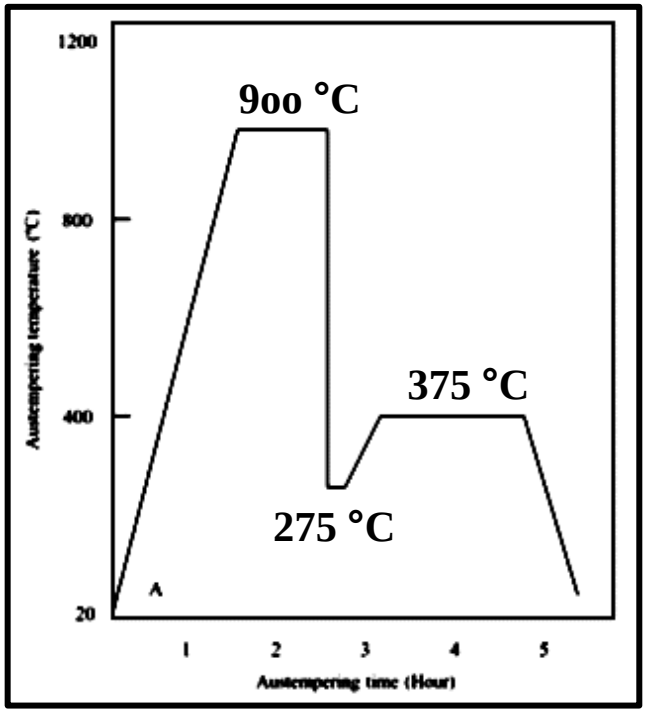
- This concept has been utilized to produce tank track center-guides, using a finite element simulation technique to match both the preform design and the die design so that a uniform equivalent strain throughout the casting averaged ~20% - No fracture or cracking tendencies have been reported.

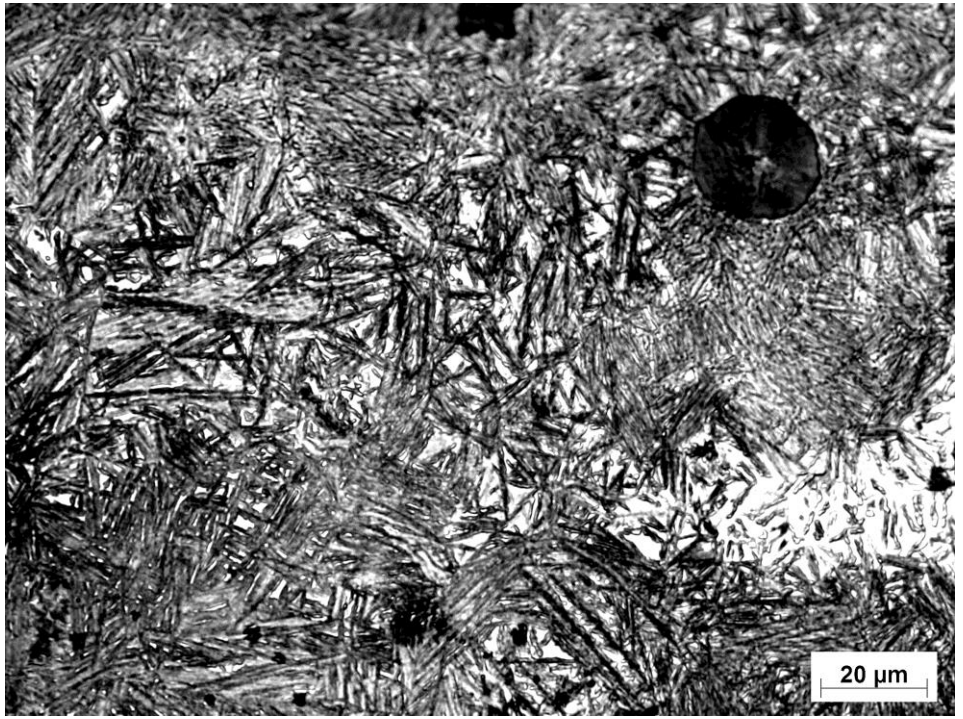
3.3. Two-Step Austempering of ADI

Two-step austempering involves:

First quenching to a lower temperature from austenitizing temperature – thus increasing supercooling and nucleation.

Raising the temperature of the quenching media to facilitate faster diffusion of carbon and thereby increasing C-content of austenite and austenitic carbon in the matrix.





A-B: heal up to the austenitizing temperature
B-C: hold at the auslenitizing temperature (2 hours)
C-D: quench to the firs! austempering temperature
D-E: hold at the first austempering temperature (for a few minutes until nucleation is completed)
E-F: raise temperature immediately to second austempering F-G: hold at the second austempering temperature (usually 2 hours)

Two-Step Austempering of ADI Cont,..

- The mechanical properties of ADI are dependent on:
  - The fineness of ferrite and austenite in ausferrite
  - The austenitic carbon (X_γ C_γ) where:

    X_γ is the volume fraction of austenite

    C_γ is the austenite C-content

- Nucleation of γ_C during austempering (and thus fineness of ausferrite) depends of supercooling, whereas higher C in austenite (C_γ) is possible at higher austempering temperature.

- Combining large supercooling and higher austempering temperature, will increase the austenitic carbon ($X_\gamma C_\gamma$) and in the same time refines the ausferrite structure.

Two-Step Austempering of ADI Cont,..

- Two-step austempering process increases the abrasion wear resistance of ADI. The increase is related to the microstructural parameters, especially :
  - $X_\gamma C_\gamma / \sqrt{d}$ (where : d is the ferritic cell size
  - Strain hardening exponent (n-value)
- The major wear resistant mechanism in ADI is:
  - The microstructural refinement in ausferrite
  - The solution strengthening effect (high C-content in austenite)
  - Strain hardening effect of the austenite phase

Two-Step Austempering of ADI Cont,..

- ADI exhibit similar fracture toughness as quenched and tempered medium carbon steel and low alloy steels. Fracture toughness of ADI increases with decreased austempering temperature.

- Since strength decreases and ductility increases with increasing austempering temperature, we have an interesting phenomena, where fracture toughness increased with increasing strength and decreasing ductility.

- Tensile toughness (the area under the stress-strain diagram) decreases with decreasing austempering temperature, while the fracture toughness increases.

Two-Step Austempering of ADI Cont,..

- Improved toughness of ADI results from:
  - Reduced ferrite particle size
  - Increased carbon content in the retained austenite, which increases the strain hardening ability and strain hardening coefficient
  - Stability of the retained austenite
- Formation of strain induced martensite is known to enhance the toughness in TRIP steels. In ADI, due to the high C-content, the martensite formed is brittle and it is debatable if the formation of strain induced martensite can improve the toughness.

Toughness and Strain Induced Martensite

- Contribution of strain induced martensite to the toughness of ADI:
  - Martensite containing ADI can be considered as fiber reinforced ductile material. Even if the fiber is brittle, it will not make the composite brittle, as long as the fiber is shorter than a critical length, as it will not be loaded to its maximum strength and will not, therefore, fracture.
  - According to this argument, if the retained austenite regions are not massive, then only very short-length of thin martensite will form and will improve the toughness of ADI.
  - Thus, ADI austempered at lower temperature and having finer ausferritic structure should benefit from the martensite formation, while that treated at higher temperatures and consisting of massive retained austenite together with coarse ferrite will not.
  - The retained austenite in upper bainite can easily transform to strain induced martensite.

Fracture Toughness of ADI

- Previous investigations have shown that ADI possesses improved fracture toughness.
- With increasing austempering temperature, the fracture toughness initially increases with increasing temperature, reaches a maximum at an intermediate temperature and then decreases with further increase in temperature.
- This is the result of competitive interplay between the effect of :
  - Ferrite grain size.
  - γ_{HC} volume fraction.
- Ferrite has the maximum fracture toughness at the lowest austempering temperature due to the refinement of it grain size.
- γ_{HC} has its fracture toughness maximized at higher austempering temperatures due to increased volume fraction of γ_{HC} .

Fracture Toughness of ADI Cont,…

THUS

- The actual fracture toughness of ADI is controlled by the “weakest link”; which is:
- The γ_{HC} created at low austempering temperature, and,
- The ferrite farmed at high austempering temperature.
- The relationship between the volume fraction of γHC and the carbon-content of the γ_{HC} is a key factor to understand the fracture toughness of ADI

$$K_{IC} = \sigma_y (X\gamma\ C\gamma)^{½}$$

- Where: **K_{IC}** the fracture toughness

  σy the yield strength

  Xγ the volume fraction of the γ_{HC}

  Cγ the C-content of γHC

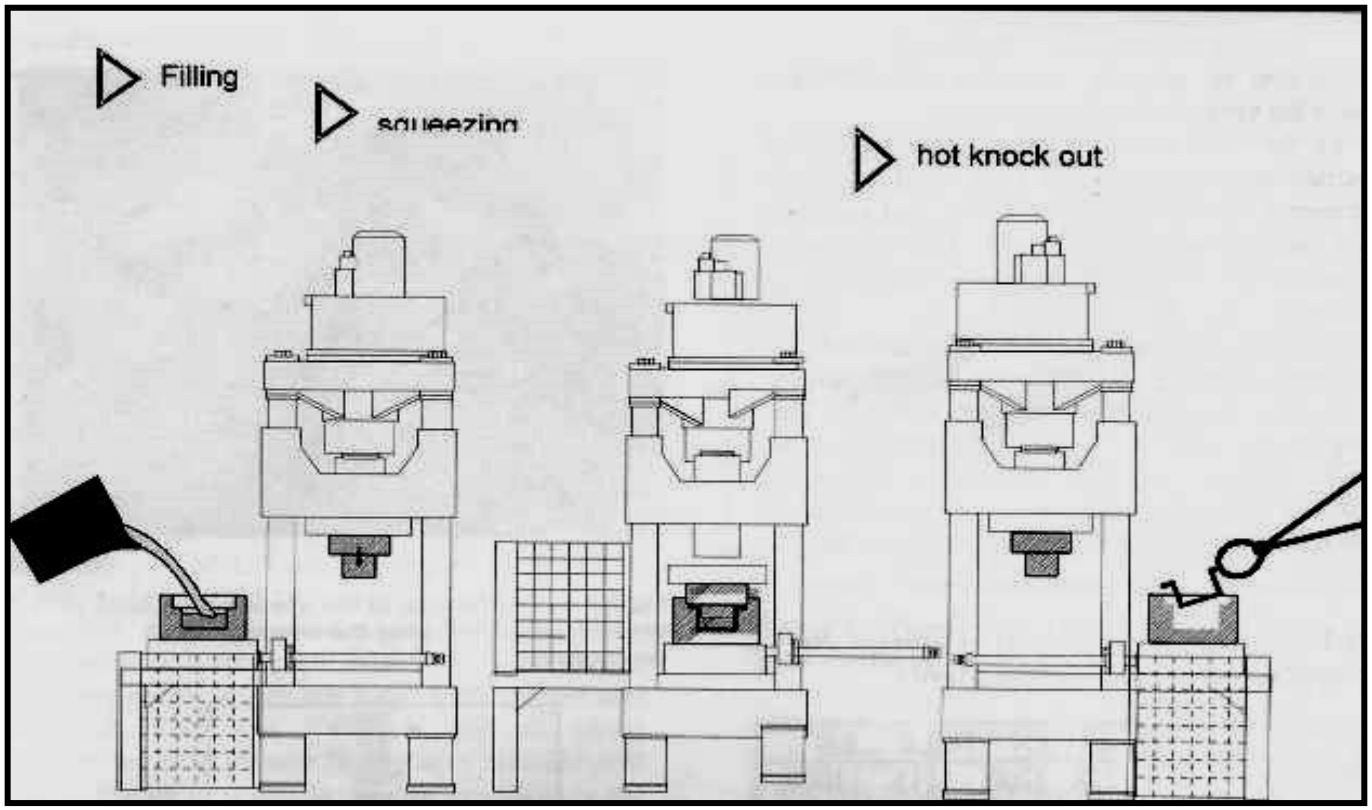
Fracture Toughness of ADI

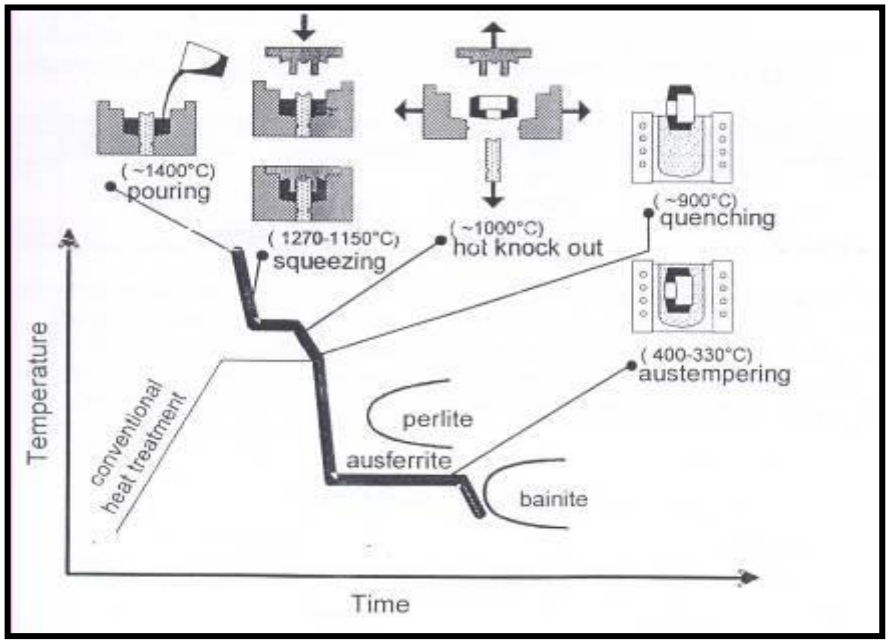
The fracture toughness of ADI can be maximized by:

- Increasing σ_y: depends on by refinement of ferrite cell size and austenite. Fine scale ferrite and austenite will also increase the impact toughness of ADI.
- Increasing C-content of γ_{HC} leads to higher interaction between dislocations and C-atoms. The C-content of the transformed austenite (γ_{HC})depends on:
    - C-conent of the initial austenite (γ)
    - Austempering time and temperature.
- Thus, if a carbon portioning mechanism can be developed so that C-content of γ will be rapidly increased, then this mechanism will help to:
    - Reduce the austempering processing time.
    - Increase the fracture toughness, fatigue strength and yield strength of ADI.

4. Squeeze Casting of ADI

- Over the past few years, a novel technique was under development simultaneously at TU Aachen-Foundry Institute (Prof Sahm) and at Component CPC, Finland (Johansson) to produce superior quality ADI castings using squeeze casting of molten metal in permanent mold followed by in-situ heat treatment of the hot knock-out castings in the austenite.





Process Steps and Temperature Regime of the SQ Process and the In-situ Heat Treatment

Some Tensile Test Results of SQ Cast Samples Compared to EN Standard

	Test 1	EN	Test 2	EN
Tensile strength MPa	1238	1200	1115	1000
Yield strength MPa	968	850	839	700
Elongation %	13,4	2	15,3	5
Hardness HB	388	340/440	363	300/360

Comparison of Different Suspension Materials

		GJS-600-5	SQ ADI (tested)	Microalloyed steel
σ_R	MPa	600	950	1000
σ_y	MP	370	750	550
ε	%	10	11	12

Results of Tensile Tests and Hardness of SQ ADI

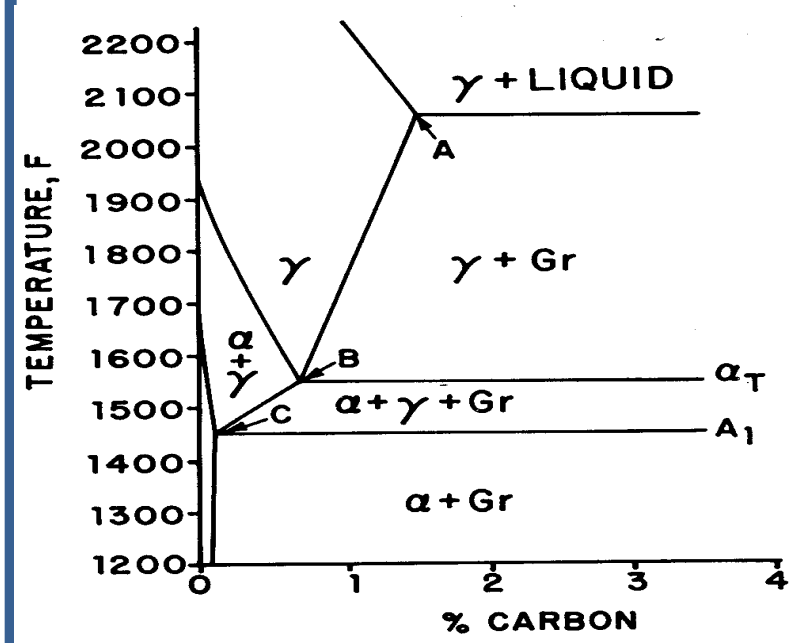
Experiment Series SQ 21	Elastic Modulus [Gpa]	Tensile Strength [N/mm²]	0.2 Offset Yield Strength [N/mm²]	Elongation [%]	Hardness [HB]
Mean Value	**152**	**1083**	**627**	**14.15**	**295/305**

Unique Advantages of SQ ADI

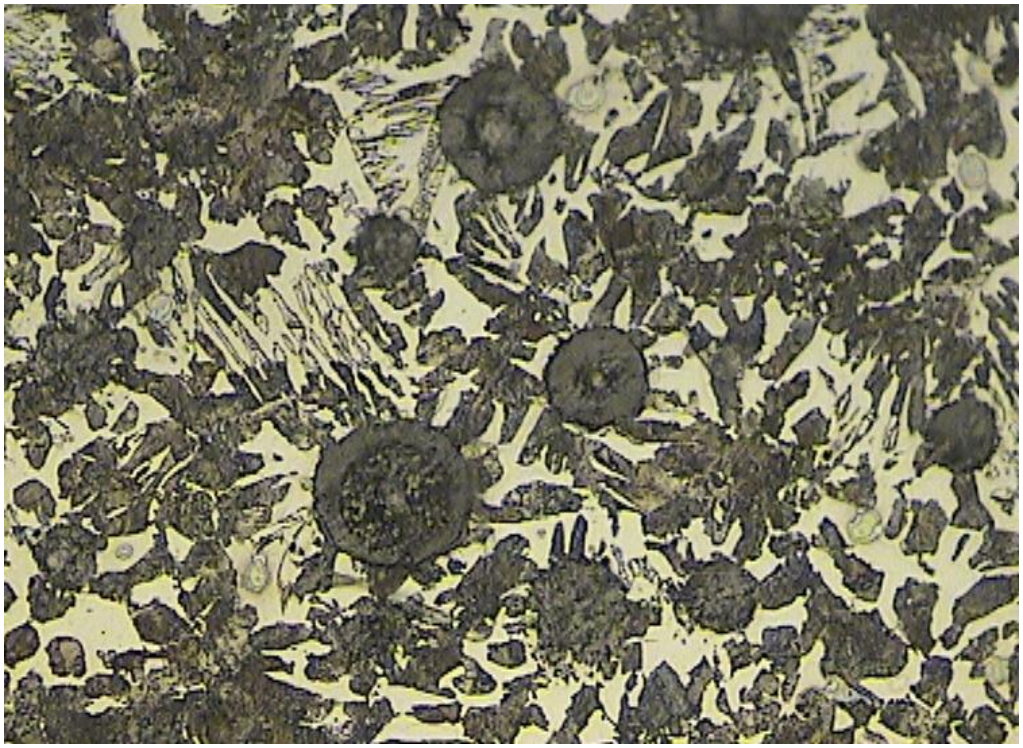
- Sound castings can be produced without feeders or gating system as the solidification expansion was used to counteract solidification shrinkage.
- Increased heat transfer avoids formation of macro- and micro-segregation, which decrease the mechanical properties of ADI.
- Chemical composition of ductile iron can be selected to avoid any metastable solidification in spite of the extremely fast solidification.
- The production process is shorter and less energy consuming as the elimination of sand from the process would allow the hot castings coming out from the permanent mold to be directly introduced to the heat treatment furnace.
- The structure of the SQ ADI is much finer (the graphite as well as the ausferrite), which means better mechanical properties (ultimate tensile strength, elongation and fatigue strength).
- The casting surface is entirely free from any surface defects, which again means higher fatigue strength.
- The machinability is better
- More environmentally friendly.

3.5 Intercritically Austempered Ductile Iron (IADI) Or Dual Phase Matrix DPM-ADI

- The new ADI grade was suggested with optimal ductility through the development of dual phase matrix (DPM) of ferrite and ausferrite by:
  - Intercritical annealing (partial austenitization) in the ($\alpha + \gamma$ + graphite) region
  - Austempering at 250-400°C
- Thus, colonies of proeutectoid ferrite are introduced within the ausferrite matrix.



Section of the Fe-C-2% Si equilibrium phase diagram



Intercritically Austempered Ductile Iron (IADI)

- Intercritically Austempered Ductile Iron (IADI) has an exciting combination of:
  - Good tensile properties: σ_y comparable to pearlitic ductile irons (~ 490 MPa) and elongations at fracture comparable to ferritic ductile irons (~18%) together with good machinability.
  - Due to this combination of properties, IADI can absorb more energy during deformation than either pearlitic or ferritic ductile irons, which leads to improved flaw tolerance and thus, excellent fatigue resistance.
- The production of IADI is dependent upon chemistry and heat treatment. Improper chemistry and/or heat treatment will result in poor hardenabiltiy (the IADI microstructure will not be obtained throughout the component thickness).

Chemistry Requirements of IADI

- **Silicon:** ferrite stabilizer – raises and widens the ferrite to austenite transformation temperature interval.
- **Copper:** promotes pearlite in the as-cast microstructure and slows graphite spheroids dissolution during asutenitizing.
- **Nickel:**
  - ✓ austenite stabilizer and increases hardneability by delaying the transformation of austenite to pearlite.
  - ✓ lowers the ferrite to austenite transformation temperature.
- **Molybdenum:**
  - ✓ increases hardenability by delaying austenite to pearlite transformation upon cooling.
  - ✓ Segregates to the last areas to solidify, forms stable carbides and promotes micro-porosity (> 0.2%).

Heat Treatment Requirements of IADI

Heat treatment for IADI looks very similar to ADI, but what happens in each step is very different. The heat treatment for IADI is as follows:

- Heat into the two phase $\alpha + \gamma$ region
- Hold in this "intercritical austenitizing" temperature long enough to form the desired quantity of austenite and raise the carbon and alloy content of austenite (the source of carbon is the decomposition of pearlite).
- Quench in molten salt to a temperature above the Ms at a rate fast enough to prevent pearlite formation.
- Hold at this "austempering" temperature long enough to allow remaining austenite to become sufficiently enriched in carbon and austenite stabilizing elements such as it becomes thermo-mechanically stable.
- Cool to room temperature.

Further considerations with the Heat Treatment of IADI

- The asutenitizing time & temperatural strongly affects the mechanical properties since this determines:
    - The ratio of γ / α
    - How much carbon and alloying elements are put into solid solution in γ
- The austempering time & temperature have little effect on mechanical properties, but high austempering temperatures and long times should be avoided to prevent carbide formation (over – aging).
- The hardenability of austenite in IADI is not as high as the austenite in ADI due to lower C-content. Thus lower asutempering temperatures are desirable to increase the cooling rate and thus, prevent pearlite formation.

3.6 Nanostructured ADI with Dual-Phase Microstructure

In a recent US Plant (2016), Putatunda illustrates a method for forming an ADI composition with nanoscale microstructure. The method includes:

- Heating to a first temperature lower than A1.
- Adiabatic deformation rises the temperature to a second temperature typically above α-tranus for the Fe-Si-C alloy, sufficient to form proeutectiod ferrite and austenite.
- Cooling to first low asutempering temperature and then heating to a second austempering temperature to form a dual phase microstructure (proeutoid ferrite and asuferrite).
- Characteristically, the bainitic ferrite and the high-C austenite each independently has at least one spatial dimension less than about 150mm.
- Cooling to room temperature.

Nanostructured ADI with Dual-Phase Microstructure

- The combination of very high yield strength, fatigue strength and fracture toughness, that cannot be generally obtained in structural materials could be achieved in this nano-structured ADI_ the exceptional combination of mechanical and physical properties obtained is comparable to Maraging Steel without excessive alloying and costly processing.
- This invention requires much shorter austempering time than conventional methods for forming ADI and is therefore, more energy efficient.

3.7. High Strength Thin Wall ADI Castings

Justification

- Limitations related to casting modulus are dictated by the capability of the quenching medium to extract heat from the part at a rate that avoids the austenite to pearlite transformation.
- In heavy sections, segregation to cell boundaries of alloying elements (e.g., Mn and Mo) needed to achieve the required hardenability levels embrittles the austempered structure.
- In thin wall components, the formation of as-cast carbides, if not totally dissolved during austenitization, by high Si-content or due to an excessive nodule count can limit the ductility.
- It is then possible to further improve the properties of such castings with the austempering process. As a result, the thin wall ADI becomes a logical choice for the production of small, light weight and cost effective automotive components, e.g., hollow connecting rods.
- A hollow connecting rod for a two-cylinder car engine and a front upright for a racing car were successfully made of thin wall ADI, which confirms the capability of ADI to build complex thin walled parts of high strength.

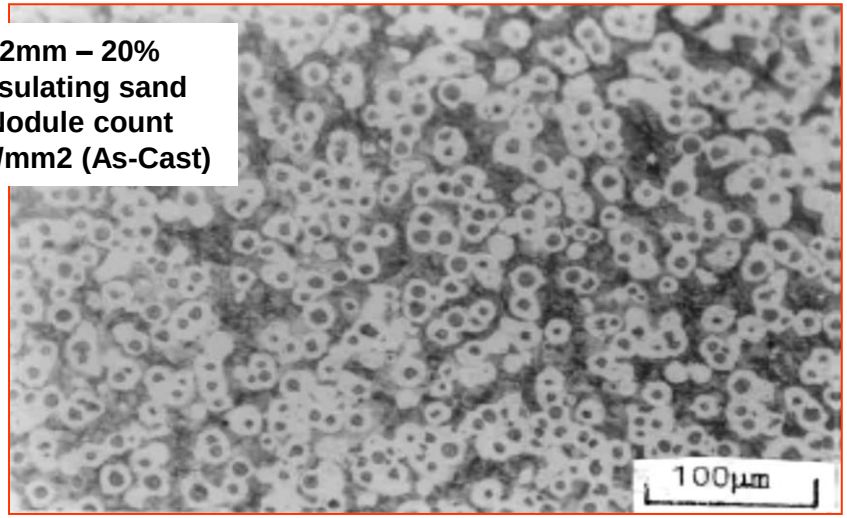
Thin-Wall DI Castings

- Numerous examples have been recently reported, where DI castings started again to replace aluminum in automotive industry – encouraged by the increased strength, ductility, stiffness, vibration damping capacity as well as reduced cost.
- Thin-wall ductile iron has been successfully produced for many years, thanks to the optimization of some critical production parameters: pouring temperature, chemical composition, thermal conductivity of the molding materials, type and amount of inoculating material in combination with the spheroidizing method adopted, casting design and other foundry basic practices.

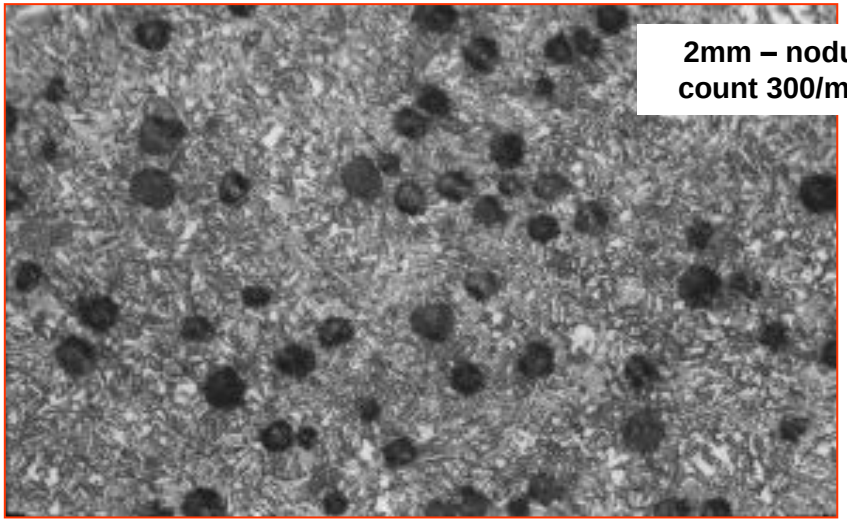


Thin-wall ductile iron castings produced by **General Motors Research Laboratories**, exhaust manifold, differential carrier and power steering gear housing.

Thin-Wall Ductile Iron Castings



2mm – 20% insulating sand Nodule count 600/mm2 (As-Cast)



2mm – nodule count 300/mm^2

Increased undercooling of thin wall ductile iron castings results in:

(a) Nodule count increase + refinement of austenite dendrites

Increased G/γ surface area enhances austempering transformation kinetics, alleviates segregation and promotes austemperability.

(b) Higher tendency for carbide formation – could be avoided by:

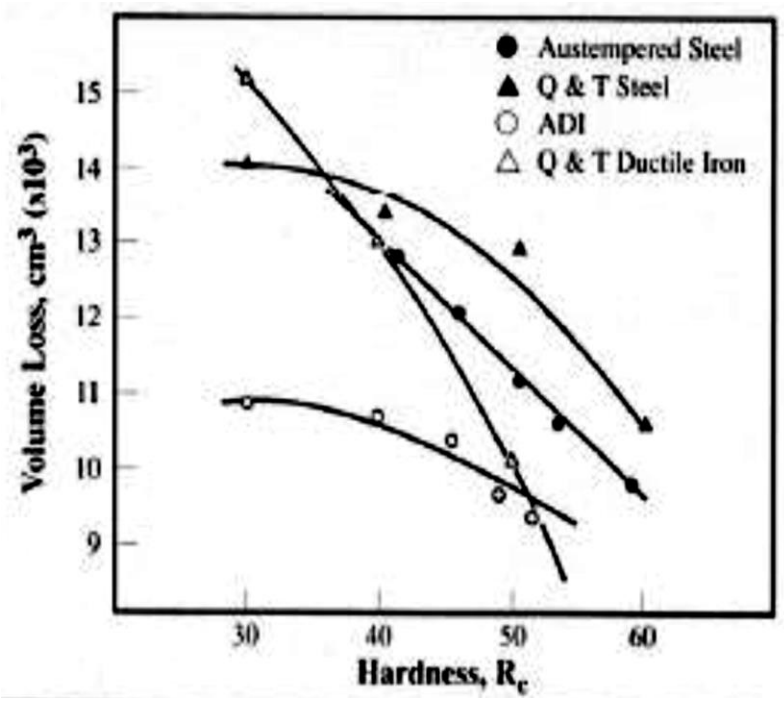
- Adjusting chemical composition and increasing carbon equivalent
- Addition of insulating sand to the mold material
- Investment casting
- More potent and double inoculation
- Dissolution of carbides during austenitization

4

ABRASION RESISTANCE ENHANCEMENT TECHNIQUES

Abrasion Resistance of ADI

- ADI has enhanced wear characteristics at similar hardness levels.
- Hard grades of ADI (480-550 BHN) have excellent wear resistance.
- Softer grades austempered at higher temperatures (280-320 BHN) contain large amounts of retained austenite, which can work harden and/or transform to martensite when subjected to mechanical strain at the surface under abrasive conditions



Pin abrasion test comparing volume loss at equivalent hardnesses

4. ADI WITH ENHANCED ABRASION RESISTANCE

4.1. Carbidic ADI (CADI)

Modification of CADI with Nano Ceria

4.2. Bainitic-Martensite ADI (B/M ADI)

4.3. Surface Hardened ADI

i. Laser Surface Processing

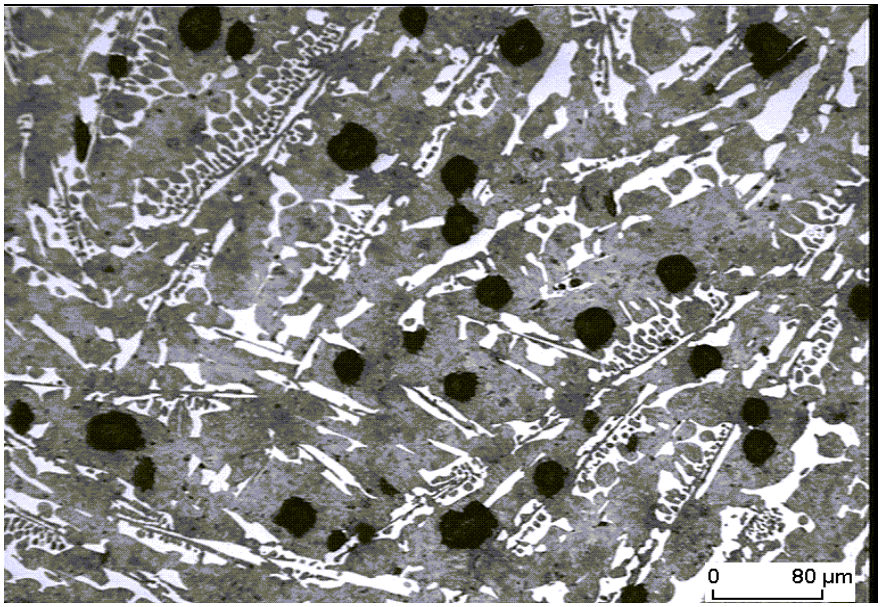
ii. Locally Austempered DI (LADI)

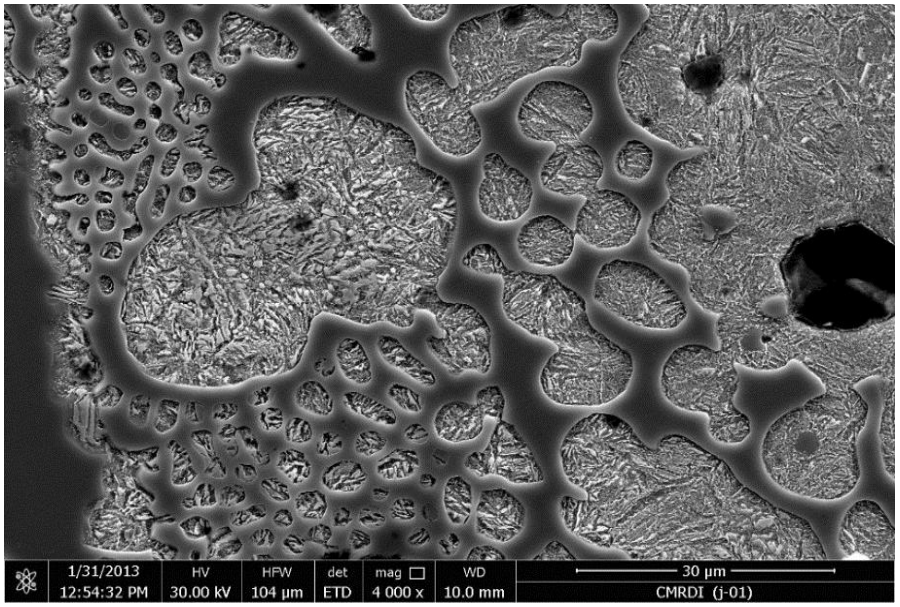
iii. Surface Treatment Involving Cold working

4.4. applications at CMRDI

4.1 Carbidic ADI (CADI)

- Ductile Iron containing carbides that is subsequently austempered to produce ausferritic matrix with an engineered amount of carbides.
- CADI exhibits adequate toughness and superior wear resistance – compete favorably with high Cr-AR irons with improved toughness





2% Cr (275°C)

2% Cr (375°C)

Methods of carbide introduction include:

A. As-Cast Carbides:

- alloying with carbide stabilizers
- higher cooling rate during solidification
- lower C.E
- surface chilling

B. Extended Second Stage Austempering

$\gamma_{HC} \rightarrow \alpha$ + Carbides

C. Mechanically Introduced Carbides:

crushed M_xC_y carbides are strategically placed in mold cavity at the desired locations

Modification of CADI with Nano Ceria

- Improvement in wear resistance due to introduced hard carbides is generally accompanied by a decrease in impact toughness, which limits its applications.
- In a recent publication, additions of nano ceria were made to tailor the morphology, size and quantity of carbides.

- Carbides were refined by the nano ceria leading to improved toughness, higher hardness and enhanced wear resistance.

4.2. Bainitic / Martensitic ADI (B/M ADI)

- A new grade of high wear resistant ADI is produced by adding less expensive alloying elements such as Si and Mn in the range of 2.5-3.0% (Si/ Mn ratio is 1.5) with minor additions of B, Ti.

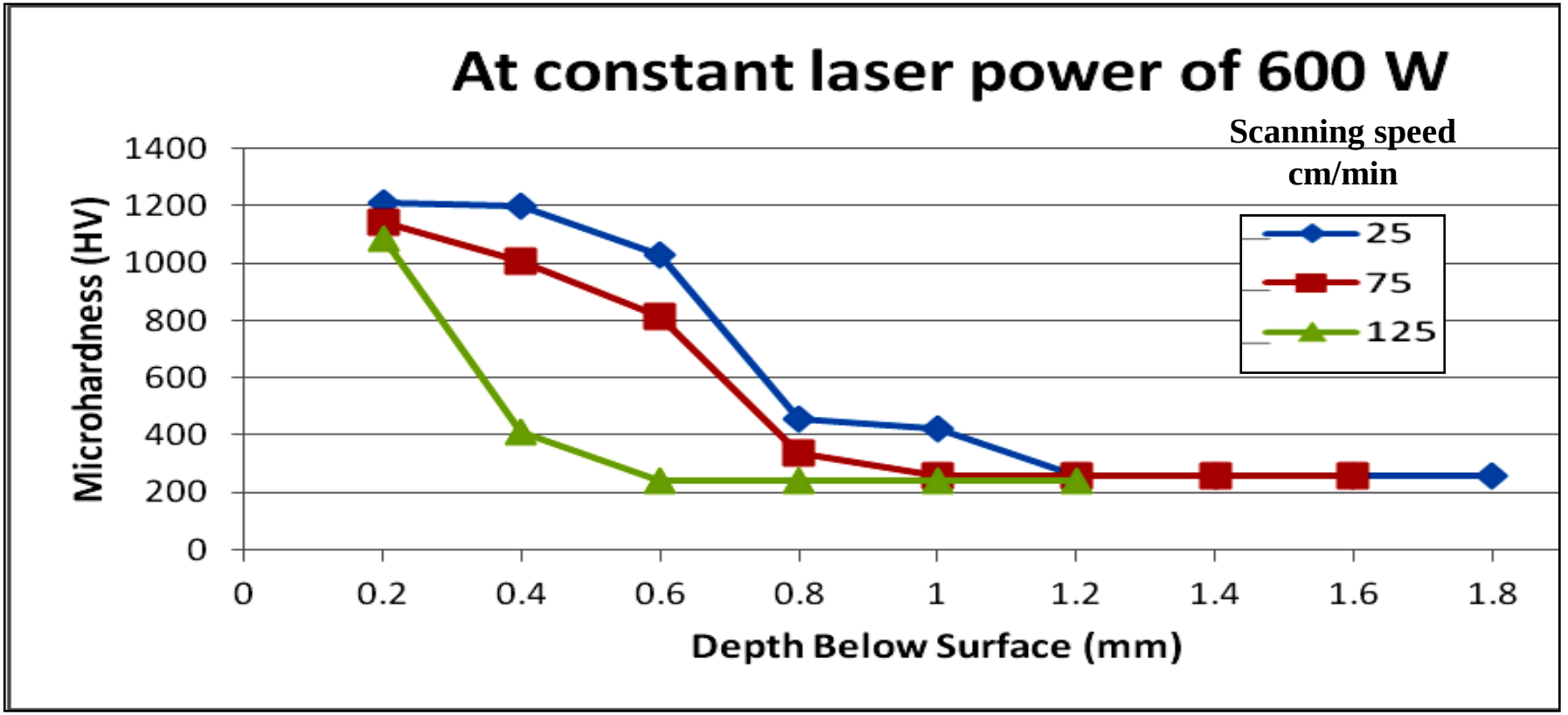
- The structure contains mainly acicular structure; bainite and martensite with some retained austenite. Castings are quenched and then tempered at a temperature range as for austempering (250-400°C).

- B/M ADI dual-phase structure has heigher toughness than single bainite or martensite. Developed mainly for mill balls with good combination of toughness (15 J), high hardness (55 HRC) and fatigue properties that surpasses that of high Cr-cast iron.

- B/M ADI has good work-hardening capacity - the wear resistance is comparable to high Cr-white cast ion and twice of Mn-steel.

4.3. Surface Hardened ADI

i. Laser Surface Processed ADI



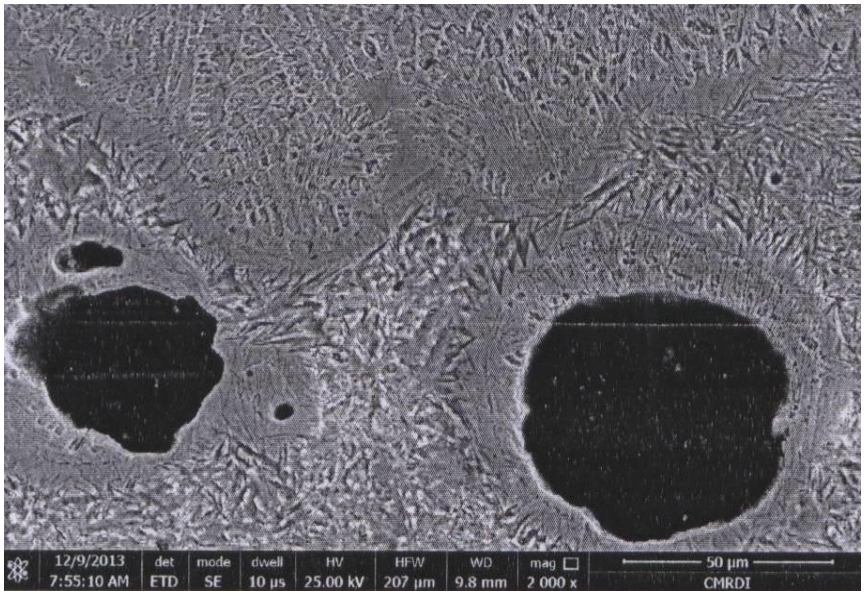
Microhardness Profile

- Hardness and depth of the hardened layer increase with the laser scanning speed at constant power level.

- Laser surface treatments, especially LSH significantly increase the wear resistance of ADI which was related to the fine microstructures of austenite, ledeburite or martensite obtained after LSM or LSH, giving hardness values up to 1000 Hv, work hardening of the structure as well as stress induced phase transformation of retained austenite to martensite.

- Moreover, such increase in wear resistance was correlated with the lower probability of micro-cracks initiation caused by sub-surface fatigue or deformation constraints at the interface between austenite and martensite produced by the stress induced austenite transformation to martensite.

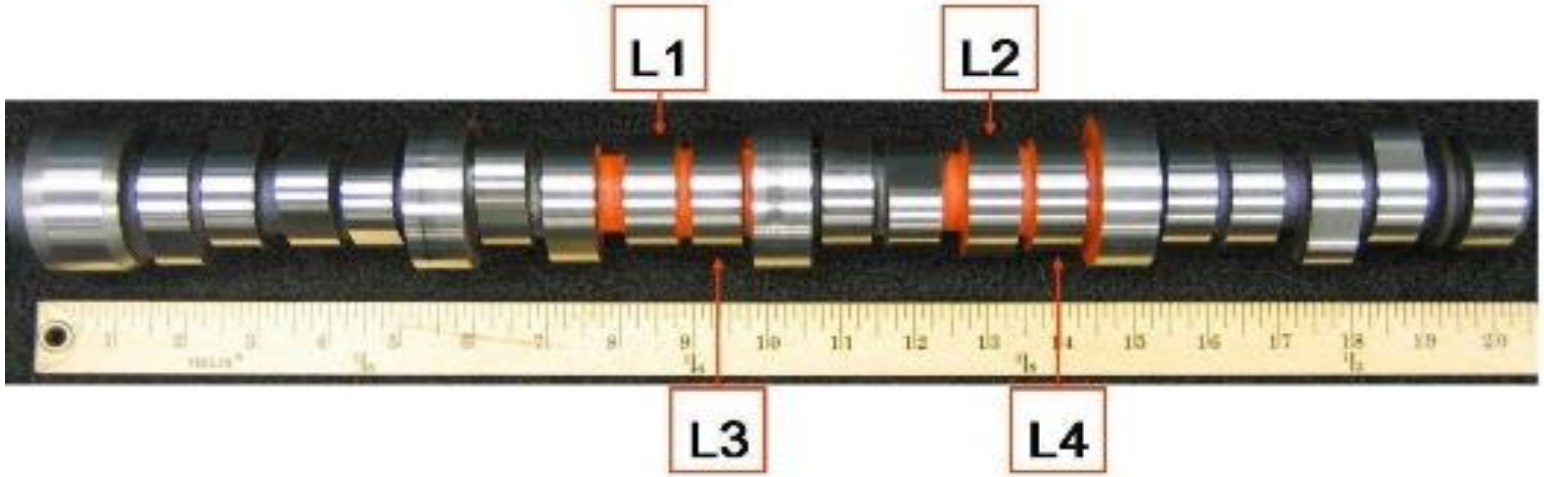
- The upper part of the microstructure indicates that the hardened zone consists of retained austenite and martensite with all the graphite spheroids completely dissolved during laser melting of that area.
- The lower part of the microstructure shows the original graphite spheroids surrounded with a halo of retained austenite dendrites as the C-content in this layer is relatively increased due to diffusion of carbon from the graphite spheroid at higher temperature.
- Graphite spheroids are contained in the original ausferritic matrix of ADI.



Microstructure of HAZ, processed with 600 W at 75 cm/min scanning speed

ii. Locally Austempered Ductile Iron (LADI)

- A surface hardening heat treatment that produces a localized case depth of ausferritic microstructure (ADI) in a desired area of the component.
- Engine camshafts are unique in that the manufacturing requirements are very different from the operating needs.
- When selecting the proper material for a camshafts, one must balance the needs of:
  - **Hard, strong and wear resistant material choice for the camshaft lobes.**
  - **Ease of machining the product.**



iii. Surface Treatments Involving Cold Working

- Austenite stress induced transformation to martensite may produce compressive stresses when ADI are subjected to surface treatments involving cold working operations such as shot peening or fillet rolling.

- Such treatments can improve the fatigue properties rather than the tribological ones.

4.4. ADI for Abrasion Resistance Applications at CMRDI

I. ADI Gears

ADI as Gear Material - Why???

- Stronger per Kg than Aluminium.
- As wear resistant as carburized and nitrided steel.
- Easer to machine than free cutting steel.
- Capable of producing gears for 20% less expensive than those now cut from steel.
- Bending and contact fatigue comparable to steel.
- Superior vibration and noise dampening capacity.
- 10% lighter than steel.









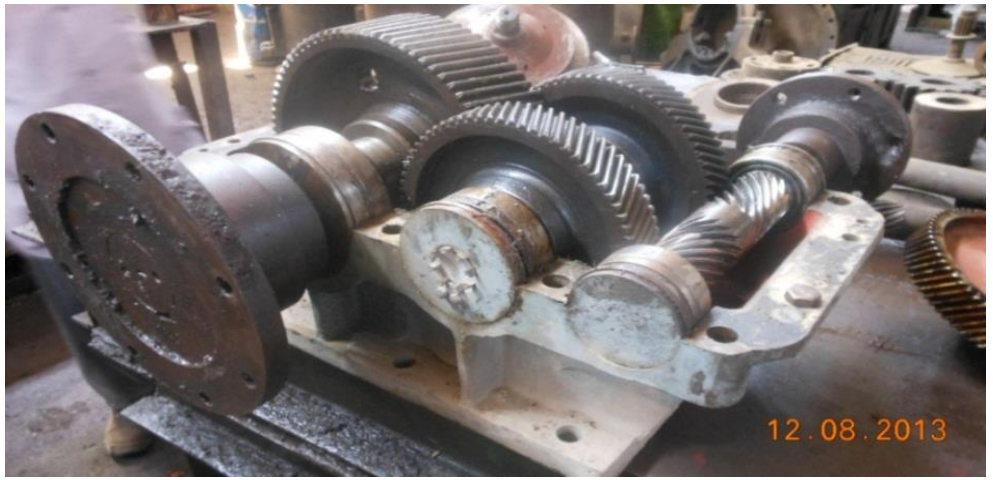







ADI Gears Produced at CMRDI for The Egyptian Iron & Steel Co,.

ADI Gear Used in the Gearbox of 16-ton Cranes for The Egyptian Iron and Steel Co. (EISCO) in Operation in Different Plants of the Company



C45 Steel Gear

ADI Gear



ADI Gear



Gears condition after working for more than 3 years at the same gearbox







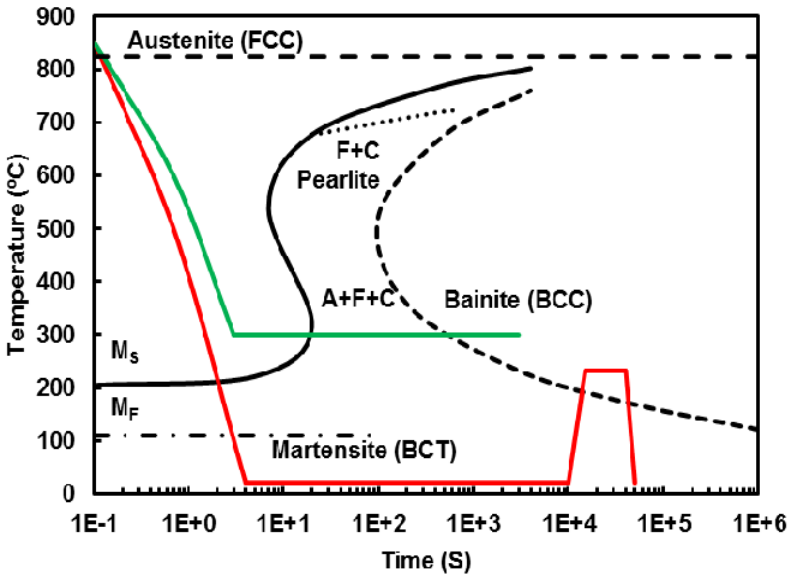
Directional Force Geared Exciter

ADI vs. Steel As Gear Material

Structural Integrity

In Quench and Tempered Steel Gears

- Formation of martensite occurs instantaneously as temperature drops below Ms.
- Non-uniform transformation in different sections can result in significant distortion and/or cracking

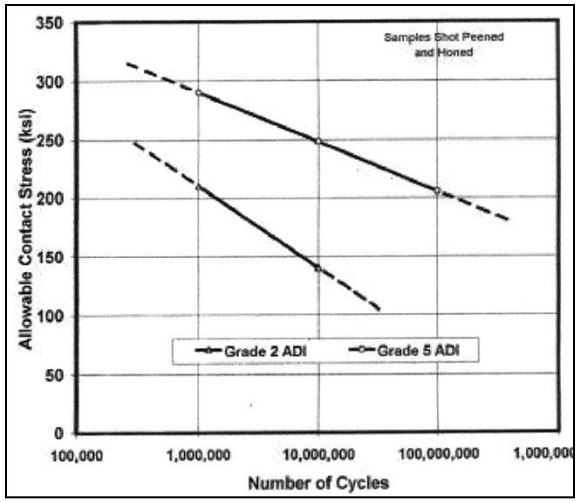


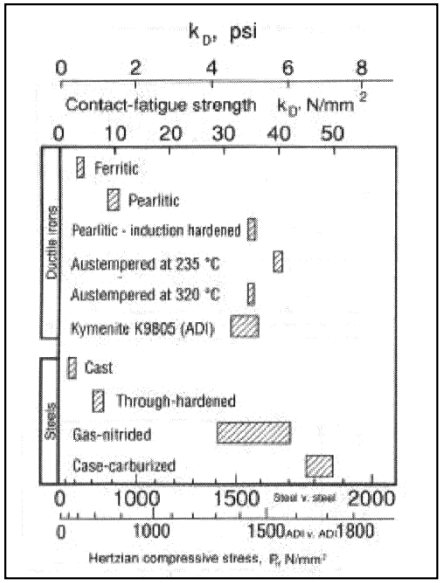
In ADI Gears

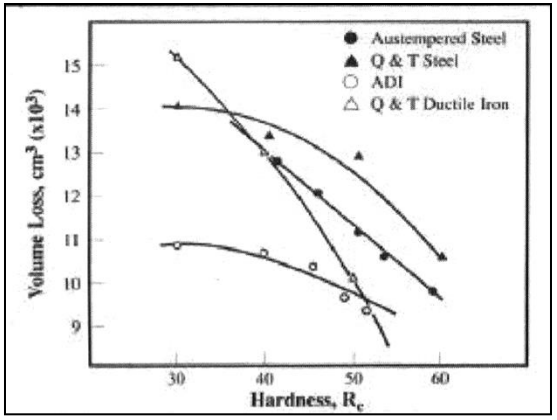
- The formation of ausferrite in the isothermal austempering process occurs over minutes or hours at a single temperature
- Absence of distortion and cracking enhances the structural integrity of gears produced from ADI

CONTACT FATIGUE

ADI LEADS ITSELF TO INCREASED CONTACT FATIGUE STRENGTH AND WEAR RESISTANCE







Compare the allowable contact stress behavior of ASTM Grades 2 and 5 (ASTM 1050-700-07 and 1600-1300-00)

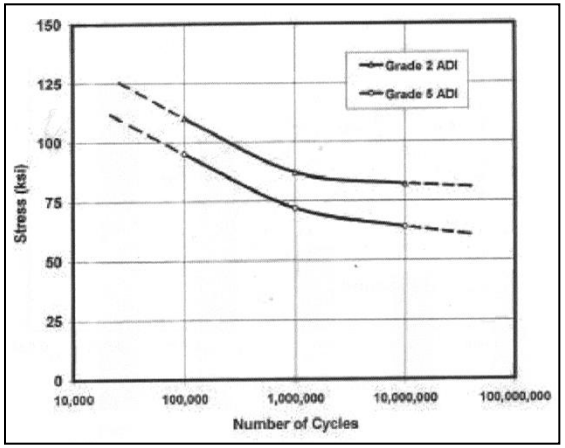
The contact fatigue properties of various grades of ADI are comparable to gas nitrided steel and competitive with carburized and hardened steel.

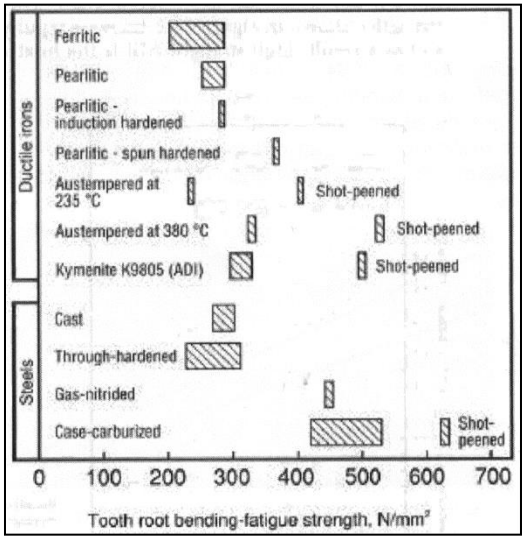
ADI has improved abrasion resistance when compared to steels and quench and tempered ductile iron.

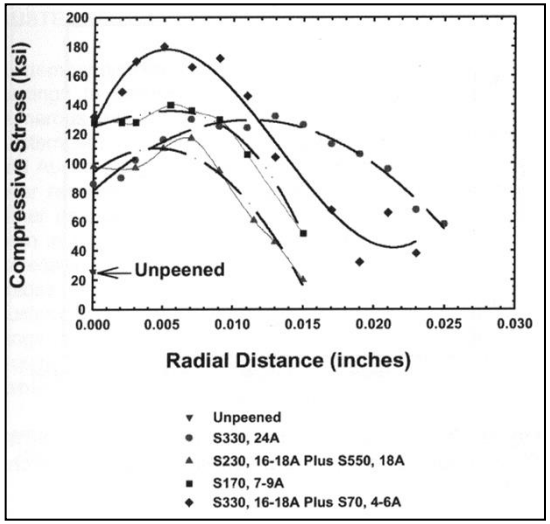
ADI experiences less volume loss at similar hardness levels, resulting in a component with improved wear characteristics

BENDING FATIGUE

ADI PRESENTS AN INCREASE IN BENDING FATIGUE FOR GEAR APPLICATIONS







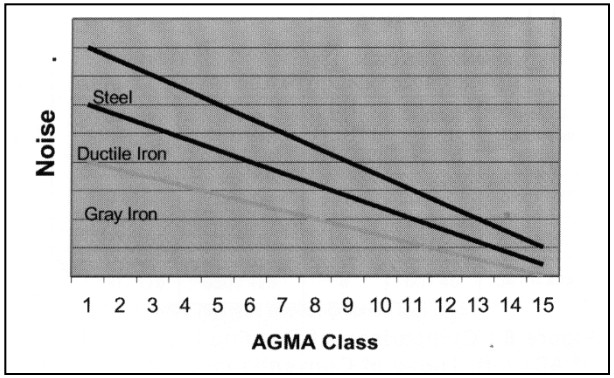
The comparative allowable tooth root bending stresses for ADI grades 2 and 5

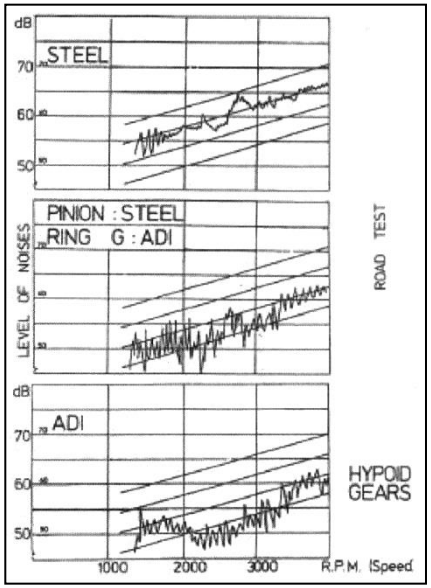
- ADI is competitive with cast and through-hardened steels.
- Shot peened ADI has improved fatigue strength that is comparable to gas nitrided and case-carburized steels.
- Shot peening can improve the allowable bending fatigue of carburized and hardened steels by 30% and that of ADI by 75%

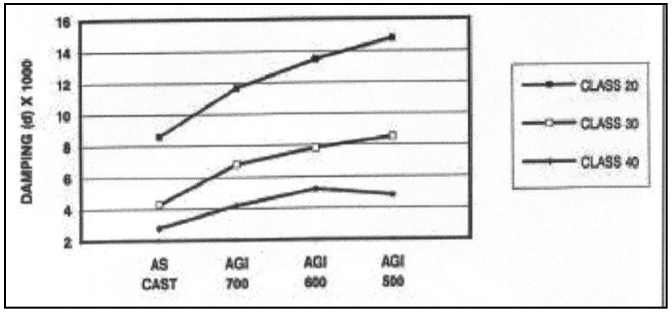
- The bending performance of ADI can be greatly enhanced by shot peening.
- Several shot peening combinations are measured for their effect on residual compressive stresses.
- The as-austempered surface compressive stress is less than 30 ksi while the maximum shot peened surface compression is more than 130 ksi.

NOISE REDUCTION

AGI AND ADI CAN GREATLY REDUCE THE NOISE FOUND IN GEARS MADE OF OTHER MATERIALS







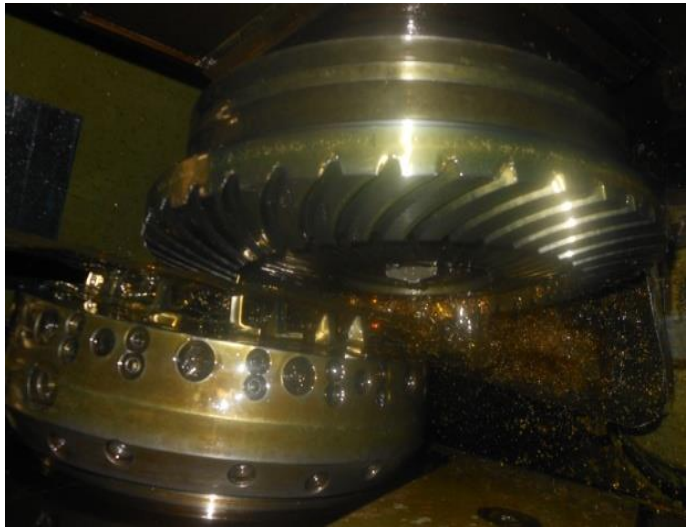
- Gear iron and ductile iron are quiter than steel due to the presence of graphite and the ausferritic matrix.
- Graphite creates a dampening effect that significantly reduces vibration.
- This allows for the possibility that gears machined to lower AGMA classes could be as quite as those machined to more precise grades

- Note the improvement in noise level of a hypoid gear set when both the ring gear and pinion are made of ADI.

- The damping characteristics of grey iron are increased with austempering, giving higher strength AGI better noise reduction characteristics than its as-cast counterparts.

Gear Power Loss

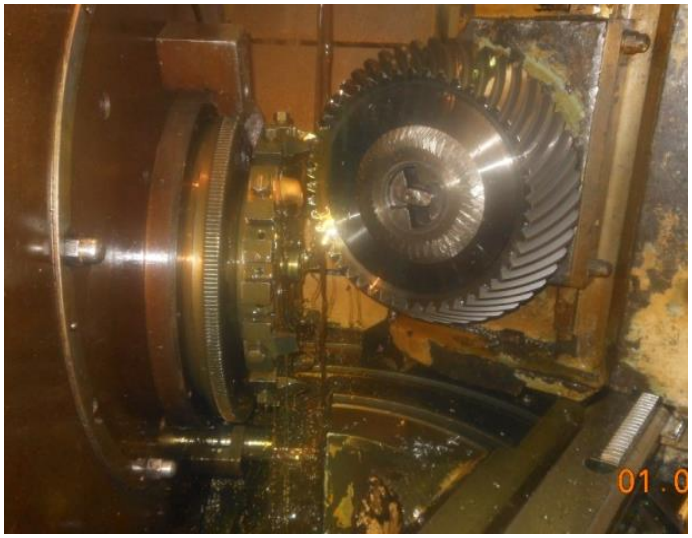
- Power transmission equipments using gears disspate significant amount of power and the evaluation of their energetic performance is, therefore, very important, and can lead to considerable reduction in energy consumption.
- So, gear power loss and efficiency are of fundamental importance for any application and it depends on gear material and lubricant characteristics.



- A recent study reached a conclusion that ADI is a material to be considered by gear designers, as the energetic behavior of ADI gears is similar to carburized steel gears, although being slightly worse at high input power.

- Recently, it has been reported that Cu-Mn ADI gears perform very well, compared to carburized steel gears, with better efficiency in many situations, particularly when the speed and load were not too high.

- ADI gears were shown to be always more efficient than the steel ones using ester oil, namely when transferring high torque.



- It was concluded that a good combination of materials and lubricants depends on the operating conditions, i.e. speed and load, which will determine the proportion of speed- and load-dependent power losses and in this aspect, ADI was considered as a good choice for replacing steel at moderate load and speed.

Wind Turbine Gears

- A wind turbine is one of the most demanding applications of a gearbox. It requires a relatively small, compact, high-power density gear drive and electric generator to transmit fluctuating loads in a very demanding environment of deflections, high vibrations and temperature extremes.



- Through the 1990s and into this century, wind turbine gearbox failures were beyond the slow development of the wind energy industry.

- It was obvious that a standard was needed, and the first draft of ANSI/AGMA/AWEA 6006-A03 to supersede AGMA 921-A97 was developed in March 2000.
- The Standard was approved by the AGMA in October 2003 and then approved as an American National Standard in January 2004.
- This standard can be viewed as a tool, whereby wind turbine and gearbox manufactures can communicate and understand each other’s needs in developing a gearbox specification for wind turbine applications.

- Over the last few years, heat treating equipment for the production of ADI has steadily advanced; increasing the both process capability and capacity.
- Currently, engineers routirtely specify ADI components for gearbox components up to several tons.
- The leading ADI producers and developers Applied Processes of US & ADI Treatment Ltd of UK have recently adopted new plans to heat treat large diameter gearbox parts for wind turbine systems.
- The renewable energy market has the potential to fully utilize those new capacities in manufacturing large size gears used in wind turbines.



A photograph of a 7 metric ton ductile iron gear carrier for a wind turbine gearbox being transferred into the vestibule of the furnace as a first step in the austempering process

- The growth of ADI applications and the production of large size ADI castings has either been accelerated or hindered by the knowledge or lack of:
  - The metallurgy of both heavy section ductile iron and ADI,
  - The mechanical properties of the material, specifically the dynamic properties, and
  - The equipment to properly and cost effective process such components.
- The lack of austempering facilities needed for large gearbox components used in wind turbines, was obviously beyond the delay of using ADI as a material for manufacturing those components.

Agricultural Equipment Components

ADI Plough Blades Produced at CMRDI





Field Evaluation Reports For Plough Blades









Redesign of Hammer Mill

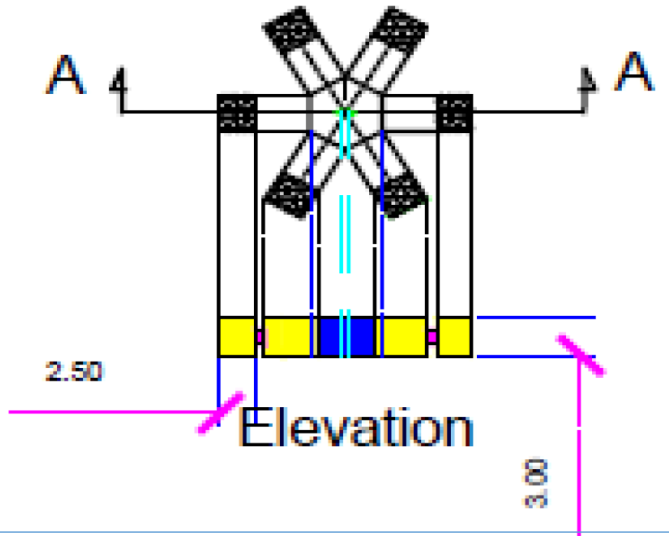
Weld Steel



Cast ADI

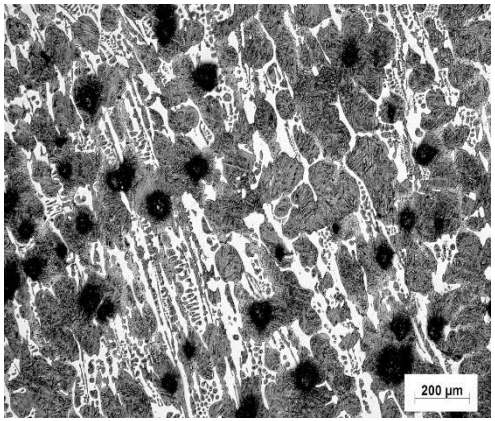


Layout





Steel Rolling Mill







Rolling Rings and Static Parts for Steel Industry

Grain Milling



ADI Air lock

Railways Spare Parts







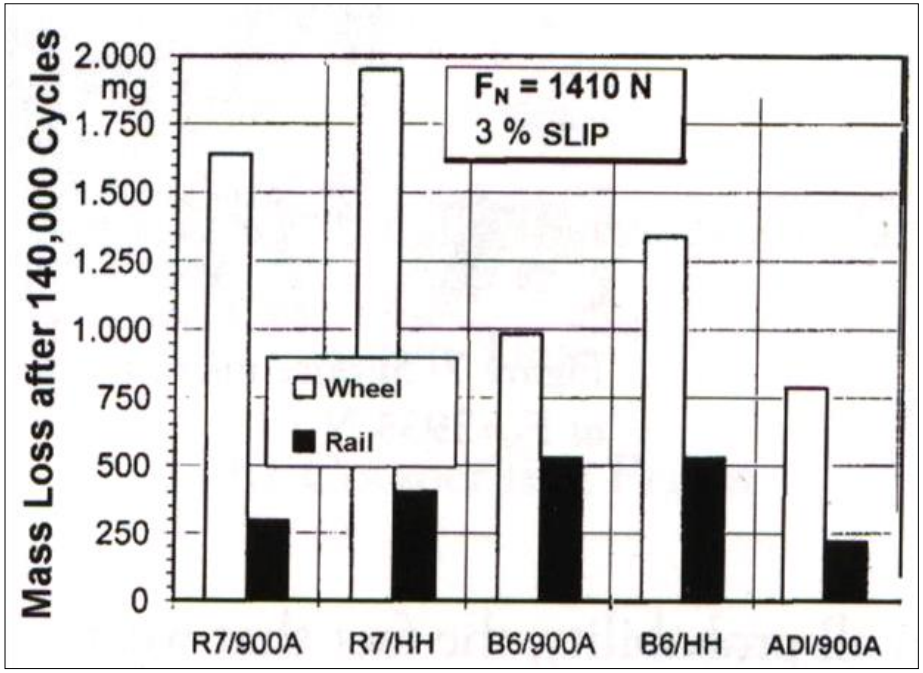
Basalt Tamping Tine used by Egyptian Railways

- Modern track maintenance machinery is known for for its long term availability. However, the working parts are subjected to excessive wear.
- Now, its urgent to develop and test new material that significantly extent the service life of work units like tamping tine
- A tamping machine or basalt tamper is a machine used to pack (or tamp) the track basalt under railway tracks to make the tracks more durable.

ADI AS AN ALTERNATIVE MATERIAL FOR RAILCAR WHEELS

- At low contact forces: ADI/steel pairing shows the most favorable wear characteristics.

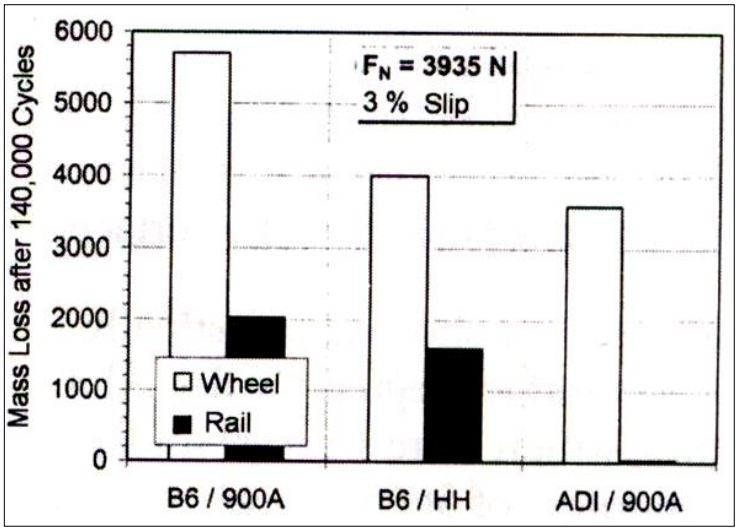
K. Mädler: Deutsche Bah, AG-Technical Centre, Germany				
	Rail Steels		Wheel Steels	
	900 A	HH	R7	B6
C-content, %	0.6-0.8	0.7	0.5	0.6
Yield strength, N/mm^2	880-1030	1200	850	1000
Elongation, %	10	11	20	14



Mass Loss for Various Wheel/Rail Material Combinations at 3% Slip and F_N = 1410 N

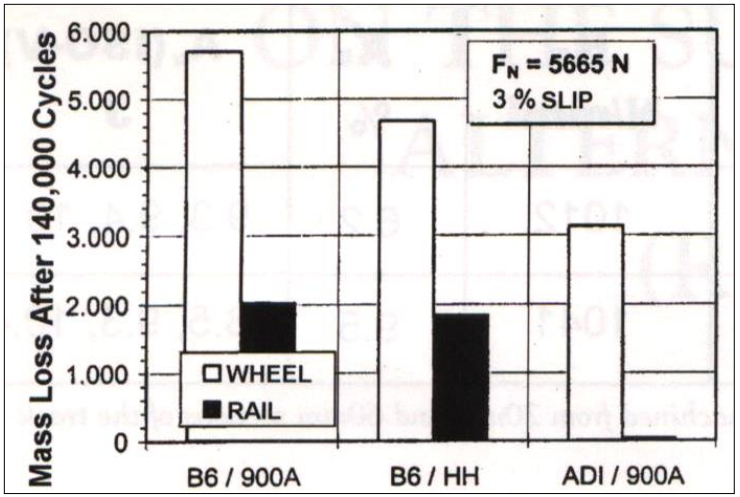
ADI AS AN ALTERNATIVE MATERIAL FOR RAILCAR WHEELS

- At higher contact (normal) forces: the favorable influence of wear systems becomes more apparent.



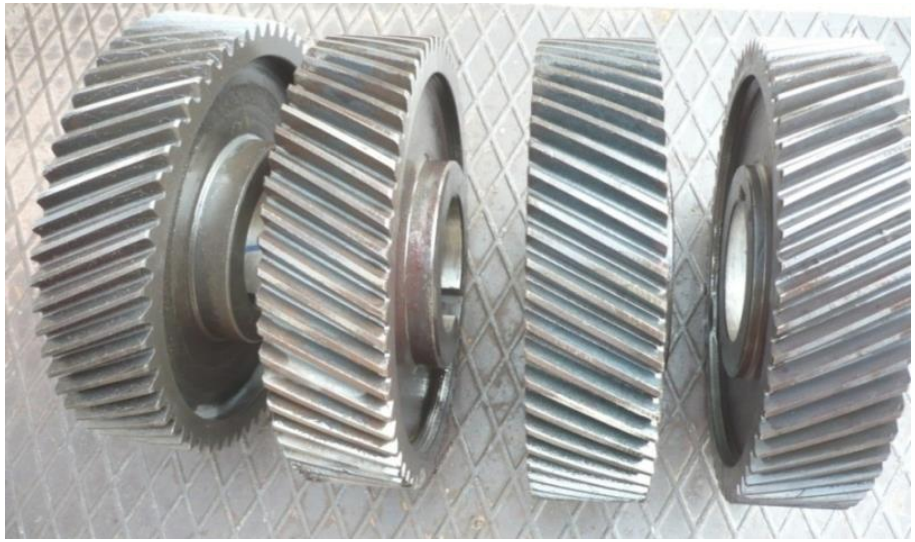
Mass Loss for Various Wheel/Rail Material Combinations at 3% Slip and F_N = 3935 N

- Mass loss at higher contact forces can be reduced considerably through the use of ADI, especially in the rail sample due to:
  - Lubricating action of graphite
  - Strain-hardening tendency of the ausferritic matrix



Mass Loss for Various Wheel/Rail Material Combinations at 3% Slip and FN = 5665 N

GERF Project



Gear (Tribological + contact fatigue)



Connecting rods (tensile fatigue)



Steering knuckle (Strength under high strain rate)



Plough blades (abrasion resistance)

5

MACHINING & MACHINABILITY

Machining

- When ADI first started to be used for engineering applications, there were many difficulties experienced in trying to machine it, and some of these doubtlessly persist to this day.

- The hardest grades of ADI reach a hardness of ~ 50 HRC which would pose a challenge for any high volume machining operation.

- Although the softer grades of ADI have a typical hardness of 300–350 BHN, their matrix structure contains up to 40% retained austenite. When subjected to strains in service, this phase rapidly work hardens and can transform to martensite; this can thereby reduce the machinability compared with a steel of equivalent hardness.

- ADI components are now used in a very wide range of applications having an equally wide range of requirements regarding accuracy and surface finish.

- Figure 9 summarizes the options regarding the integration of the machining operations into the ADI production route.

- At one end of the scale, substantial numbers of ADI components do not require to be machined; examples include ground-engaging agricultural and earth-moving tools.

- However, most automotive components will need to be machined. Most of those made in the softer grades of ADI can be machined after heat treatment using appropriate machine tools and inserts.

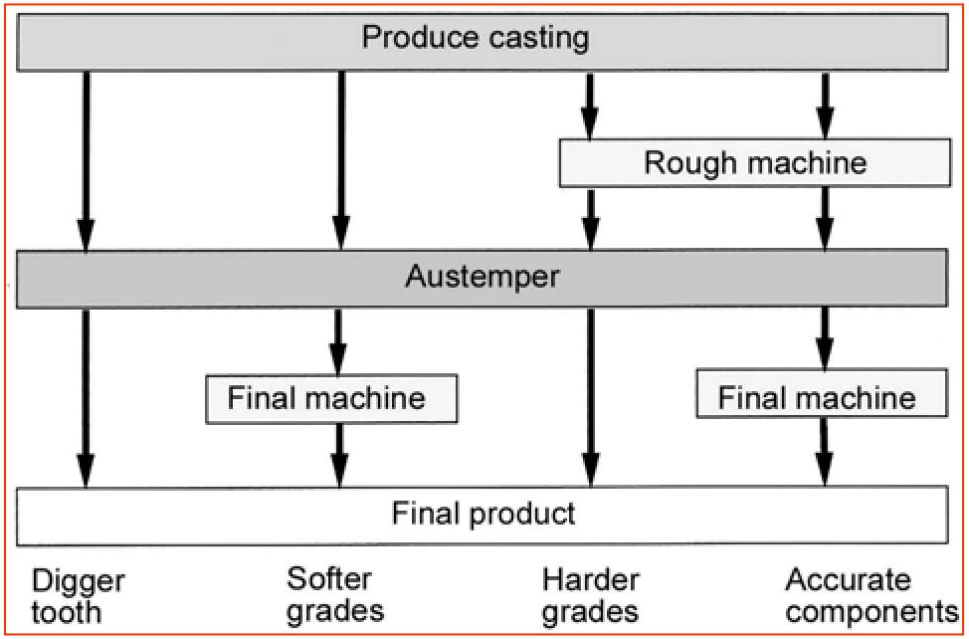


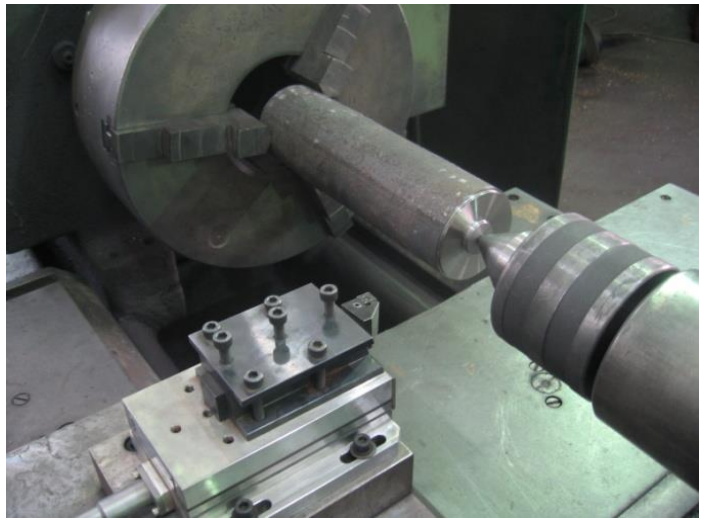
Fig. 9. Options for integrating casting, machining and heat treatment of ADI components

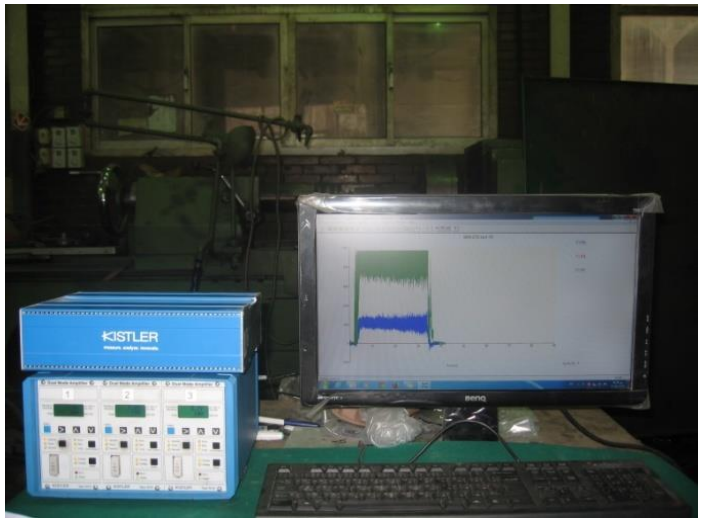
- This becomes progressively more difficult as the hardness increases and it is often preferable to machine before heat treatment by making an allowance for the dimensional growth, assuming that this is predictable and that there is no significant distortion. If the dimensional growth is not sufficiently consistent, the only option is to do most of the machining before austempering, and to finish machine any critical dimensions after austempering.

- This can create logistical difficulties if the casting, machining and heat treatment are done by different companies located at some distance from each other.

- Nevertheless, this route has been widely used for ADI gears which must be extremely accurate for them to operate quietly and to have a long life.

Cutting Force Measurements





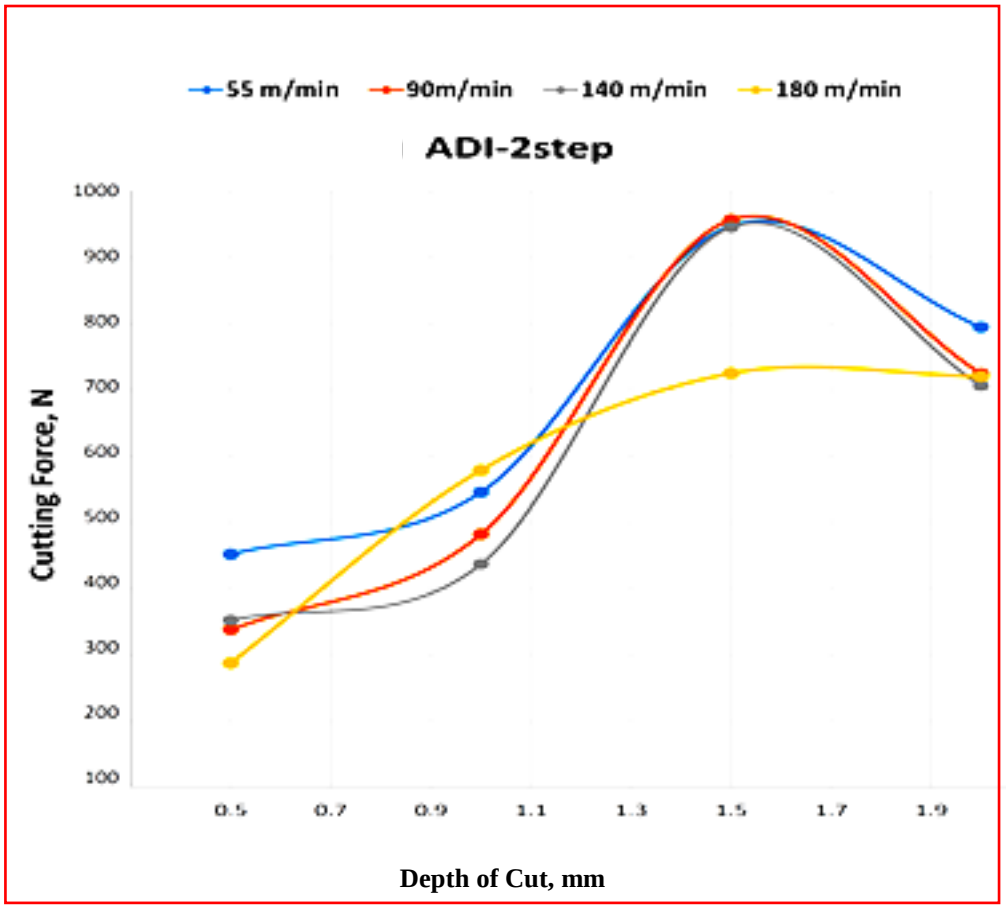
Experimental set up using KISTLER dynamometer 9255B

- The cutting force data used in the analyses were measured by a three-dimensional force dynamometer type ***9255B*** (Kistler, Coherent**)**.
- The dynamometer correspondingly measures forces along the X, Y and Z-directions using the charge generated by the quartz crystals. The charge generated was received by the Kistler charge amplifier type ***5814B1***, which converts the charge into analogue signal and gives the output (force)

Cutting Force vs. Depth of Cut and Cutting Speed

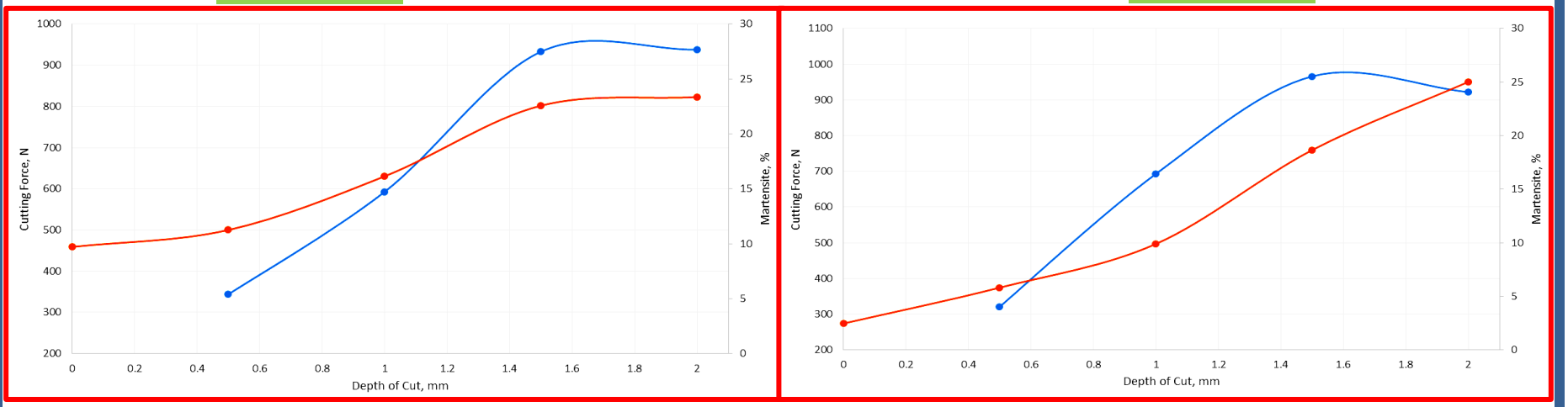
- The cutting force of the two-step ADI reaches the same maximum values of about 980 N at 1.5 mm cutting depth for the cutting speeds range of 55-140 m/min, further increase in the cutting depth leads to a sudden drop in the cutting force to almost 700 N.

- It is noteworthy that increasing the cutting speed of this alloy to 180 m/min leads to much lower cutting force of about 700 N at both cutting depth of 1.5 and 2.0 mm. the same cutting force is recorded for the other lower speeds at 2.0 mm depth of cutting.



Strain induced martensite transformation during machining

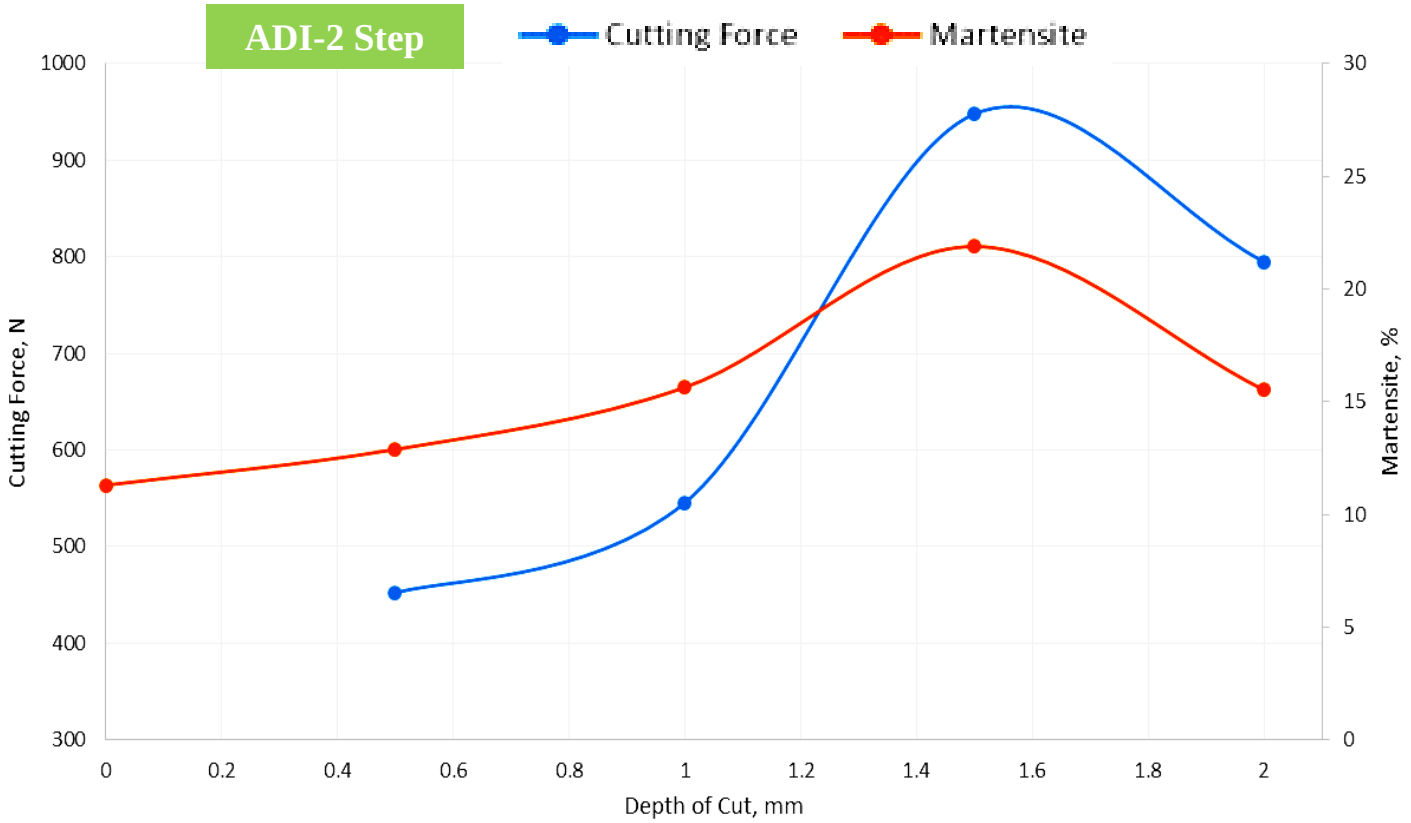
ADI-375



ADI-275

- It is evident that the increase in cutting force is always associated with a corresponding increase in the martensite content when the cutting depth was increased from 0.5 – 2.0 mm.
- The **ADI-375 and ADI-275** alloys, being subjected to a cutting depth of 2.0 mm **had the same total martensite** (which is the sum of original content before machining + the martensite formed by deformation induced transformation from the retained austenite).
- The fact that the two alloys, **ADI-375 and ADI-275 reached to the same cutting force at 2.0 mm depth of cut gives a good indication that the martensitic transformation due to induced strains is closely related to the machinability behavior of the ADI-alloys.**

Strain induced martensite transformation during machining



- Such correlation is even more evident with the **ADI-2step alloy**.
- At 1.5 mm cutting depth, **the martensitic content and the force of cutting reached almost the same levels** observed for the other two previously discussed alloys ADI-375 and ADI-275, However, increasing the cutting depth to 2.0 mm, both the martensite content and the cutting force decreased in very similar manner.

- The machinability of the different ADI-grades were determined as a function of the cutting force experienced during machining. The effect of different parameters of machining like cutting speed as well as cutting depth on the force of cutting was investigated and correlated to the strain induced martensitic transformation from retained austenite during machining.

- Retained austenite transformation to martensite through the TRIP effect was found to play a profound role in determining the cutting force and machinability behaviour of ADI-grades.

- The thickness of the hardened layer by martensite formation is a function of different factors, among them are the cutting depth and cutting speed added, to the amount and stability of the retained austenite in the different alloys of ADI.

- If the depth of hardened layer is lower than 1.5 mm then the cutting depth of values over this thickness will result in decreasing the cutting force, and the cutting force will show a maximum value at 1.5 mm depth of cut.

- With increasing the cutting depth values, the cutting tool will avoid the hardened layer and the cutting action will proceed through the base of unhardened metal, with a drop in the cutting force.

- It was found that optimum machinability of different ADI-grades requires different combinations of cutting speed and depth of cutting.

6

HIGH-STRAIN DYNAMIC DEFORMATION OF ADI

Dynamic Deformation of ADI

- Engineering material used in different applications such as agricultural, mining and other special applications, particularly military ones face new demands, one of which is the resistance to dynamic loads.

- Those materials are subjected to specific, non-static types of tests as the phenomena taking part in such interaction is rather complex.

- Recently, the dynamic properties of the austempered ductile iron ADI have attracted the interest of several researchers.

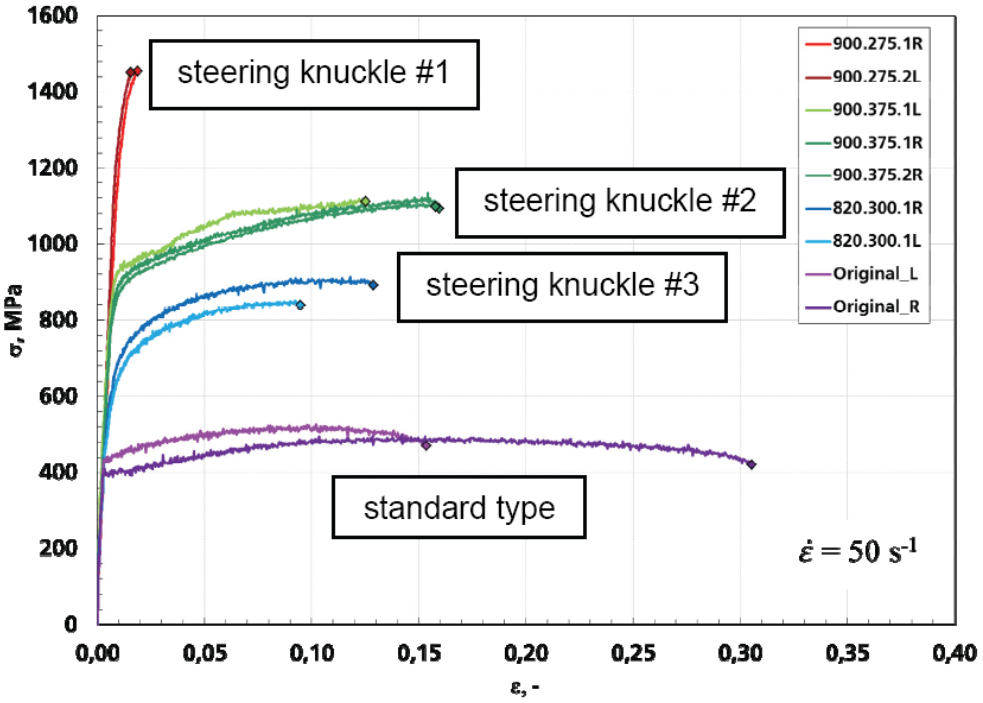
- The unique combination of ADI properties renders it the material ideal for use in structures operating under the conditions of high dynamic loads.

- Under such conditions the phase of particular interest in this material is the austenite, with its hardenability resulting from the strain-induced martensitic transformation.

- Such transformation is triggered by the action of stress or strain and results in the excellent properties of the material, such as those noticed in Mn-Hadfield steel used for various impact structures.

- The elevated contents of high-carbon retained austenite (10-50%) in ADI nominate this material for similar applications.

ADI For Crash Loading Applications



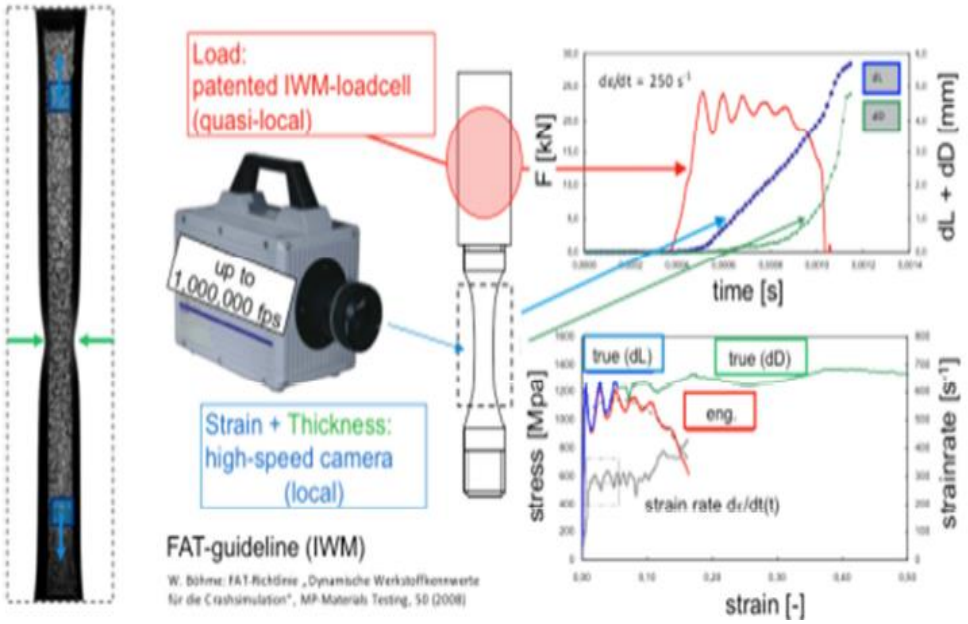


- High strain rate tests are (ε°= 50 s-1) necessary to assess the material behavior under misuse and crash load conditions.
- ADI austenitized at 900˚C and austempered at 375˚C shows high strength (1110 MPa) and high elongation at fracture (14%).
- Intercritically austenitized ADI showed lower strength (~900 MPa) and lower elongation (9-12%).
- Since higher deformations are recommended for suspension parts, in particular for legal reasons in context of accidents, both ADI grades can be considered as potential material for steering knuckle production.

ADI For Crash Loading Applications



IWM setup: High speed servo hydraulic testing machine up to 20 m/s and 100 KN

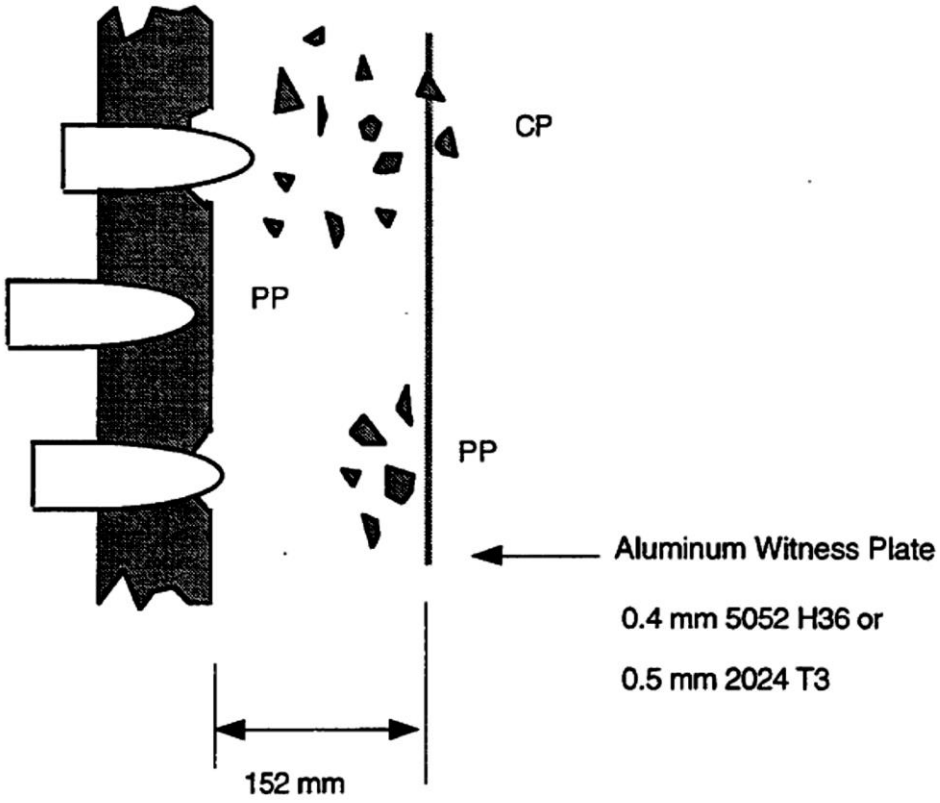


Theoretical set up for IWM high speed tensile test

- Tensile tests were performed in a servo hydraulic testing machine at crash-like strain rates of $\varepsilon^{\circ} = 50\ s^{-1}$.
- The elongation of the gauge length of the specimens was measured by a high speed video camera with a time resolution of 70,000 frame.sec-1

ADI and Ballistic Performance

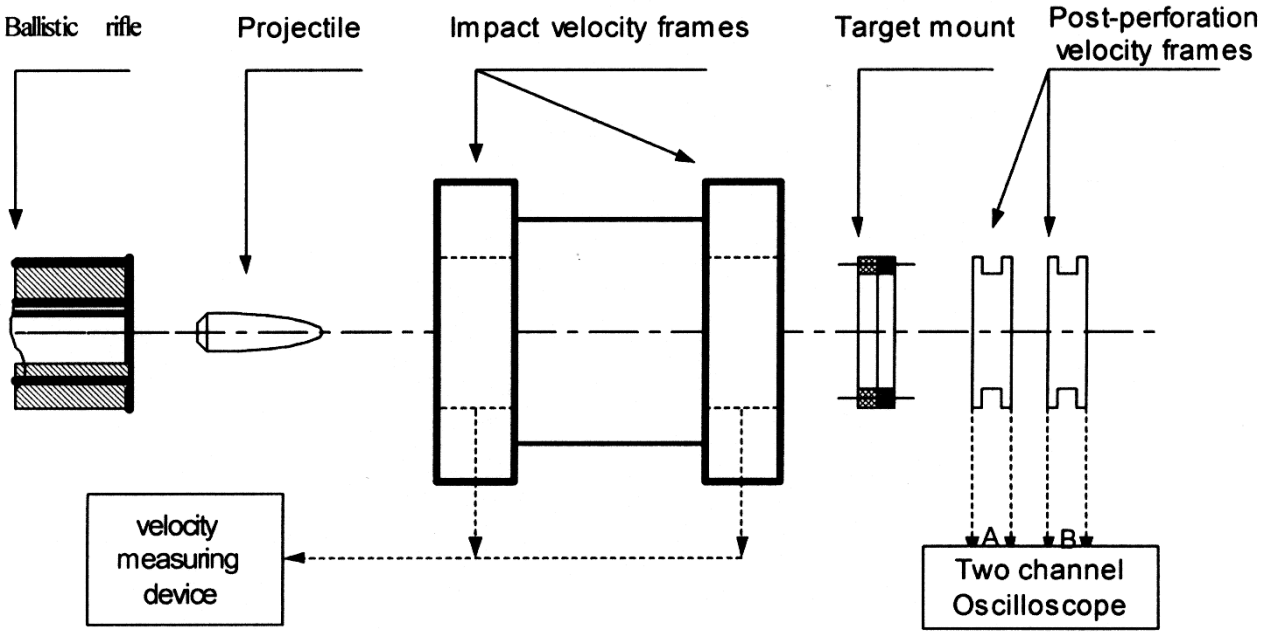
- Components used for military applications often include design objectives of ballistic tolerance for prevention of structure failures in service.
- Mechanical tests cannot replicate conditions of ballistic impact and mechanical tests cannot reliably predict ballistic performance.
- The V-50 ballistic test is very often used to measure the resistance to penetration of armor material.



Protection Criteria for Determination of V-50 Ballistic Limit. Complete Penetration (CP), Witness Plate Is Perforated by Either a Fragment of the Plate or the Projectile, Permitting the Passage of Light. Partial Penetration (PP), No Passage of Light Is Visible Through the Witness Plate Whether or Not Perforation of the Target Occurs.

Comparison of ADI targets (Hardness of 32 and 42 HRC) and steels MIL-A-12560 (Hardness range of 35.4 – 40.5 HRC) revealed that;-

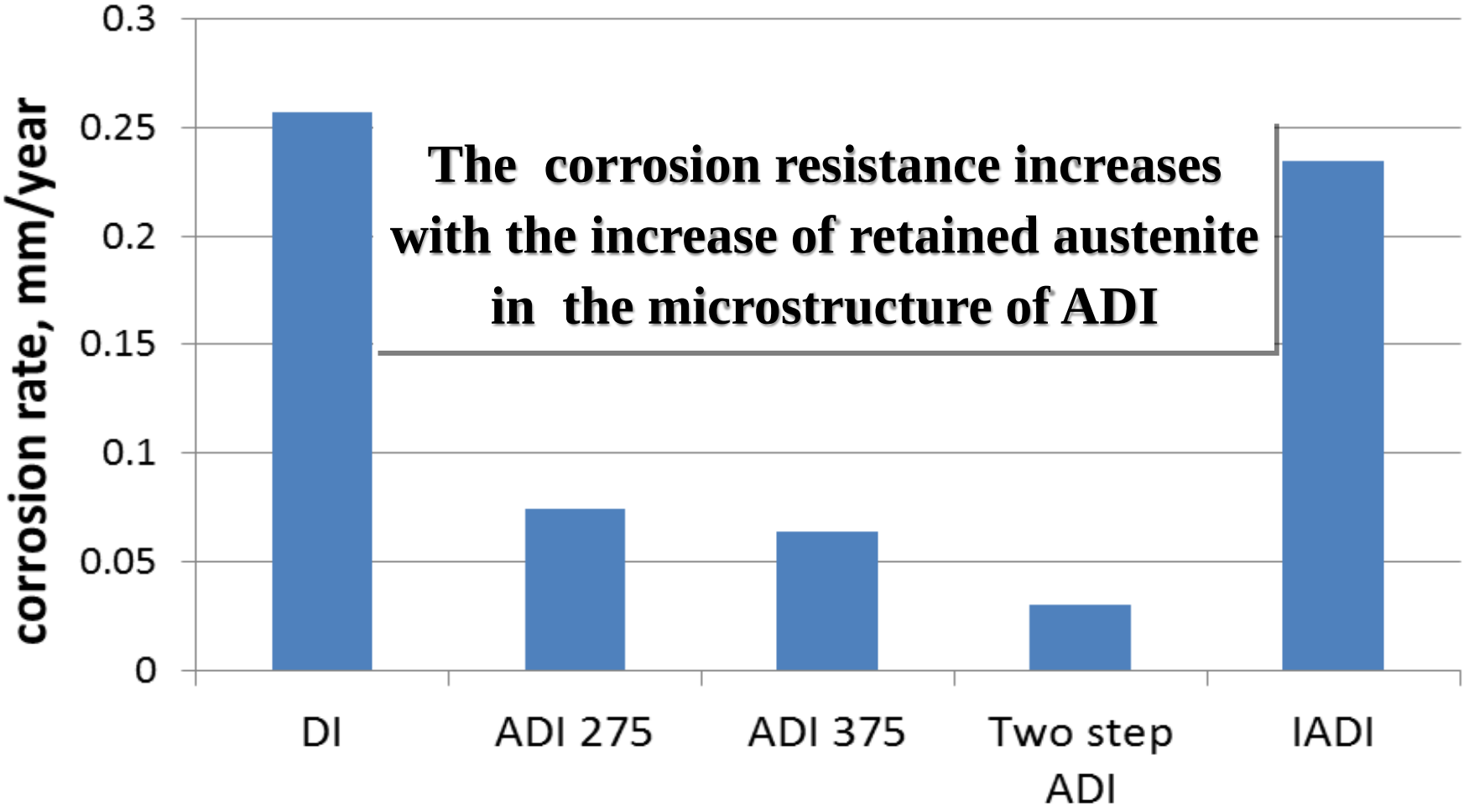
- Steels have greater resistance to penetration vs. 0.5 cal.APM2 projectiles.
- ADI has equal or greater resistance to ballistic penetration vs. 0.3 cal APM2 projectiles.
- ADI targets austempered to lower values of hardness and strength, but greater toughness and ductility, provide greater V50 velocities than ADI with higher values of hardness and strength.
- Strain hardening capacity as well as uniform distribution of graphite nodules in ADI increase resistance to ballistic penetration.



7

CORROSION RESISTANCE OF ADI

Corrosion Resistance of ADI in 3.5% NaCl Sodium chloride



The corrosion resistance increases with the increase of retained austenite in the microstructure of ADI

8

WELDING OF ADI

Weldability of ADI
a problem is still to be solved

1. Repair welding of the parent DI castings;

   - To rectify casting imperfection (shrinkage and gas defects) in DI castings before austempering.

   - The welding electrodes should be of composition that gives a weld gone of sufficient austemperability.

2. Welding of ADI may be considered during different phases of ADI production.

2.1 Welding of conventional ductile iron items before austempering; which may involve two main problems:

- Carbide formation in the as-welded ductile iron weld itself as well as the partially fused zone due to the high cooling rate. The formation of such carbides would inevitably increase cooling cracking susceptibility of the welded joint and impairs its machinability.

- The low austemperability of the unalloyed weld is usually the main reason that the microstructures and properties of the weld do not match those of the low alloy ADI and therefore, becomes a main problem affecting the weldability of ADI.

- The austemperability of the weld refers to the ability to avoid eutectoid transformation and the formation of pearlite upon cooling.

2.2 Welding of conventional ductile iron items before austempering; which may be dissimilar metals (steel or ductile iron) or another ADI parts:

- As the austempering process is performed at temperatures not higher than 400°C, the higher temperatures involved in the welding of ADI would necessarily damage the structure of ADI and result in deteriorated properties.
- During the welding procedure, the base metal near the weld would be heated to higher temperatures to form a heat affected zone (HAZ) of the same composition as the ADI base metal.
- Therefore, its as-welded microstructure would suffer reversion transformations leading to different microstructures and mechanical properties.
- Commonly, the toughness of the HAZ is poor and welding cracks are liable to arise in that zone.

CONCLUDING REMARKS

1. Extensive research work over the past decade has helped to develop the property combination of ADI in three directions:

   - Increased strength, ductility and toughness
   - Enhanced wear resistance/toughness combination
   - Improved machinability

2. ADI offers high levels of mechanical properties at a competitive cost. When the high strength of ADI is taken into account, it could successfully compete with lightweight alloys, as the additive weight required to give unit strength is lower. Moreover, when the relative cost of ADI required to give unit strength is considered, ADI seems to be one of the cheapest alloys. These points have yet to be fully appreciated by many design engineers. Currently, novel processing techniques adopted in achieve better strength and toughness properties include ausforming, cold-rolling, two-step austempering, squeeze casting and others.

CONCLUDING REMARKS

3. Carbidic as well bainitic/martensitic ADI offer opportunities for superior wear resistance, combined with reasonable toughness, which may open new applications for ADI.

4. The current research work aiming at improving machinability of ADI looks rather vital for the future of this material. The available machining techniques required for forged steel are not always suitable for ADI components, particularly on a high volume machining line dedicated to the production of one specific product. This problem can be minimized with the development of ferritic + ausferritic ADI structures. The high strain hardening capabilities nominate ADI for high strain dynamic applications such as crash loading components and military ballistic applications.

CONCLUDING REMARKS

5. There is still an obvious need for more extensive research work to improve the weldability of ADI, either for repair welding of ductile iron castings before austempering or construction welding of ADI components.

6. The experience gained at CMRDI over 15 years of development of ADI can serve as a strong base for more applications in the Egyptian market in agriculture, automotive, metallurgical and military applications.

7. There is still an obvious need for more extensive research work to improve the weldability of ADI, either for repair welding of ductile iron castings before austempering or construction welding of ADI components.




Thank you