Industrial Training Project Report

On

Selection of Hardening Process on the basis of Gear material

UNDER THE GUIDANCE OF: Mr. V.Sridhar

(Research and Development Unit, EICHER TRACTORS, Bhopal)

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COMPANY PROFILE:

Tractors and Farm Equipments Limited (TAFE) is a unit company of the Amalgamations group, one of India's largest light engineering groups with diverse interests in diesel engines, automobile components, tractors and related farm machinery, lubricants, panel instruments, hydraulic pumps, engineering tools, storage batteries, paints, engineering plastics, automobile franchises and printing apart from interests in agribusiness, book selling and publishing. The group's leadership technology, built on foreign know how has been nurtured through indigenous efforts.

TAFE was established in 1961 to manufacture and market a range of Massey Ferguson tractors and related farm equipment in India. One of the largest tractor manufacturers in India, TAFE's vision is to be the first choice of customers in India and to also move towards a growing presence in the international markets. TAFE has collaboration with AGCO Corporation, headquartered in Duluth, Georgia, which is one of the largest manufacturers, designers and distributors of agricultural equipment in the world. Its products are sold in more than 140 countries. With a network of more than 500 dealers, branches, service outlets as well as its own sales offices and depots covering the entire width and breadth of India, TAFE is committed to provide complete farming solutions to its customers and empowering them to work towards increased farm productivity, prosperity and profits.

<u>DECLARATION</u>

I hereby declare that the project work entitled "**<u>Selection of Hardening Processes on the basis of Gear material</u>**" is an authentic record of my own work carried out at **EICHER Tractors, Bhopal** as a part of academic curriculum for the award of degree of **B.Tech (Mechanical Engineering)**, at **Maulana Azad National Institute Of Technology, Bhopa**l under the guidance of **Mr. V. Sridhar (R & D Unit, EICHER Tractors, Bhopal) during summers 2010.**

Yash Verma
Scholar No. 071116002

Date: _____

Certified that the above statement made by the student is correct to the best of our knowledge and belief.

V.Sridhar
(R & D Unit, EICHER Tractors, Bhopal)
Project Coordinator

ACKNOWLEDGEMENT

I take this opportunity to explicit my gratitude and arrearage to my counselor**, Mr. V. Sridhar** for his eternal stimulus, precious exhortations and charismatic supervision during the course of the project. I also cherish his immense exuberant inclination to make people work as a team, primacy skills and an immense freedom; he has allowed me in my work, which indeed nourished my self-confidence. He has been wonderfully approachable and was ever helpful in his efforts to show me the right direction whenever I ran out of ideas. Working with him was a great learning experience

I am also thankful to the entire EICHER team (R & D) who helped me directly or indirectly to collect suitable information for the successful completion of my project.

Yash Verma

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Important Physical Properties

1. **Hardness:** The measure of a material's resistance to deformation by surface indentation or by abrasion.
2. **Hardenability:** It determines the depth of the hardened zone or the diameter of the cross section which can be hardened through.
3. **Toughness:** It is the amount of energy absorbed by the material till its fracture. Mathematically, it is the area under the stress-strain curve (up to the fracture point).
4. **Strength:** It is the maximum stress a material can handle.
5. **Modulus of resilience**: It is the strain energy absorbed per unit volume up to the elastic limit of material. Mathematically, it is the area under the stress-strain curve up to the elastic limit.
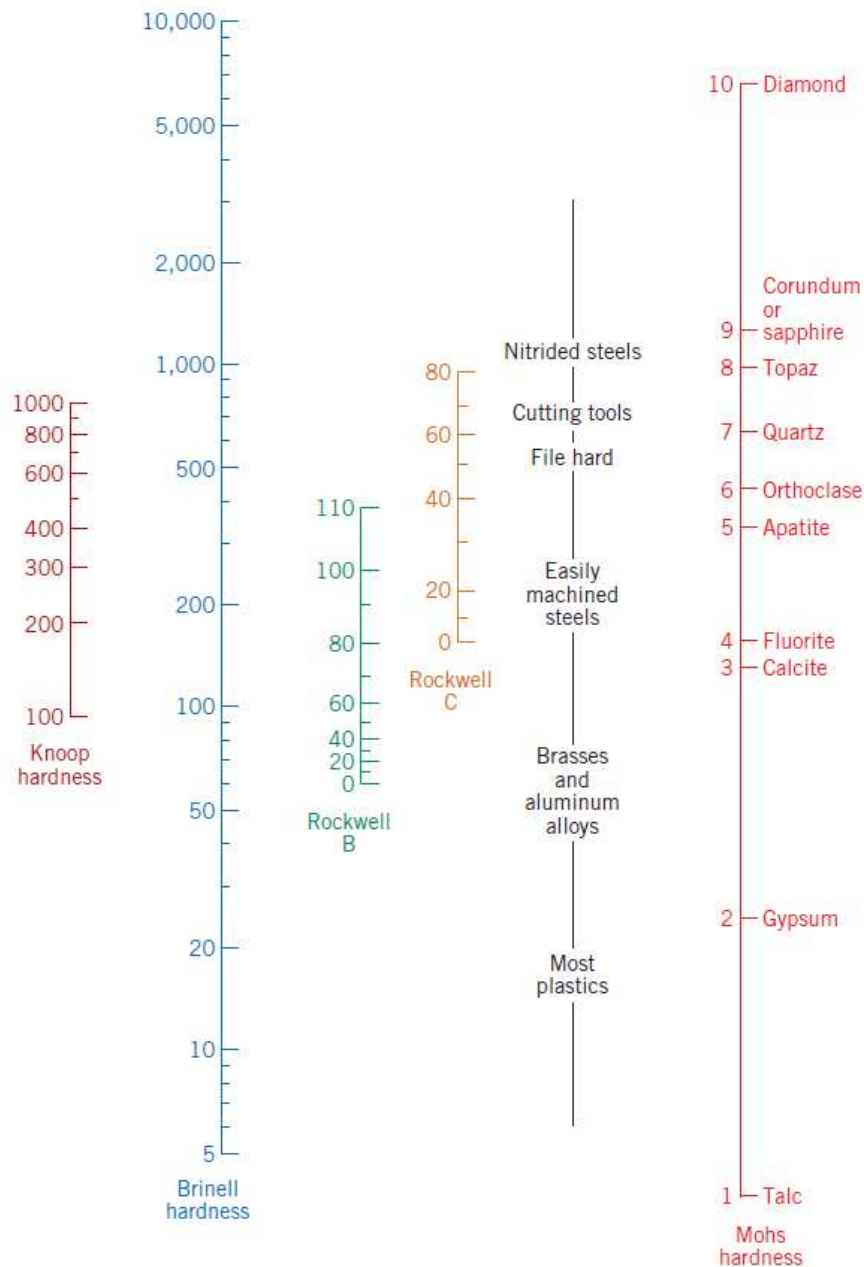
Allotropes of Iron

Iron Form	Crystal Structure	Temperature Range
α-Iron	Body Centre Cubic	Up to 769°C
β-Iron	Body Centre Cubic	769°C - 912°C
γ-Iron	Face Centre Cubic	912°C - 1392°C
δ-Iron	Body Centre Cubic	1392°C - 1536°C
Molten Metal	-	Above 1536°C

1. **Ferrite:** It is the interstitial solid solution of carbon in α-Iron. It has BCC structure. Maximum solubility of carbon in α-Iron is 0.025% at 723°C.(After 769 °C α-iron becomes β-iron crystal structure being same, but iron losses its magnetic properties.769 °C being its curie temperature.)

2. **Austenite:** It is the interstitial solid solution of carbon in γ-Iron. It has FCC structure. Maximum solubility of carbon in γ-Iron is 2.14% at 1147°C.

3. **δ-Ferrite**: It is the interstitial solid solution of carbon in δ-Iron. It has BCC structure. Maximum solubility of carbon in δ-Iron is 0.07%.

4. **Cementite**: It is the intermetallic compound of iron and carbon i.e. Iron Carbide. It has orthorhombic unit cell. Maximum solubility of carbon is 6.67%.

5. **Ledeburite**: It is the mechanical mixture of Cementite and Austenite and contains 4.27% carbon in it. It is a special mixture and obtained as the product of Eutectic Transformation.

6. **Transformed Ledeburite**: It is the Ledeburite the Austenite part of which is transformed to BCC structure.

7. **Pearlite**: It is the mechanical mixture of Ferrite and Cementite and contains 0.8% carbon. And the ratio of ferrite to Cementite is 7:1. It is a special mixture and is obtained by breakdown of Austenite of Eutectoid composition.
8. **Martensite:** When Austenite is cooled rapidly then it doesn't have time to breakdown into Cementite and ferrite and all the carbon remain dissolved in solid solution. The mixture is ferrite highly supersaturated with carbon known as Martensite. In this process FCC structure of

austenite is transformed to BCC structure of ferrite but in order to accommodate all the carbon the structure is transformed to Body Center Tetragonal (bct) for Martensite. It is the hardest form while reason of hardness is not the nucleation and growth but a shearing process. This involves very little atomic movement but considerable internal stress due to shear. 2% volume is increased when Martensite is formed.
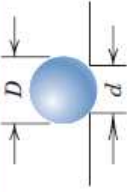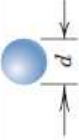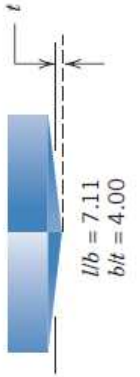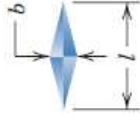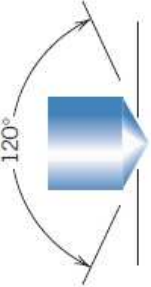
9. **Bainite**: When austenite is cooled rapidly but the rate is slower as required for Martensite then the product formed is Bainite.

Various Hardness Test and Scales:

Figure1: Hardness Test Scales

Test	Indenter	Shape of Indentation		Load	Formula for Hardness Number[a]
		Side View	Top View		
Brinell	10-mm sphere of steel or tungsten carbide	D, d	d	P	$HB = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid	$136°$	d_1, d_1	P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid	t $l/b = 7.11$ $b/t = 4.00$	b, l	P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ in. diameter steel spheres	$120°$		60 kg, 100 kg, 150 kg } Rockwell 15 kg, 30 kg, 45 kg } Superficial Rockwell	

Shape of Indentation

Iron-Carbon (Fe-C) equilibrium diagram:
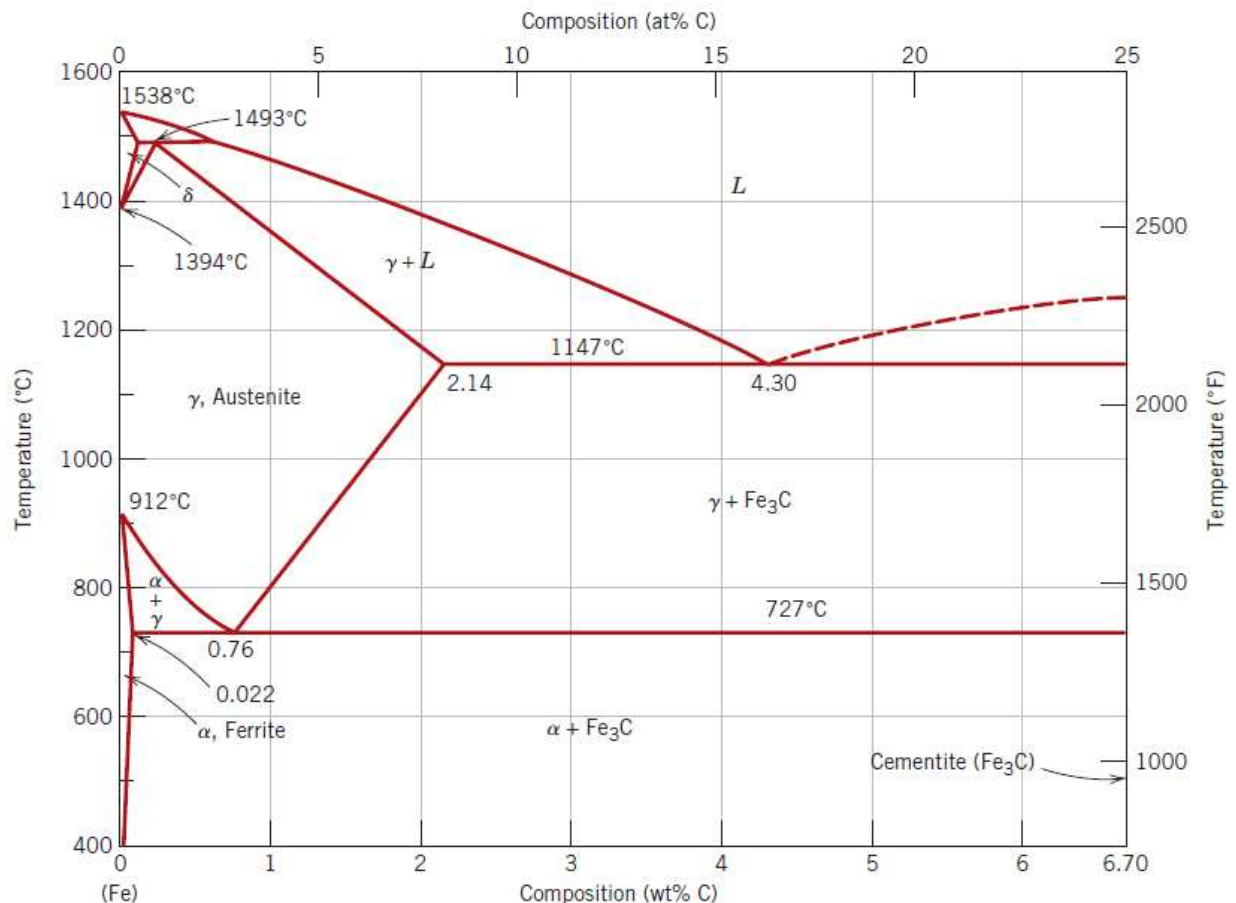
Iron-Carbon equilibrium diagram is used to determine the Hardening Temperature i.e. the temperature up to which the alloy should be heated in order to obtain the austenitic phase. As this temperature plays a major role in the hardening of alloy correct selection of this temperature is mandatory.

Time-Temperature-Transformation and Continuous Cooling Transformation Curves:

These diagrams gives the information of the Holding time (the time up to which alloy is to be held at temperature for the formation of austenitic phase) and Rate of Cooling (rate at which heated alloy should be cooled in order to obtain martensitic phase)

Time-Temperature-Transformation curves: It is a plot of temperature versus the logarithm of time for a steel alloy of definite composition. It is used to determine when transformation begins and end for an isothermal heat treatment of a previously austenitized alloy.

Continuous Cooling Transformation: It is the plot of temperature versus the logarithm of time for a steel alloy of definite composition. Used to indicate when transformation occurs as the initially austenitized materials is continuously cooled at a specified rate; in addition, the final microstructure and mechanical properties can be predicted.
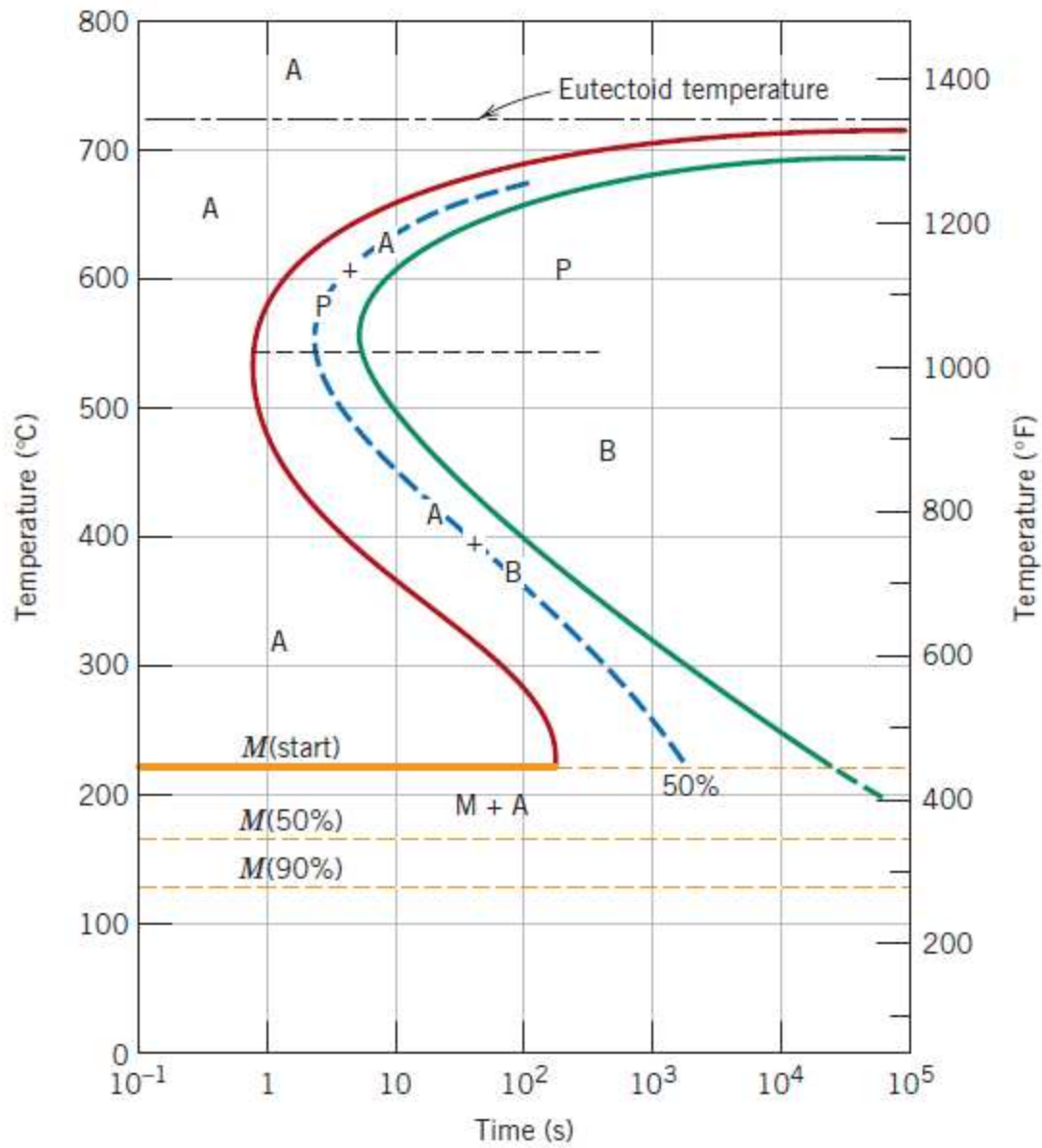
Figure 2: TTT diagram for iron-carbon alloy of eutectoid composition.
A-Austenite, B-Bainite, P-Pearlite, M-Martensite.
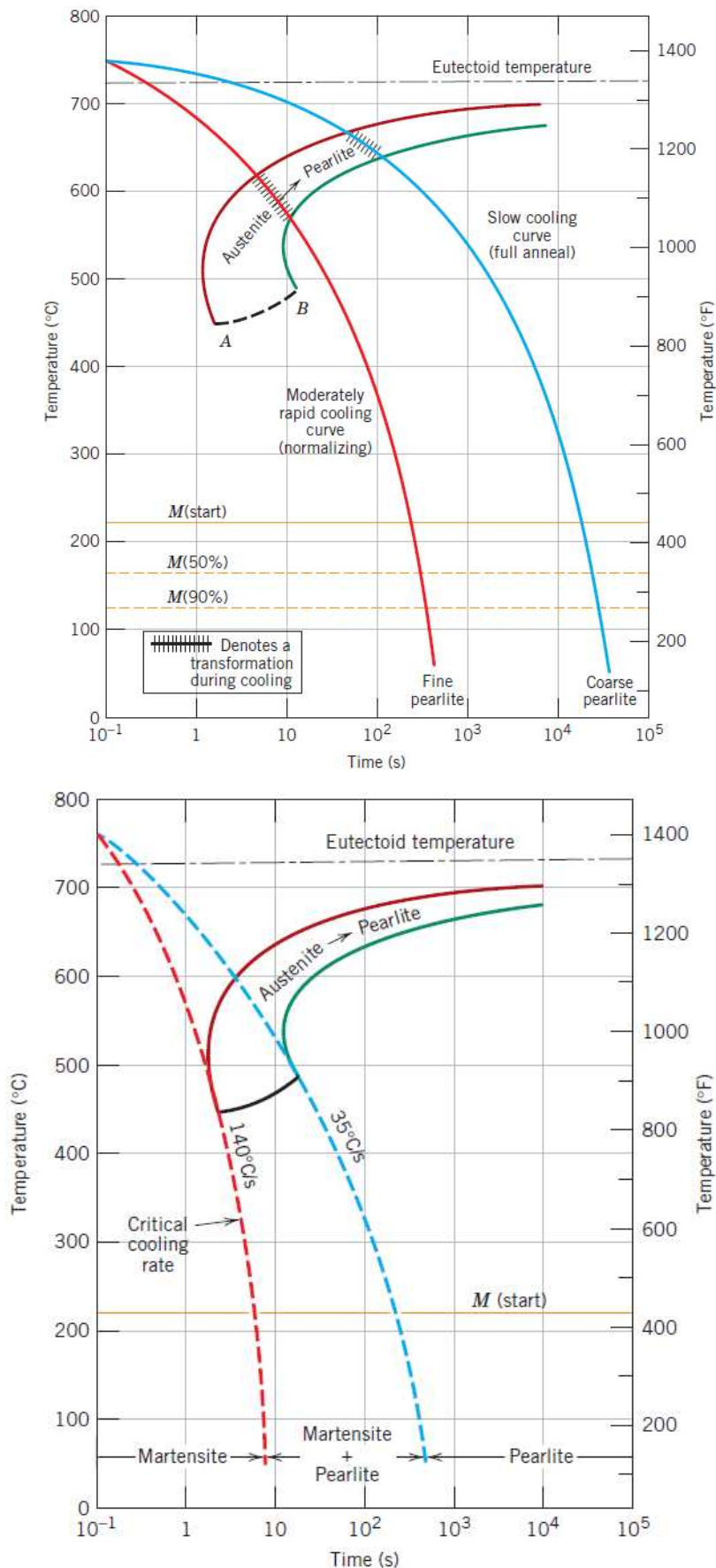
Figure 3: CCT diagram along with TTT diagram for iron-carbon alloy of eutectoid steel to show the dependence of microstructure on the rate of cooling.

Cooling very slowly produces Ferrite and Pearlite. Cooling more rapidly produces a phase called Bainite. Two different types of these phases can be produced – Upper Bainite and Lower Bainite
Upper Bainite: Between 500°C and 350°C, upper Bainite forms with initial nuclei are ferrite. Cementite then precipitates from the carbon enriched layer of austenite, allowing further growth of ferrite.
Lower Bainite: Below 350°C coherent ferrite, supersaturated with carbon.
This is then followed by precipitation of carbide within the ferrite needle. Cooling more rapidly then this produces Martensite which is the hardest phase. All heat treatment processes (except Nitriding) are based on hardening through formation of Martensite.
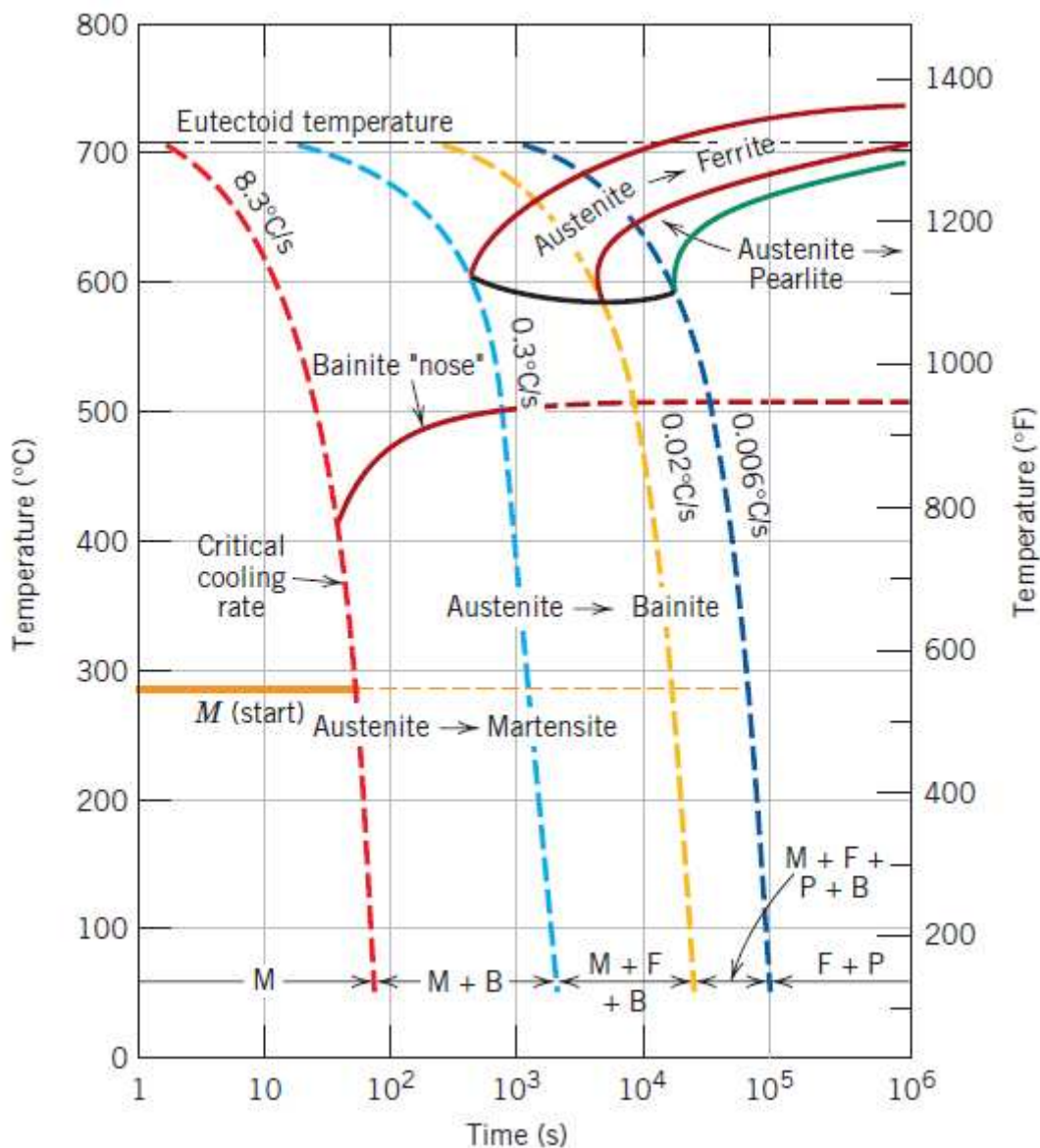
Figure 4: Isothermal transformation diagram along with CCT diagram for an alloy steel **AISI 4340**
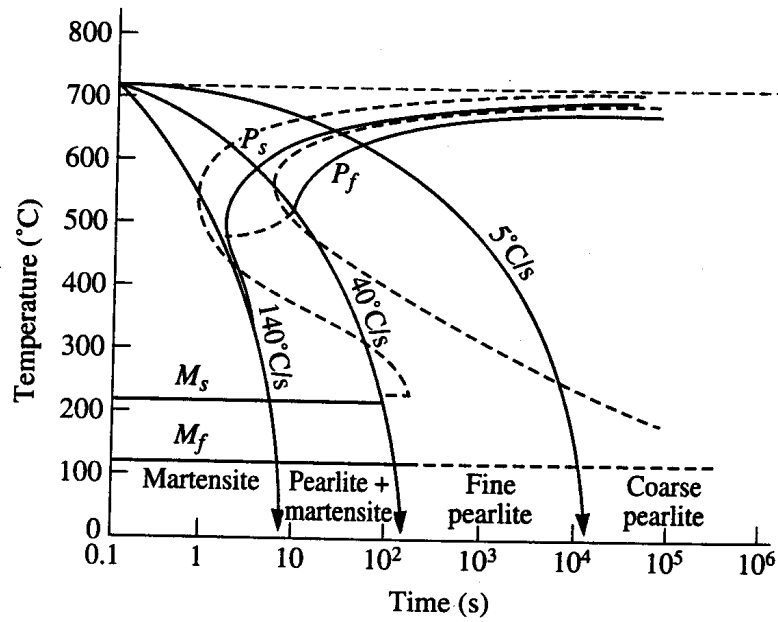
Figure 5: CCT diagram for an alloy steel **AISI 1080**
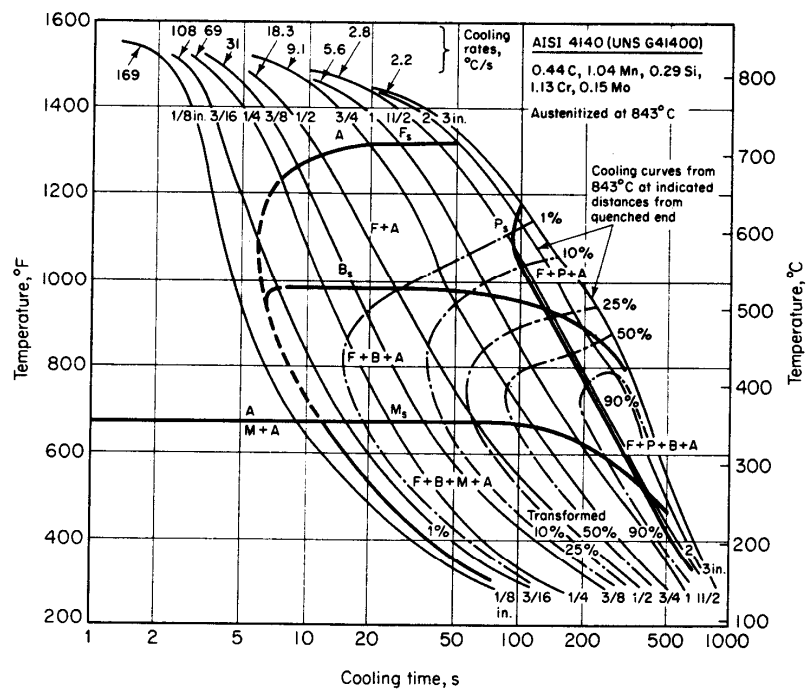
Figure 10-11 Continuous cooling transformations for AISI 4140 steel (UNS G41400). Cooling rates are at 700°C. A = austenite, F = ferrite, P = pearlite, B = bainite, M = martensite. [From Homer Research Laboratories, Bethlehem Steel Co., reprinted in *Source Book on Industrial Alloy and Engineering Data* (Metals Park, Ohio: American Society for Metals, 1978), pp. 125, 129.]

Figure 6: CCT diagram for an alloy steel **AISI 4140**
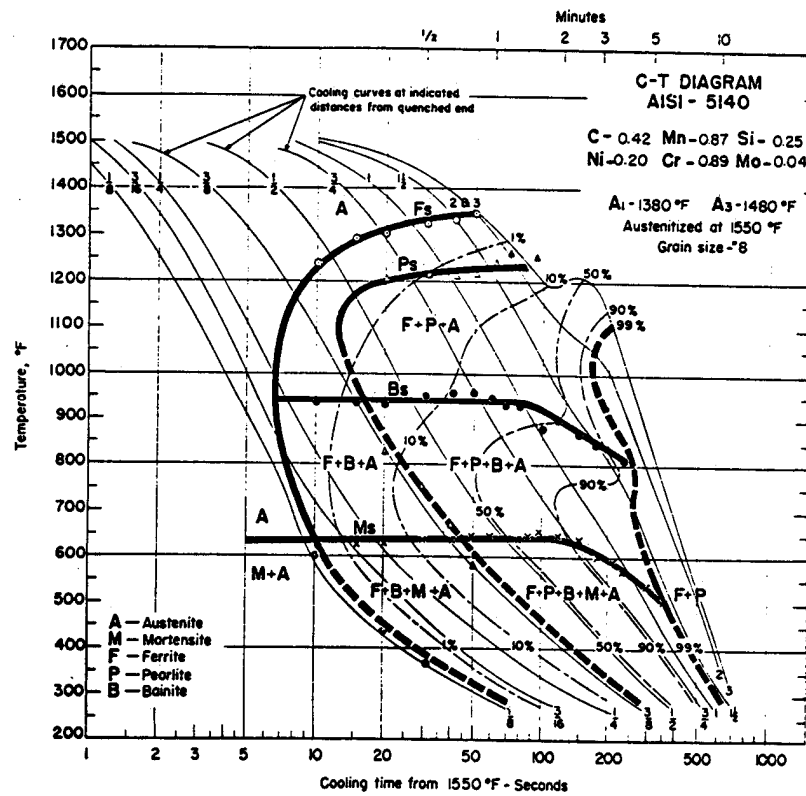
Figure 7: CCT diagram of an alloy steel **AISI 5140**

Types of Heat treatment

Heat Treatment: It is a process of heating cycles where the metal is subjected to controlled temperature changes in solid state. Heating process can change the size and shape of grain structure and can also change the constituents and hence the properties of steel.
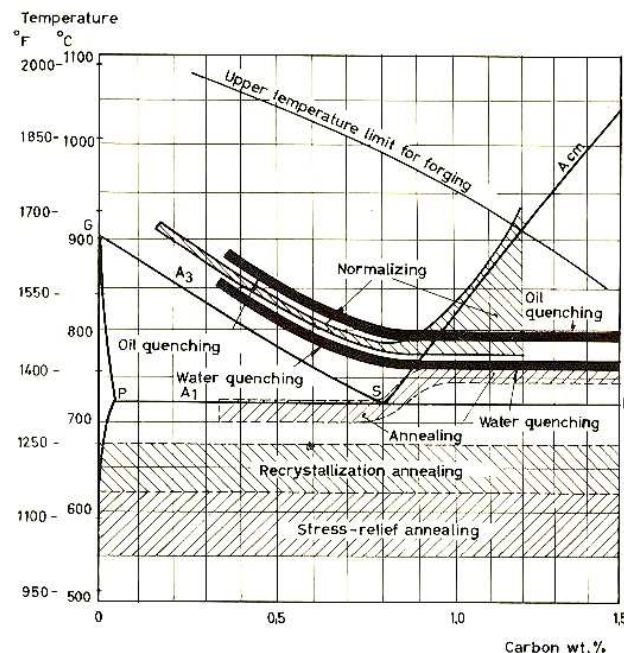
Figure 8: Fe-C equilibrium diagram showing temperature ranges for various heat treatment processes.

<u>Various Heat Treatment processes</u>:

1.**Annealing**: It is a process that produces equilibrium conditions by heating and maintaining steel at a suitable temperature(below or above the critical temperature) and then cooling it slowly often in furnace. It is done to induce softness, relieve internal stress, refine structure and improve cold working properties.
The transformation occurs in this process is from Austenite to Pearlite.

2. **Normalizing**: In this process steel is heated to a temperature 40°C above the upper critical temperature and then is allowed to cool in still air. It is done to refine grain structure, to increase hardness, strength but a little loss in ductility.

3. **Quenching or Hardening**: In this process steel is heated to a temperature so that austenite phase is obtained and then it is cooled rapidly to obtain Martensite. Rapid cooling can be done by immersing heated steel in oil or water bath (sometimes called as SALT BATH) or in a blast of air. In order to confirm complete conversion of austenite into Martensite, minimum cooling rate of heated steel is set which is called as Critical Cooling Rate. For water it is 500°C, for oil it is 250°C and for blast of air it is 50°C.
Sometimes problem of Cracking arises due to the more expansion of inner core material (Pearlite) as compared to surface material (Martensite) due to difference in cooling rate; this can be avoided by selecting the proper cooling medium for steels. Like Alloy steels should be cooled in Oil, Special Alloy steels should be cooled in Air Blast and Plain Carbon Steels in Water.

4. **Tempering**: This process is done to relieve the internal stresses developed in the steel and to increase the ductility and toughness at the expense of hardness and strength. In this steel is heated gently between 180°C to 650°C (sub-critical temperature).

5. **Surface Hardening**: This is a special hardening process in which a particular surface of steel is made hard without altering the hardness of any other portion. This process includes – (a) Induction Hardening, (b) Flame Hardening.
In Induction Hardening heating of steel is done by heating the portion (only that portion of steel is heated which is to be hardened) with the help of high frequency induction coil while in Flame hardening heating is done through oxy-acetylene flame. The transformation that takes place is from austenite to Martensite.

6. **Case Hardening**: This is also a hardening process but requires heating of whole component. In this process steel is heated in an environment of carbon or nitrogen and then heated steel is tempered to reduce brittleness. Case hardening consists of mainly three processes – (a) Carburizing, (b) Nitriding, (c) Carbu-Nitriding. Nitriding is used mainly for Low alloy steels while it is preferably not used for Plain carbon steels as formed nitride causes brittleness.

7**. Austempering**: In this process transformation of austenite takes place into Bainite. When austenite is cooled rapidly and the cooling is arrested before the formation of Martensite (or at the temperature when Martensite just starts to form) and then temperature is held is constant the result is Bainite rather then Pearlite.

8. **Marquenching**: This process is done to reduce the cracking of surface in quenched surface due to difference in expansion of core material and surface material. In this steel is quenched to a temperature where Martensite just begins to form and is allowed to reach equilibrium and then

cooled slowly to form Martensite thus avoiding severe stresses. This steel is then tempered to improve the ductility of steel.

9. **Ausforming**: This process is done to produce exceptionally strong steel. In this after heating the steel up to austenitic phase during cooling the process is interrupted at 340°C to 440°C, the steel is then tempered to improve ductility.

Hardening Process for Gears

There are mainly following 3 processes which are used for hardening the gears – (i) Through Hardening,
(ii). Case Hardening: (a) Carburizing, (b) Nitriding, (c) Carbo-Nitriding.
(iii). Surface Hardening: (a) Induction Hardening, (b) Flame Hardening.
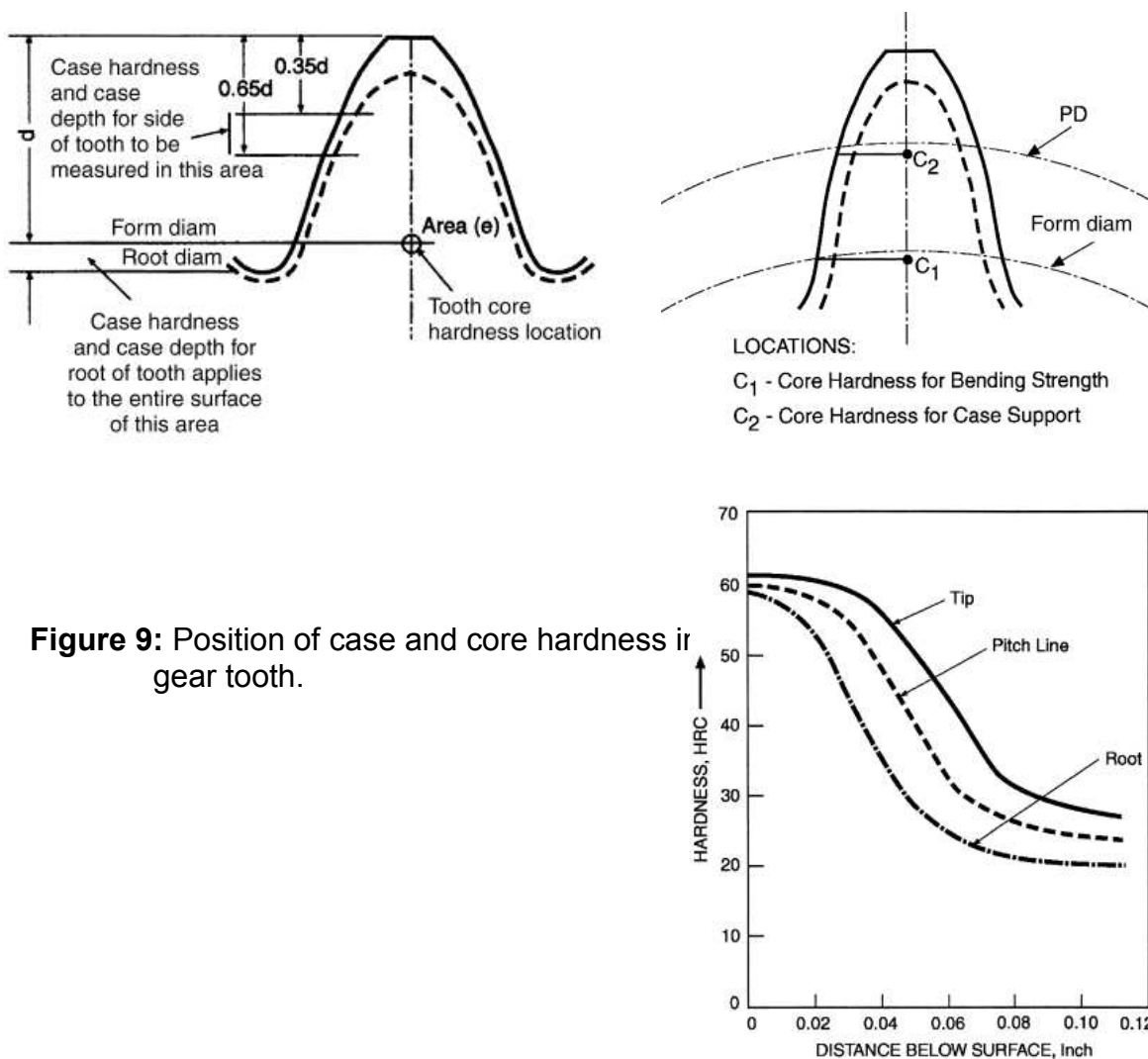
Figure 9: Position of case and core hardness in gear tooth.

(i). Through Hardening: This includes heating of the whole material to form austenite and then cooling it the right medium to produce martensitic phase in it. The process consists of general hardening process like quenching and post process like tempering (to reduce severe internal stresses and to make the material machinable). Through hardening should not be

confused with constant hardness. Hardness of material is not constant but a gradient of hardness exists. Achievable hardness is based upon the amount of carbon in steel while depth of hardness depends upon hardenability of steel which in turn depends on alloy content. The minimum hardness which must be obtained after quenching, in order to obtain sufficient strength after tempering depends on the desired strength. The higher the necessary strength, more complete has to be the formation of Martensite.

Through hardened steels are used for gears carrying small specific loads and are usually unalloyed or lean alloy steel. They have lowest hardenability. Examples of commonly Through Hardened gear steels are AISI 1045, 4130, 4140, 4145, 4340, 8640.

(ii). <u>Case Hardening</u>: Case Hardening produces a hard, wear resistance case or surface layer on the top of a ductile, shock resistance interior or core. **The idea behind the case hardening is to keep the core of the gear tooth at a level around 30 to 40 HRC to avoid tooth breakage while hardening the outer surface to increase the pitting resistance**. The higher the surface hardness value, the greater the pitting resistance. Bending strength increases for surface hardness up to 50 HRC, after which increase in bending strength is offset by increase in notch sensitivity. Case hardening consists of three processes: (a) Carburizing; (b) Nitriding; (c) Carbo-Nitriding.

(a) <u>Carburizing</u>: Carburizing is a heat treatment process in which iron or steel is heated in the presence of another material which liberates carbon as it decomposes, **at temperature between 850 and 950°C**, at which austenite, with its high solubility for carbon, is the stable crystal structure. Hardening is accomplished when the high-carbon surface layer is quenched to form Martensite so that a high-carbon martensitic case with good wear and fatigue resistance is superimposed on a tough, low-carbon steel core.

Carburizing followed by quenching leaves a layer of high strength and hardness, usually with high residual compressive stress. Plain low carbon case hardened steel is unsuitable for heavily loaded gears. **Gears are almost always oil quenched because distortion must be held to the lowest possible level. After case hardening, the hardness obtained lies in the range HRC 58 to 62** but in heavily loaded gears a minimum of HRC 60 is required**.** Hardness of HRC 64 and above, in gear steels, may indicate defective case hardening control; although this hardness is expected in rolling bearing races.

Carburizing steels for case hardening usually have base-carbon content lying between 0.1% to 0.25%, with the carbon content of the carburized layer generally being controlled at between 0.8 and 1%. However, surface carbon is often limited to 0.9% **because too high a carbon content can result in retained austenite and carbide network formation which result in reduction of hardness and hardenability. Presence of Chromium, Manganese and Nickel promotes the formation of retained austenite**. Case hardness of carburized steels is primarily a function of carbon content. When the carbon content of the steel exceeds about 0.50% additional carbon has no effect on hardness but does enhance hardenability. Carbon in excess of 0.50% may not be dissolved, which would thus require temperatures high enough to ensure carbon-austenite solid solution.

Case depth of carburized steel is a function of carburizing time and the available carbon potential at the surface. When prolonged carburizing times are used for deep case depths, a high carbon potential produces a high surface-carbon content, which may thus result in excessive retained austenite and free or network carbides. These microstructural elements have

adverse effects on the distribution of residual stress in the case-hardened part. Consequently, a high carbon potential may be suitable for short carburizing times but not for prolonged carburizing. **Retained austenite reduces the hardness of gear steel as austenite being softer than Martensite while Carbide network can cause a serious or catastrophic loss of bending strength. Presence of other elements like chromium, manganese, nickel, molybdenum etc. also helps in increasing the hardenability of steel only if present in right amounts. Otherwise, problems like internal oxidation and carbide formation may takes place which actually reduces the amount of these elements in austenitic phase and hence reduces hardenability**. Refinements include the control of carbon gradient and hardness gradient, which are consistently achieved only with gas carburizing (a method of carburizing in which steel is heated in an atmosphere of a gas usually methane to impart carbon in steel).

Fatigue strength of a case carburized gear is improved by residual compressive stress at surface. The effect of this is significant but needs to be controlled as teethes are weakened by surface decarburization and grinding of fillet curve as grinding induces some tensile stress on surface. Fatigue strength and toughness relative to tensile strength are required in applications where high shocks and bending stresses are expected. The fatigue strength and toughness can be improved by having a gear steel of high hardenability. While if wear resistance is of primary importance steel with lower hardenability or higher surface hardness is necessary. Unlike hardness which depends on carbon content hardenability depends on total alloy content. **Carburizing is used for gears which are required to have maximum load capacity. Common examples are AISI 1018, 4320, 5120, 8620, 9310 and 20MnCr5, 16MnCr5, ZF-7B, 20MoCr4 and V2525.**

To obtain maximum hardenability i.e. high fatigue strength and toughness with carburizing the gear steel should have following content: C – 0.11% maximum, Ni – 1.75%, Cr – 0.45% to 0.65%, Mo – 0.5% to 0.7%. While to obtain maximum wear resistance the gear steel must have a minimum hardness of HRC 60. And for a steel to have this hardness the carbon content should be 0.45%.
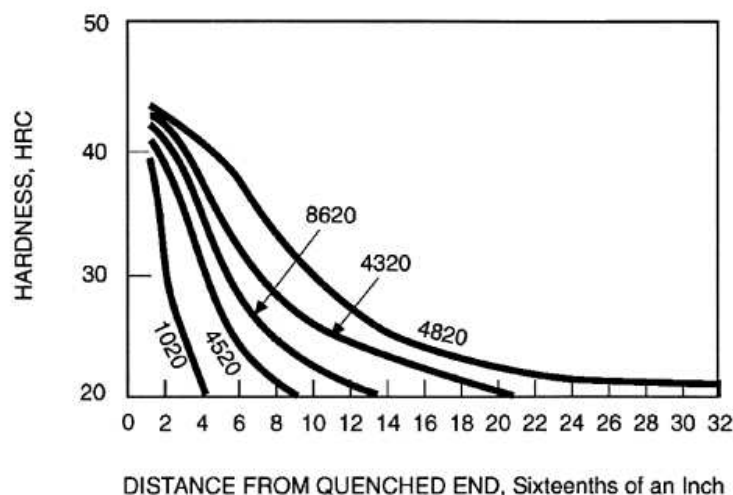
Figure 10: Comparative hardenability of 0.2% C AISI alloy steels
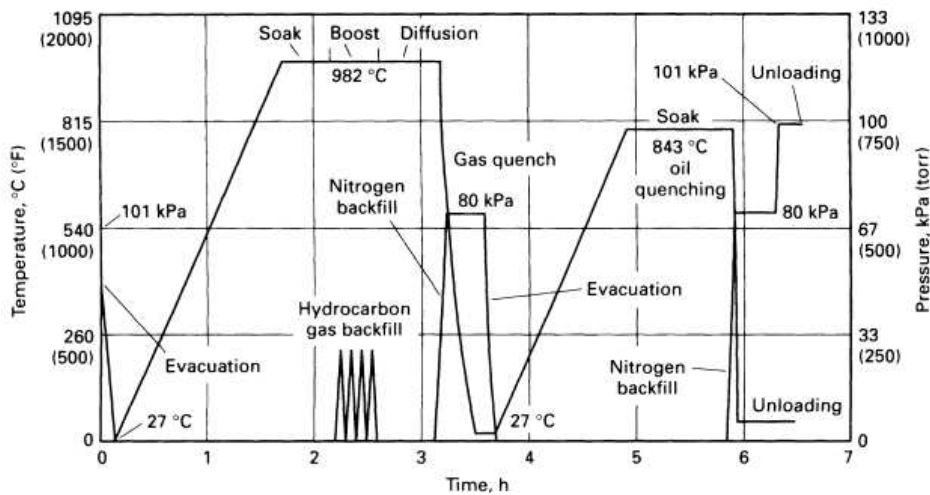
Figure 11: Plot of Temperature and Pressure versus Time for typical Vacuum Carburizing.

(b) <u>Nitriding</u>: Nitriding is a surface-hardening heat treatment that introduces nitrogen into the surface of steel at a **temperature range of 500 to 550°C**, while it is in the ferrite condition. Thus, nitriding is similar to carburizing in that surface composition is altered, but different in that **nitrogen is added into ferrite instead of austenite.** Because nitriding does not involve heating into the austenite phase field and a subsequent quench to form martensite, nitriding can be accomplished with a minimum of distortion and with excellent dimensional control.

The mechanism of nitriding is generally known, but the specific reactions that occur in different steels and with different nitriding media are not always known. Nitrogen has partial solubility in iron. It can form a solid solution with ferrite at nitrogen contents up to about 6%. At about 6% **N**, a compound called gamma prime (γ'), with a composition of Fe_4N is formed. At nitrogen contents greater than 8%, the equilibrium reaction product is ε compound, Fe_3N. Nitrided cases are stratified. The outermost surface can be all γ' and if this is the case, it is referred to as the white layer. Such a surface layer is undesirable: it is very hard profiles but is so brittle that it may spall in use. Usually it is removed; special nitriding processes are used to reduce this layer or make it less brittle. The ε zone of the case is hardened by the formation of the Fe_3N compound, and below this layer there is some solid solution strengthening from the nitrogen in solid solution.

Nitriding is done to to obtain high surface hardness, increase wear resistance, improve fatigue life, improve corrosion resistance (except for stainless steels), obtain a surface that is resistant to the softening effect of heat at temperatures up to the nitriding temperature. **Nitrided steels are generally medium-carbon (quenched and tempered) steels that contain strong nitride-forming elements such as aluminum, chromium, vanadium, and molybdenum.** The most

significant hardening is achieved with a class of **alloy steels (nitralloy type) that contain about 1% Al**. When these steels are nitrided the aluminum forms AlN particles, which strain the ferrite lattice and create strengthening dislocations. Titanium and chromium are also used to enhance case hardness although case depth decreases as alloy content increases.**Typical case depths are between 0.20 to 0.65 mmand take from 10 to 80 hours to produce**. Of the alloying elements commonly used in commercial steels, aluminum, chromium, vanadium, tungsten and molybdenum are beneficial in nitriding because they form nitrides that are stable at nitriding temperatures. Molybdenum in addition to its contribution as a nitride former also reduces the risk of embrittlement at nitriding temperatures. Other alloying elements such as nickel, copper, silicon and manganese have little, if any, effect on nitriding characteristics. **Common examples of Nitrided steels are AISI 4140,4150, 4340, 7140, 8640,and AMS 6475 (Nitralloy N**)
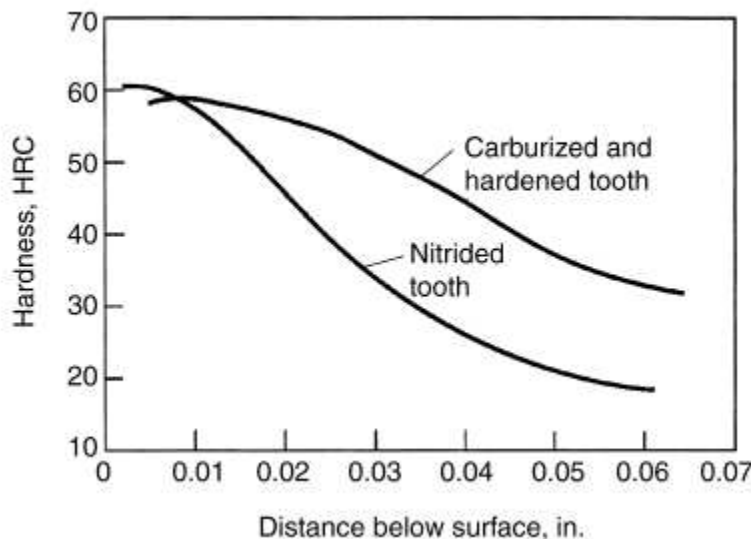
Figure 12: Comparison of hardness gradient for a carburized tooth and a nitrided tooth.

(c) <u>Carbo-Nitriding:</u> Carbonitriding is essentially a modified version of gas carburizing. The modification consists of bringing in ammonia into the gas carburizing atmosphere. This adds nitrogen to the carburized case. Nascent form of nitrogen is produced at the work surface by the disintegration of ammonia in the heat of furnace atmosphere. The nitrogen gets diffused simultaneously into the steel along with carbon. Generally a carbonitriding process is done at a lower temperature and for a quicker span of time than that of gas carburizing.

Carbonitriding is one of most common type of case hardening processes for gears. Case **depths are generally restricted to 0. 03 inches**. Carbonitriding is designed for only specific types of steels. **Carbonitriding is preferred choice for plain carbon and mild steels. Examples of steels which are Carbonitrided are AISI 1018, 1117 and 12L14.**Carbonitriding case-hardening treatment provides a way to enhance the wear and strength of relatively inexpensive and easily worked parts. Typically it is applied to near-finished components. Along with providing a substantial sufficient depth it also improves fatigue strength.

It has been found that after **Carbo-Nitriding of Gears there has been considerable improvement in useful life for many of the gears. Advantages for gears include temper resistance, heightened lubricity during cold start, better strength of the base metal in terms of tensile, yield and fatigue, an increase in throughput, also elimination of problems like quench cracking.**

(iii). <u>Surface Hardening</u> : This is a special hardening process in which a particular surface of steel is made hard without altering the hardness of any other portion.

<u>**Induction Hardening**</u>: Induction hardening is a heat treating technique that can be used to selectively harden portions of a gear, such as the flanks, roots and tips of teeth, providing improved hardness, wear resistance, and contact fatigue strength without affecting the metallurgy of the core and other parts of the component that don't require change.

In contrast to carburizing and nitriding, induction hardening does not require heating the whole gear. With induction, heating can be localized to only those areas in which metallurgical changes are required. For example, the flanks, roots and tips of gear teeth can be selectively hardened. A major goal of induction gear hardening is to provide a fine-grain martensitic layer on specific areas of the part. The remainder of the part is unaffected by the induction process. Hardness, wear resistance, contact fatigue and impact strength increase. Another goal of induction gear hardening is to produce significant compressive residual stresses at the surface and in a subsurface region. Compressive stresses help inhibit crack development and resist tensile bending fatigue. Not all gears and pinions are well suited for induction hardening. **External spur and helical gears, worm gears and internal gears, bevel gears, racks and sprockets are among the parts that are typically induction hardened. Conversely, hypoid gears and noncircular gears are rarely heat treated by induction.**

Gear operating conditions, the required hardness and cost are important factors to consider when selecting materials for induction hardened gears. **Plain carbon steels and low-alloy steels containing 0.40 to 0.55% carbon content are commonly specified**. **Examples include AISI 1045, 1552, 4140, 4150, 4340, and 5150**. Depending on the application, **tooth hardness after tempering is typically in the 48 to 60 HRC range.** Core hardness primarily depends upon steel chemical composition and steel condition prior to induction hardening. **For quenching and tempering, prior structure core hardness is usually in the 28–35 HRC range.**

When discussing induction hardening, it is imperative to mention the importance of having favorable steel conditions prior to gear hardening. Hardness pattern repeatability is grossly affected by the consistency of the microstructure prior to heat treatment (referred to as microstructure of a "green" gear) and the steel chemical composition.

Favorable initial microstructure consists of a homogeneous, fine-grain, quenched and tempered, martensitic structure with hardness of 30–34 HRC; **it leads to fast and consistent metal response to heat treating, with the smallest shape/size distortion and a minimum amount of grain growth.** This type of initial microstructure results in higher hardness and deeper hardened case depth compared to the ferritic/ pearlitic initial microstructure. If the initial microstructure of a gear has a significant amount of coarse pearlite, and most importantly, coarse ferrites or clusters of ferrites, then these microstructures cannot be considered favorable, because gears with such structures will require longer austenization time and/or higher austenizing temperatures to make sure that diffusion- type processes are completed and homogeneous austenite is obtained. Ferrite is practically a pure iron and does not contain the carbon required for martensitic transformation. That's why large areas (clusters) of free ferrite require a longer time for carbon to diffuse into low-carbon regions. Actually, clusters of ferrites act as one very large grain, which often is retained

in the austenite. Steels with large carbides (i.e., spheroidized microstructures) have poor response to induction hardening and also require prolonged heating and higher temperatures for austenization. **Longer heat time leads to grain growth, appearance of coarse martensite, data scatter, extended transition zone and essential gear shape distortion.** Coarse martensite has a negative effect on tooth toughness and impact strength, and it creates favorable conditions for cracking. As opposed to other heat treating techniques, heat treatment by induction is appreciably affected by variation in metal chemical composition. Therefore, favorable initial metal condition also includes tight control of the specified chemical composition of steels and cast irons. Wide compositional limits cause surface hardness and case depth variation.

Presence of large stringers of manganese sulfide inclusions can act as stress raisers, resulting in inter-granular cracking. Sulfur level and nitrogen contents should be closely controlled. The surface condition of the gear is another factor that can have a pronounced effect on gear heat treating practice. Voids, micro-cracks, notches and other surface and sub- surface discontinuities as well as other stress concentrators can initiate cracking during hardening when the metal goes through the "expansion-contraction" cycle; thermal gradients and stresses can reach critical values and "open" notches and micro-cracks. Conversely, **a homogeneous metal structure with a smooth surface free of voids, cracks, notches, etc., improves the heat treating conditions and positively affects important gear characteristics, such as bending fatigue strength, endurance limit, impact strength, gear durability and gear life**. Insufficient hardness as well as an interrupted ("broken") hardness profile at tooth contact areas will shorten gear life due to poor load carrying capacity, premature wear, tooth bending fatigue, rolling contact fatigue, pitting, spalling and can even result in some plastic deformation of the teeth. A through-hardened gear tooth with a hardness exceeding 62 HRC is typically too brittle and will often experience a premature fracture. Hardened case depth should be adequate to provide the required gear tooth properties.
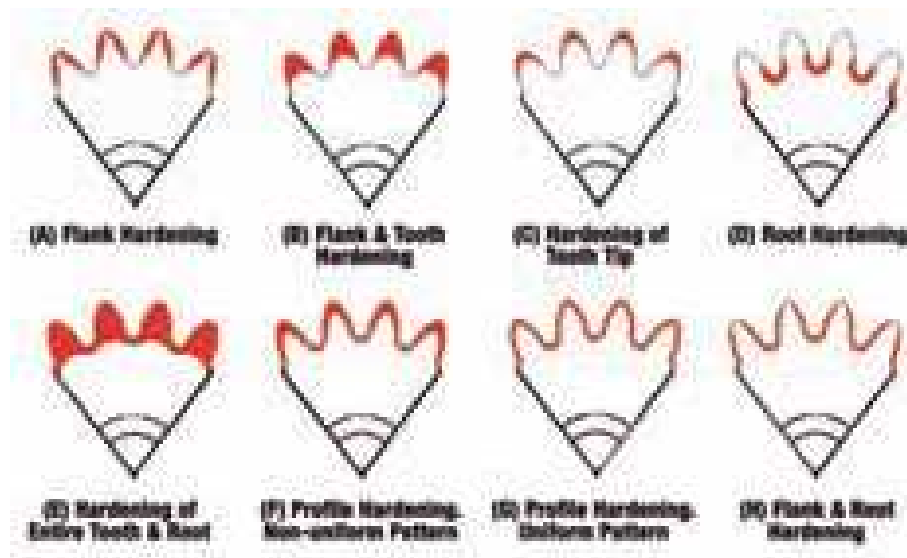
Figure 13: Induction Hardening Patterns.

Effect of percent carbon and alloys on the Hardness and Hardenability of gear steels:

In order to harden any steel its phase is transformed to martensite. To transform the phase into martensite, steel is first heated to a specific temperature (Hardening Temperature) and then held at this temperature for particular time (Holding Time) to obtain austenitic phase after this the heated steel is cooled at to a particular temperature at a particular rate (Cooling Rate) to obtain martensite.

All these variables for heating (temperature and time for heating) and cooling (temperature and rate of cooling) depend on the amount of carbon and alloys in the steel.

Maximum Hardness of steel depends mostly on the carbon content. And **Hardenability** determines the depth of hardened zone or the diameter of cross section which can be hardened through. It depends on total alloy content and to a certain extent on grain size.

Depth at which original carbon content of steel is reached is called as **Total Depth.**

And the perpendicular distance below the surface to the point at which the carbon content has dropped to 0.40% i.e. hardness of HRC 50 is called **Carburizing Depth.** For higher hardness the grain size should be small.

Hardening Temperature and Holding Time:

Hardening temperature is determined from Iron-Carbon equilibrium diagram while the holding time from Time-Temperature-Transformation (TTT) diagram. Each hardening temperature requires a holding time to obtain maximum hardness and this holding time varies with process used. Holding time of various processes is given below:

- Plain carbon and low alloy steel requires few minutes holding time after they have reached Hardening Temperature. Holding time is between 5 to 15 minutes.
- For medium alloy structural steels, holding time of 15 to 25 minutes is recommended irrespective of any dimension.
- For flame and induction hardening time of holding is reduced to very few minutes or sometimes in second.
- For low alloy tool steels definite holding time is necessary. Suggested holding time is 0.5 minutes per millimeter of section thickness. Minimum recommended time is of 5 minutes which may extend to a maximum of 1 hour. Holding time is increased with section thickness because of the increase in reluctance of carbide grains to go into solution and also due to increase in their size.
- Carburizing and nitriding requires holding (soaking) time of several hours in the temperature range of 850 °C to 950 °C.
  Lower Hardening temperature will give rise to formation of Pearlite and Bainite and so Holding time required is large to obtain austenite. With increase in temperature the holding time required is small but grain size and retained austenite increases. So if at higher hardening temperature we hold the steel for larger time it will result in reduction of hardness due to formation of residual austenite.
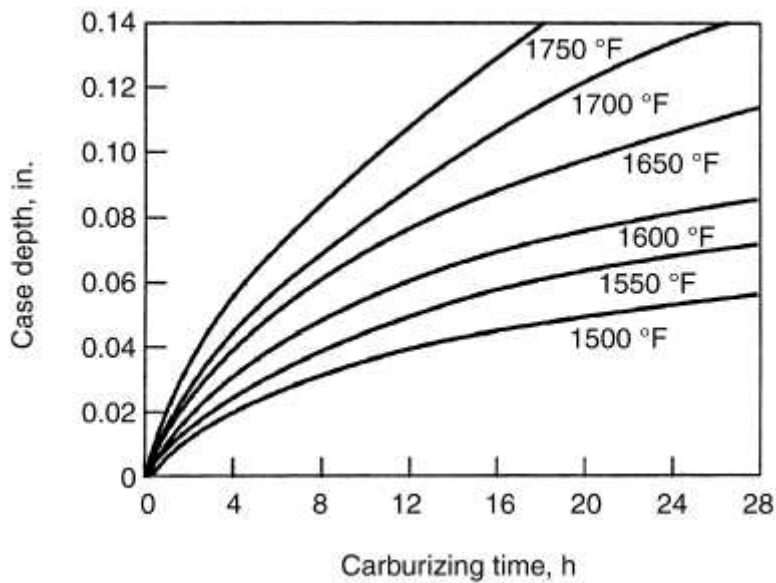
Figure 14: Depth of penetration for different time and different temperatures for a gear steel.

Problems occurred during Heating of Gear Steel:

During heating of steels to austenitic phase the problem of **Internal Oxidation** and **Spheroidal Carbide formation** has to be taken care.

The oxidation of certain alloying elements in the surface layers of components can have detrimental effects upon hardenability and fatigue strength. Also as the grain size of steel decreases, the probability of oxide formation within the grain increases. The metallic elements which form the oxides are taken from solid solution on austenitizing with the result that the austenite matrix adjacent to oxide particle is impoverished of those elements involved in the oxide forming reaction. However, not only are the substitutional elements removed but the carbon level may also be reduced. The consequence of the removal of the elements from the solid solution at high temperatures is that the hardenabilty of the affected layer is correspondingly reduced.

Specified surface hardness value for carburized and hardened components generally fall within the range 58 - 62 HRC. In order to achieve these values, a martensitic surface microstructure is necessary prior to tempering. However, a consequence of internal oxidation is that non-martensitic microstructures may be with the result that, in the surface regions, low hardness values are obtained in the affected zones, hardness fall below the equivalent of about 59 HRC for a decrease in fatigue to occur. **For components the presence of internal oxidation at depths greater than 13µm is detrimental.** It affects the microstructure, the micro hardness and the bending fatigue resistance and the residual stresses at the surface of the case are adversely affected. With materials having surface fatigue values satisfactory have non martensitic layers of depth less than 7µm, whereas those which are considered to have low values of fatigue have non martensitic layers of over 15µm. this confirms that there is a threshold depth of 13µm up to which internal oxidation does not influence the bending fatigue strength of carburized material.

As the microhardness of the surface and bending fatigue limit decreases the tensile residual stresses in the surface increases. Since it is difficult to control the endothermic carburizing atmosphere to eliminate internal oxidation or to replace the gas economically with one which is less likely to oxidize, or perhaps to install a vacuum carburizing plant, then alternative means of control are necessary. **The formation of internal oxides is related to the presence of certain alloying elements and their quantity in solid solution in austenite.** Thus, the basic alloy would contain **carbon to adjust the core strength, but not too much as to adversely affect the development of favouarable residual stresses; nickel to contribute primarily to the toughness of both the case and the core; wnd molybdenum to provide case and core hardenability.** Added to these, optimum amounts of deoxidizing and grain refining elements must be included**.**

Core hardenability can be boosted further with moderate additions of chromium and manganese , but less than 0.5% of each. However, the introduction of 0.5% or more of molybdenum is claimed to be very beneficial, especially in those steels where it has been sensibly balanced with elements having a positive oxygen affinity but which impart necessary hardenability etc. Another way of getting rid from internal oxidation is by heating the component in an atmosphere oxidizing to iron. Any scale layer so formed on the surface is likely to include the layer of internally oxidized material and together they will be removed during a final shot blasting operation. In this technique care must be taken when dealing with large components as decarburization may occur.

Globular carbides are formed in a surface by slowly heating the components through the temperature range for the ferrite to austenite transformation and up to carburization temperature in the presence of a carburizing atmosphere. These carbides tend to be unconnected. They have a Cementite structure in which part of iron may be replaced by other element. The actual amount of the element combined with carbide depend, to some extent on the time and temperature of heat treatment but mainly on the amount of that element originally in the steel. As carbide grows they will extract carbide forming elements from the solid solution. The outcome is the local lowering of hardenability in the vicinity of carbides and the possible formation of low alloy martensite or even non-martensitic phase upon subsequent oil quenching. As carbide does not undergo martensite expansion of the steel and neither any localized non-martensitic phase adjacent to carbide, this reduces overall transformation expansion of the part. This results in reduction of surface compressive stress. And with reduced compressive stress or with tensile stress on the surface the bending strength and the bending fatigue strength of a component will be adversely affected. **Although massive spheroidal carbides are detrimental but if they are finely distributed their presence of improves component's wear, abrasion and scuffing resistance and as the amount of carbon increases so too does the values of these properties.**

Cooling Temperature and Rate of Cooling:

The cooling temperature is that temperature at which martensite begins to form and the rate of cooling is the rate at which this temperature should be achieved. Both the variables depend on percent carbon in the steel. Cooling temperature is determined by the empirical formula given by Steven and Haynes and the rate of cooling is determined by Continuous-Cooling-Transformation (CCT) curve.

The cooling temperature is important as at this temperature martensite just begins to form, if this temperature becomes too low it would become very difficult to achieve martensitic phase as rate of cooling also has to be fast. It is observed that with increase in percent of carbon the martensite starting temperature decreases, while percent of other elements also affect the martensite starting temperature but their effect is negligible as compared to that of carbon. The empirical formula given by Steven and Haynes for calculating the Martensite Starting Temperature is

M_s (°C) = 561 – 474(%C) – 33(%Mn) – 17(%Ni) – 17(%Cr) – 21(%Mo)

Where, M_s denotes Martensite starting temperature

There is Martensite finish temperature (M_f) also it is the temperature at which 99% of the austenite is converted into Martensite. M_f is about 215°C below M_s. As can be deduced from the formula that on increasing the percent carbon M_s decreases. A table for which is shown

% Carbon	0.02	0.2	0.4	0.8	1.2
M_s (°C)	520	490	420	250	150

At 0.5% carbon M_f is not achieved so we get Retained Austenite. And from the CCT diagram we know that for the formation of martensitic phase cooling has to be rapid. So, if amount of carbon is high then M_s will be low and we need to cool the material at a much faster rate to obtain martensite. In such conditions due to the incompletion of the transformation to martensite we face the problem of retained austenite.

Problems occurred during Cooling of Gear steel:

On cooling the steels from austenitic phase, austenite becomes unstable and decomposes to new constituent, the type of which depends up on the chemical composition of the steel and the rate of cooling. When transformation involves diffusion processes, i.e. to form ferrite, pearlite or bainite, it will be total and no austenite will survive. If on the other hand the reaction produces martensite it is possible for some austenite to remain in the final structure. In cases when M_s reached some lower values (with M_f near to room temperature) it becomes impossible for the transformation to complete and we get retained austenite. However, small amount of retained austenite have been detected in quenched steels even though their M_f temperatures were above ambient. Thos suggests that austenite becomes stable during the course of a conventional quench. **Therefore, austenite may be retained in the hardened steel due to 2 reasons, first is the position of M_s - M_f range relative to the ambient temperature (depends mainly on the amount of carbon in steel and rate of cooling) and second involves Austenite stabilization.** The range of M_s- M_f relative to ambient temperature and role of amount of carbon in it has already been discussed. And with the help of M_s and Quenchent temperature the volume of untransformed austenite can be determined

V_γ = exp(-0.011x(M_s – T_q))

Where, V_γ is volume of Retained Austenite.

A feature often observed in hardened surface containing retained austenite is that the quantity of austenite at the surface is less than that at some depth beneath the surface. During the quench

from the austenitic condition transformation takes place in the core material while the high carbon surface is still austenitic. It is known that about the M_s plastic deformation can take place at stresses well below the yield stress of the material and that martensite reaction can be stimulated.

The residual stresses developed at the surface of a hardened part near the M_s could lead to more of the austenite being transformed than would be otherwise. Another reason for the austenite layering involves thermal stabilization. it involves a strain ageing process, the strain being that due to accommodation of the martensite, as well as the possible presence of applied or residual tensile stresses. Stabilization requires that interstitial atoms are present, and that sufficient time is available for these atoms to segregate to dislocation or to the martensite – austenite interfaces, thereby pinning them. Once this has taken place the austenite will be stiffened somewhat and the growth of martensite inhibited. Slower cooling rates may also lead to the formation of Network Carbides.

Critical Failure Modes Of Gears:

(a) Bending Fatigue (Root Fillet Crack)

(b) Macropitting (Pitch Line Surface Degradation)

(c) Contact Fatigue

Bending Fatigue: It is caused by a load applied along the line of action which generates stress gradient in root fillets. The origins of bending fatigue failures typically are imperfections in the surface of the root fillet (e.g., tooling "witness" marks) or nonmetallic inclusions near the surface. Cracks slowly propagate around the origin until they reach the critical size for the case material at the prevailing stress level. For hardened high carbon material typically used for gears, when the crack reaches this critical size, it "pops" through the case (i.e., the entire case fractures). At this point, the rigidity of the tooth is reduced (compliance increases), and dynamic load increases significantly. This produces a readily detectable increase in noise and vibration and represents failure. The classical bending fatigue failure is that which occurs and progresses in the area designed to receive the maximum bending stress. There are five conditions that make a failure a perfect tooth-bending fatigue failure:
• The origin is at the surface of the root radius of the loaded (concave) side of the tooth.
• The origin is at the midpoint between the ends of the tooth where the normal load is expected to be.
• One tooth failed first, and the fracture progressed slowly toward the zero-stress point at the root, which shifted during the progression to a point under the opposite root radius and then proceeded outward to that radius.
• As the fracture progressed, the tooth deflected at each cycle until the load was picked up simultaneously by the top corner of the next tooth, which (because it was now overloaded) soon started a tooth-bending
fatigue failure in the same area. The fracture of the second tooth appears to be of more recent origin than the first fracture.
• The material and metallurgical characteristics are within specifications.
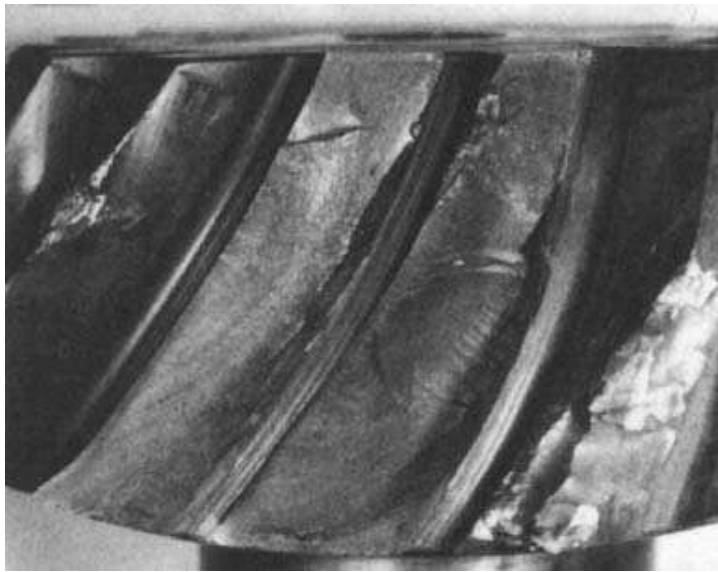
Figure15 : Spiral bevel pinion showing classic tooth bending fatigue. The origin is at the root radius on the concave (loaded) side.

Figure 16: Photoelastic study of mating teeths indicate the shift of the zero stress point during crack propagation until final fracture reaches the opposite root radius. At the same time deflection of the tooth allowed the adjacent tooth to pick up the load.
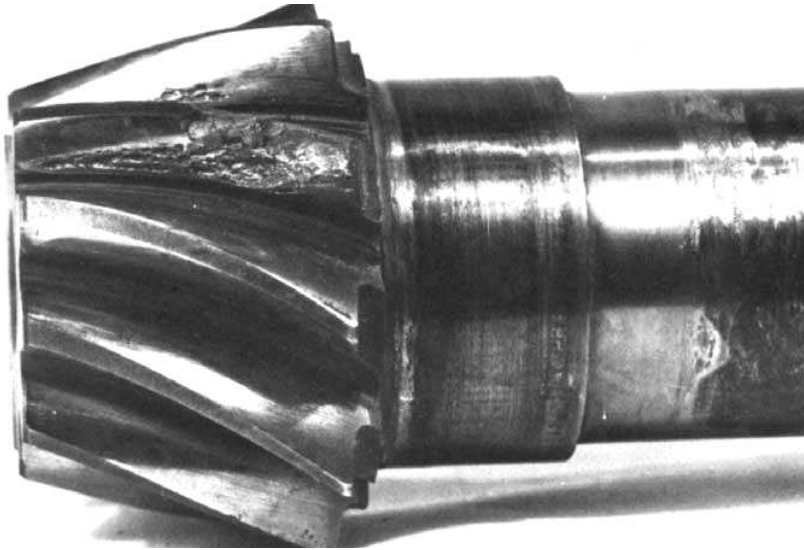
Figure 17: Bending fatigue in the heel of one of the tooth of spiral bevel pinion of AISI 8617 steel , carburized and hardened up to 57 HRC in this case.

Macropitting: Macropitting is a general term that includes spalling and other forms of macroscale damage caused by Hertzian contact fatigue. Macropitting of gear teeth is generally due to contact fatigue, which occurs from localized plastic deformation, crack initiation, and finally macropitting from crack propagation in and near the contact surface. Macropitting results from the subsurface growth of fatigue cracks, which may have a surface or subsurface origin. When circumstances cause surface-origin pitting, crack growth often occurs within and beyond the range of maximum shear stresses in the contact stress field (so-called hydraulic pressure propagation crack paths that may be due to chemical reactions at the crack tip as well as to lubricant viscosity effects). When fully developed, the craters exist at a depth comparable to that of the maximum alternating Hertzian shear stress. A macropit does not result from the gradual enlargement of a small cavity, but rather it results from the subsurface growth of a fatigue crack, which eventually separates from the main body of material. Macropitting fatigue life is inherently statistical because defect severity and location are randomly distributed among macroscopically identical contact components. Two major classes of macropitting damage are distinguished according to the location of the initiating defect: subsurface and surface-origin macropitting.

Subsurface-origin macropitting: It results from defects in the bulk material subjected to the Hertzian cyclic stress field. The defects that cause subsurface-origin macropits are inclusions and/ or material microstructure alterations. The defects that most likely produce this type of macropit are located above the depth of maximum alternating Hertzian shear stress. Variables governing the life of a component with respect to this type of macropit are Hertzian shear stress level, material matrix fatigue resistance, defect severity, and defect location. Inclusion-origin fatigue is normally initiated at nonmetallic inclusions below the contact surface. The initiation and propagation of fatigue cracks are the result of cyclic stresses that are locally intensified by the shape, size, and distribution of nonmetallic inclusions in steels. Oxide inclusions from deoxidation, reoxidation, or refractory sources are the most frequently observed origins of inclusion-origin fatigue damage.

Surface-origin macropitting: It is caused by defects in the immediate subsurface material subject to asperity scale cyclic stress fields and aggravated by surface tractive forces. These

defects are either preexisting defects, such as nicks, dents, grinding furrows, surface discontinuities, and so forth, or microscale pits. The distinguishing features of a surface-origin macropit are in the entrance zone of the macropit. The entrance zone may exhibit a shallow-angle entry wall (inclined less than 30° to the contact surface), an arrow-head configuration, the presence of a visible surface defect, or an association with a stress concentration due to design geometry. Surface-origin macropits have been classified by the nature of the defect: geometric stress concentration (GSC) and point surface origin (PSO).

Geometric stress concentration macropits are distributed on the contact surface at the ends of line contact. When the contact geometry, deflection under applied loads, and alignment cause the contact stress to be higher at the end of line contact, fatigue occurs within a narrow band in which the contact stresses are more severe than those associated with inclusions. The GSC macropits can propagate more rapidly in either direction—parallel or transverse to the rolling direction.

Point surface origin macropits occur randomly distributed on the contact surface, similar to inclusion-type macropits. However, PSO macropits are different in two important aspects: first, there is no consistent association with nonmetallic inclusions; second, the origin is located at or near the contact surface, whereas with inclusion-origin macropits, the initiation site is located subsurface.

Contact Fatigue: Contact fatigue is the cracking of a surface subjected to alternating Hertzian stresses produced under controlled rolling and sliding loading conditions. In addition to cracking, contact fatigue can result in microstructural alterations, including changes in retained austenite, residual stress, and martensite morphology. When sliding is imposed on rolling, the tangential forces and thermal gradient caused by friction alter the magnitude and distribution of stresses in and below the contact area. The alternating shear stress increases in magnitude and is moved nearer to the surface by sliding forces. Thus, initiation of contact-fatigue cracks in gear teeth, which are subjected to significant amounts of sliding adjacent to the pitchline, is found to be in the surface material. These cracks propagate at a shallow angle to the surface, and pits result when the cracks are connected to the surface by secondary cracks. If pitting is severe, the bending strength of the tooth may be decreased to the point at which fracture can occur. Mainly there are 3 types of contact fatigue failures: Surface Pitting, Sub-surface Pitting.

• **Surface-origin pitting**: This is the type of pitting characteristic of combined rolling and sliding, such as occurs on gear teeth slightly away from the exact pitch line, where only rolling is present. The maximum shear stress is no longer buried within the metal, but is now brought to the surface because of the friction at the interface. Because the character of the surface is intimately involved, the lubricant becomes critical. It is for this reason that transmissions, final drives, and various other types of gear systems require lubricants with special additives. Everything possible must be done to reduce surface friction, expand the contact area, and reduce the load in order to reduce the contact stress and provide a hard, fatigue-resistant structure in the metal. Unfortunately, if those things are already near optimum, little can be done to improve the fatigue life. Only minimal improvements, if any, can be expected. Improvements can best be obtained, if at all, by changes in the lubricant.
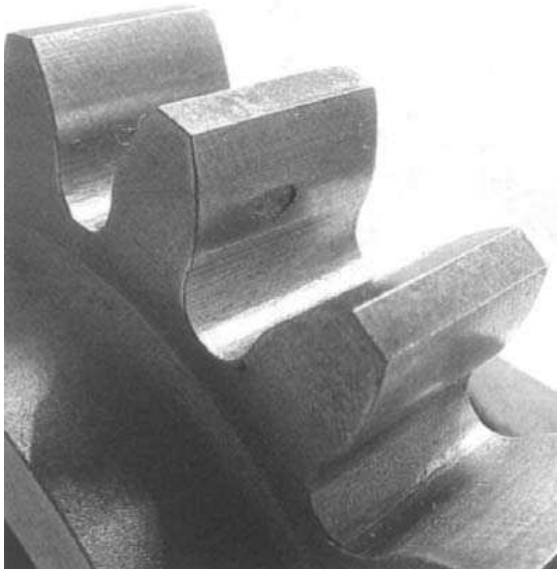
Figure 18: Gear with surface origin pit.

• **Subsurface-origin pitting:** is the result of fatigue below the surface in the region of highest shear stress. Subsurface origin pitting typically occurs only in cases where the elastohydrodynamic (EHD) lubricant film thickness is great enough to prevent significant asperity interaction. This pitting occurs in high-speed power gearing and in aerospace power drives. It is also typical in antifriction bearings (which operate with pure rolling as at the pitch diameter on spur gears). The origin is typically a nonmetallic inclusion or discontinuity in the structure, in the area of highest shear stress below the surface. Crack propagation is initially quite slow, until a crack penetrates the surface, allowing lubricant to enter.

• **Subcase fatigue***:* The previous types of contact- stress fatigue result in small, often tiny, pits in the contacting surfaces. Subcase origin fatigue is different because very large cavities may be formed, apparently in a very short time. The fatigue originates near the case/core interface. Because the basic cause is inadequate metal strength in the subcase region, the logical solution should be to strengthen the metal there. This can be done by increasing the case depth and/or the core hardness. This must be done carefully, however, because the changes could lead to through-hardening and brittle fracture, particularly on gear teeth.

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