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Case Study

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Selection of materials for camshafts

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ABSTRACT

Surface hardening heat treatment is applied to make the interior of the part softer, but the exterior harder and more wear-resistant. This surface hardening method is particularly useful in power-transmitting parts such as camshafts or ring gears where a hard outer surface is required. Surface hardening processes are divided into thermochemical processes (changing the composition of the surface with carbon, nitrogen and boron) and rapid quenching from the austenite area to form martensite. In this study, materials selection for camshafts is reviewed and candidates from cast irons and steels are criticized and classical and computer-based methods are employed for the best selection.

Keywords: Surface hardening, Induction, Cast iron & Steel, Selection, Camshaft

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1. Introduction

Surface hardening is a process wherein thermal energy is smeared to the surface of a fragment to improve hardness, fatigue and wear resistance. These developments include induction hardening, flame hardening, electron beam and laser hardening.

Induction and flame hardening are approaches of hardening selected substrates by short-term high-intensity heating after that quenching (Figure 1). Since the effects of heating and hardening are limited to a small area, the hardening depth on the surface can be controlled. Unlike thermochemical hardening processes (nitriding, cementation, etc.) practical to lesser carbon steels, induction and flame hardening does not support compositional enhancement of the surface with nitrogen or carbon. However, it is possible to harden the surfaces by rapid cooling of steel or cast iron with sufficient carbon after being held in the austenite area.

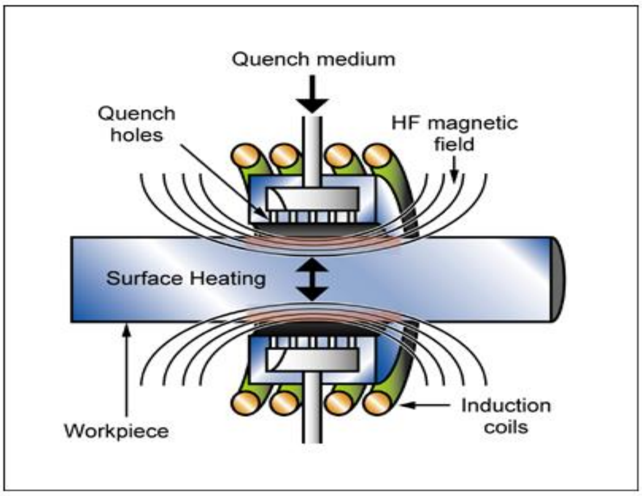
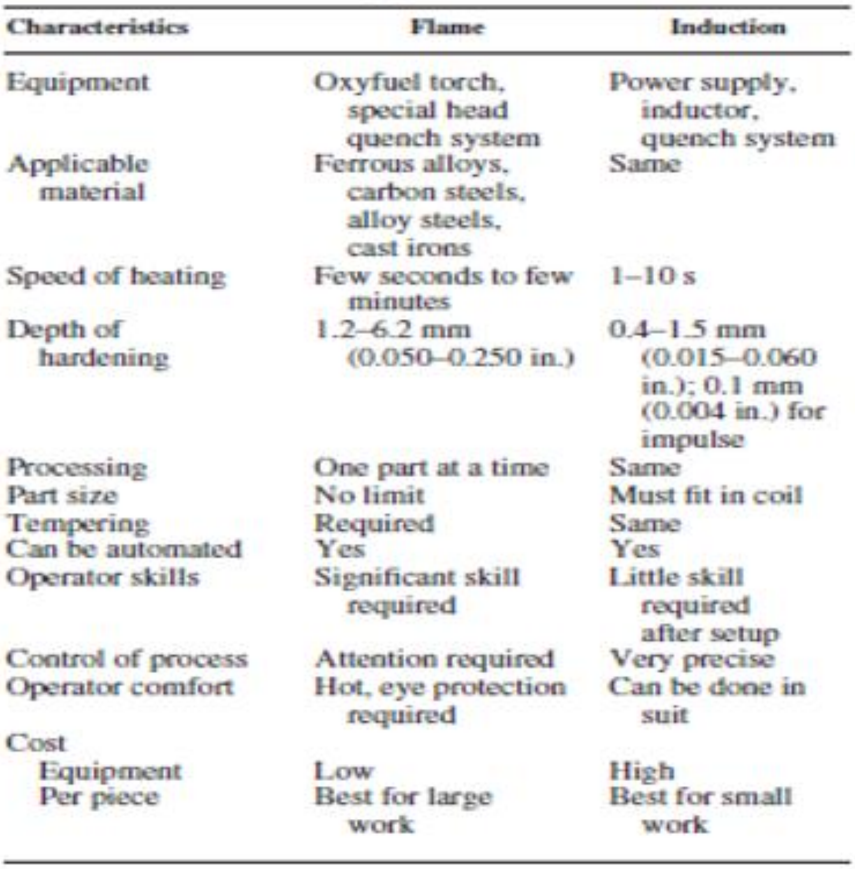


Figure 1. The schematic view of the induction hardening process

Surface heating with electron and laser beams is progressively practical for confined hardening of steels. Electron beams and laser distillate on the brink of the surface of a portion and superficial hardening and finer martensitic micrographs can improve. As with blaze and induction hardening, there are no chemical changes shaped by laser or electron beam hardening processes. Table 1 compares flame and induction hardening processes.

Table 1. Comparison of flame and induction hardening process [1]



Characteristics	Flame	Induction
Equipment	Oxyfuel torch, special head quench system	Power supply, inductor, quench system
Applicable material	Ferrous alloys, carbon steels, alloy steels, cast irons	Same
Speed of heating	Few seconds to few minutes	1–10 s
Depth of hardening	1.2–6.2 mm (0.050–0.250 in.)	0.4–1.5 mm (0.015–0.060 in.); 0.1 mm (0.004 in.) for impulse
Processing	One part at a time	Same
Part size	No limit	Must fit in coil
Tempering	Required	Same
Can be automated	Yes	Yes
Operator skills	Significant skill required	Little skill required after setup
Control of process	Attention required	Very precise
Operator comfort	Hot, eye protection required	Can be done in suit
Cost		
Equipment	Low	High
Per piece	Best for large work	Best for small work

Electromagnetic induction is a technique of creating heat inside a piece to harden or temper a cast iron or steel portion. The induction heating pattern is strongminded by the form of the induction coil creating the magnetic field, the coil numbers, the frequency, the alternative current power contribution, and the environment of the work-piece. An example of the magnetic field and induced current created by the induction coils is exposed in Figure 2.

The heating rate attained by induction coils depends upon the power of the magnetic field to which the portion is bared. The deepness of current penetration depends upon the work-piece permittivity, resistance and ac frequency. The biggest variable is frequency, as the first two factors change relatively slight. As the frequency increases, the deepness of current penetration declines. High frequency current is utilized when superficial heating is anticipated; medium and low frequencies are utilized in requests that require profounder heating.

High power and short heating cycles are used in induction hardening. Advantages of induction hardening include wear resistance and fatigue strength. Additional benefit of induction hardening is that confined heating can be utilized to reinforce the surfaces while leaving the central areas soft. Figure 4 shows the automotive component hardened by induction heat treatment. This constituent needs two different hardness zones. The "vessel" needs a hard exterior, while the soft core needs to be ductile.

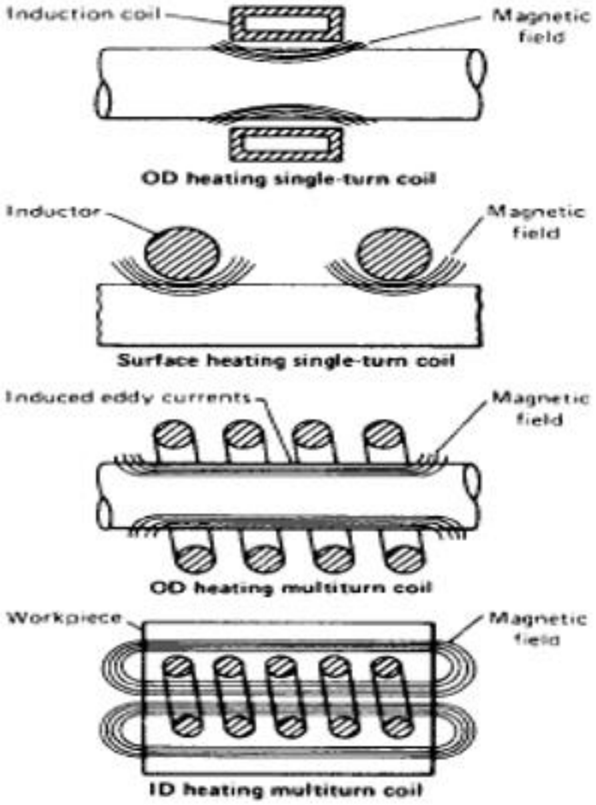


Figure 2. Magnetic fields and induced currents created by numerous induction coils, OD, outside, ID, inside diameter

In this study, materials selection for camshafts are researched via conventional method [2] as well as Cambridge Element Selector (CES) software [3]. Candidate materials from cast irons as well as several steels are studied in criticizing their physical, mechanical as well as thermal properties and highlighted their advantages and disadvantages point of view.

2. Candidate materials

For the selection process of camshafts six cast iron (EN GJL 350, 250, 150 and EN GJL 100, 200 and 300) materials and six steels (AISI 1117, AISI 1015, AISI 1030, AISI 1137, AISI 1080, AISI 1144) are selected as candidate materials [4-5]. Their compositions and mechanical properties are given in Table 2 and Table 3, respectively. In addition, their thermal properties and durability are cross checked for the camshafts' working conditions.

Table 2. Compositions of candidate materials from cast irons and steels

Cast Iron Codes	Compositions (wt%)	Steel Codes	Compositions (wt%)
EN GJL 150	Fe-3,2C-2,6Si-0,6Mn	AISI 1117	Fe-1,2Mn-0,2Co-0,1S
EN GJL 250	Fe-3,1C-2,1Si-0,6Mn	AISI 1015	Fe-0,5Mn-0,2Co
EN GJL 350	Fe-3,1C-1,5Ni-1,5Si-0,7Mn-0,4Mo	AISI 1030	Fe-0,8Mn-0,3Co
		AISI 1137	Fe-1,5Mn-0,4Co-0,1S
EN GJL 100	Fe-3,8C-2,5Si-0,6Mn	AISI 1080	Fe-0,8Co-0,8Mn
EN GJL 200	Fe-3,3C-2,4Si-0,7Mn	AISI 1144	Fe-1,5Mn-0,5Co-0,3S
EN GJL 300	Fe-3,0C-1,7Si-1,1Ni-0,6Mn-0,5Cr		

Table 3. Mechanical properties of candidate materials from cast irons and steels

Cast Iron Codes	**Mechanical properties**			**Steel Codes**	**Mechanical properties**		
	Hardness (HV)	**Adhesive wear resistance**	**Fatigue strength (MPa)**		**Hardness (HV)**	**Adhesive wear resistance**	**Fatigue strength (MPa)**
EN GJL 150	185	Excellent	60	AISI 1117	129	Acceptable	237
EN GJL 250	219	Excellent	104	AISI 1015	193	Acceptable	221
EN GJL 350	238	Excellent	130	AISI 1030	133	Limited	249
EN GJL 100	153	Excellent	54	AISI 1137	180	Acceptable	293
EN GJL 200	205	Excellent	79	AISI 1080	180	Acceptable	304
EN GJL 300	228	Excellent	122	AISI 1144	173	Acceptable	294

3. Selection steps

3.1. Conventional method

The camshaft is a rotating object made of metal that converts rotational motion into reciprocating motion. Camshafts are used in internal combustion engines and mechanically controlled ignition systems.

A- Analysis of required properties of materials

The features essential from the camshaft, or the features that the camshaft must perform when used in the car, can be listed as follows:

-The hardness must be high
-wear resistance must be high
-fatigue strength must be high
-service temperature must be high
-thermal expansion must be low
-must be cheap

B- Choice of candidate materials

Considering the above stated possessions, we can nominate the succeeding materials for the camshafts:
-cast irons (EN GJL 150, 250, 350, 100, 200, and 300)
-steels (AISI 1117, AISI 1015, AISI 1030, AISI 1137, AISI 1080, AISI 1144)

C- Development of candidates

Now, let's evaluate these aspirant materials by scoring under the light of the features requested from the camshafts. After writing the candidate materials on the columns and the desired possessions on the rows, let's find the values of the candidate materials using the material selection diagrams. The results are shown in Table 4 for selected four cast irons and four steels [5-6].

Table 4. Camshafts candidate materials and scoring.

Feature/Material	**100**	**200**	**300**	**350**	**1117**	**1144**	**1015**	**1080**
Hardness (HV)	153 (2p)	205 (7p)	228 (10p)	238 (10p)	129 (1p)	173 (4p)	193 (6p)	180 (5p)
Wear resistance	Exc. (10p)	Exc. (10p)	Exc. (10p)	Exc. (10p)	Acc. (7p)	Acc. (7p)	Acc. (7p)	Acc. (7p)
Fatigue strength (MPa)	54 (1p)	79 (2p)	122 (4p)	130 (4p)	237 (7p)	294 (10p)	221 (6p)	304 (10p)
Max. service temp. (°C)	400 (10p)	400 (10p)	400 (10p)	400 (10p)	350 (8p)	334 (7p)	350 (8p)	313 (6p)
Thermal expan. (µstrain/°C)	12 (10p)	12 (10p)	12 (10p)	12 (10p)	12 (10p)	13 (8p)	12 (10p)	12 (10p)
Price ($/kg)	0,4 (10p)	0,4 (10p)	0,6 (7p)	0,8 (5p)	0,6 (7p)	0,6 (7p)	0,6 (7p)	0,6 (7p)
Total Score	43p	49p	51p	49p	40p	43p	43p	45p

Exc: excellent, Acc: accepted, p: point (score)

D- Selection of the material that best suits the required properties
When Table 2 is examined, it is seen that the EN GJL 300 cast iron is the best choice for camshafts due to having the maximum score (51p). The second best choices for camshafts are two cast irons of EN GJL 200 and 350 having 49p score. Then AISI 1080 steel is the third best candidate material since having 45p. The following 3 candidate materials including one cast iron (EN GJL 100) and two steels (AISI 1144 and 1015) can be selected since having 43p score. The lowest score (40p) is obtained by the AISI 1117 steel. Despite having quite different scores (among 40p to 51p) of candidate materials, all candidate materials can be used for camshafts. Of course, the EN GJL 300 cast iron is most appropriate material for camshafts since supplying almost all the required properties and obtaining the highest score within the candidate materials [7-11].

3.2. Material Selection for a (Computer-Assisted) Camshafts with CES

CES (Cambridge Engineering Selector) is a material selection package program developed by M. F. Ashby et al.

Since the camshaft is bulky and a large material (bulk), “**All bulk materials**” is selected as the candidate material type in the program. Then, the following possible features given below, shown in various standards or requested from the manufacturer by the customer are written in the appropriate places after clicking the "**Limit**" command in the CES material selection package program [6]:

Price ⇒ 0.4 – 0.8 USD/kg
Hardness ⇒ 160 – 300 HV
Adhesive wear ⇒ acceptable
Fatigue strength ⇒ 60 - 180 MPa
Service temperature ⇒ -150 °C ile 450 °C
Thermal expansion ⇒ 10 – 15 µstrain/°C

Below is the screenshot of the CES material selection program after entering the "**MaterialUniverse: All bulk materials**" option as the candidate material type. Then the relevant specifications requested from the camshafts above are written in the appropriate places.

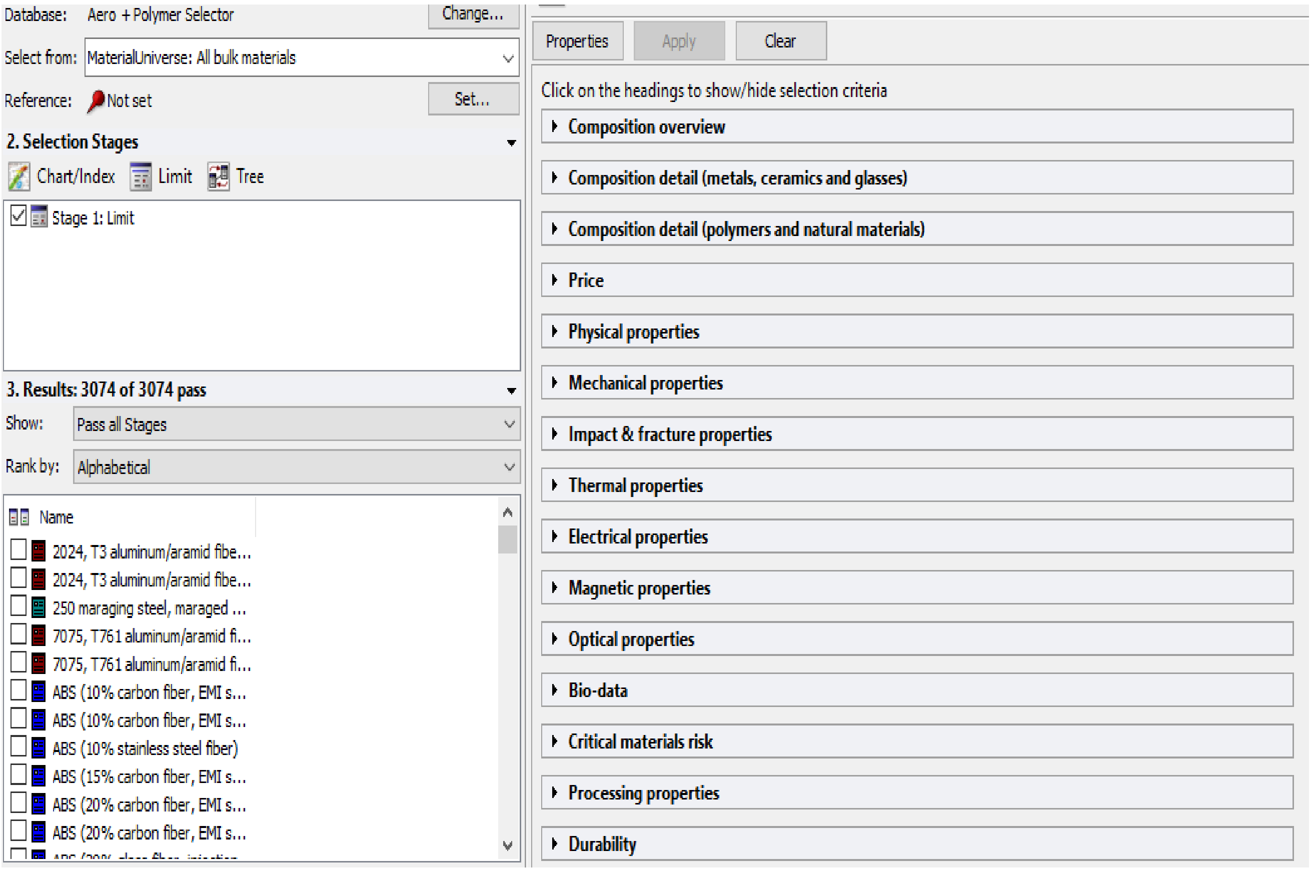
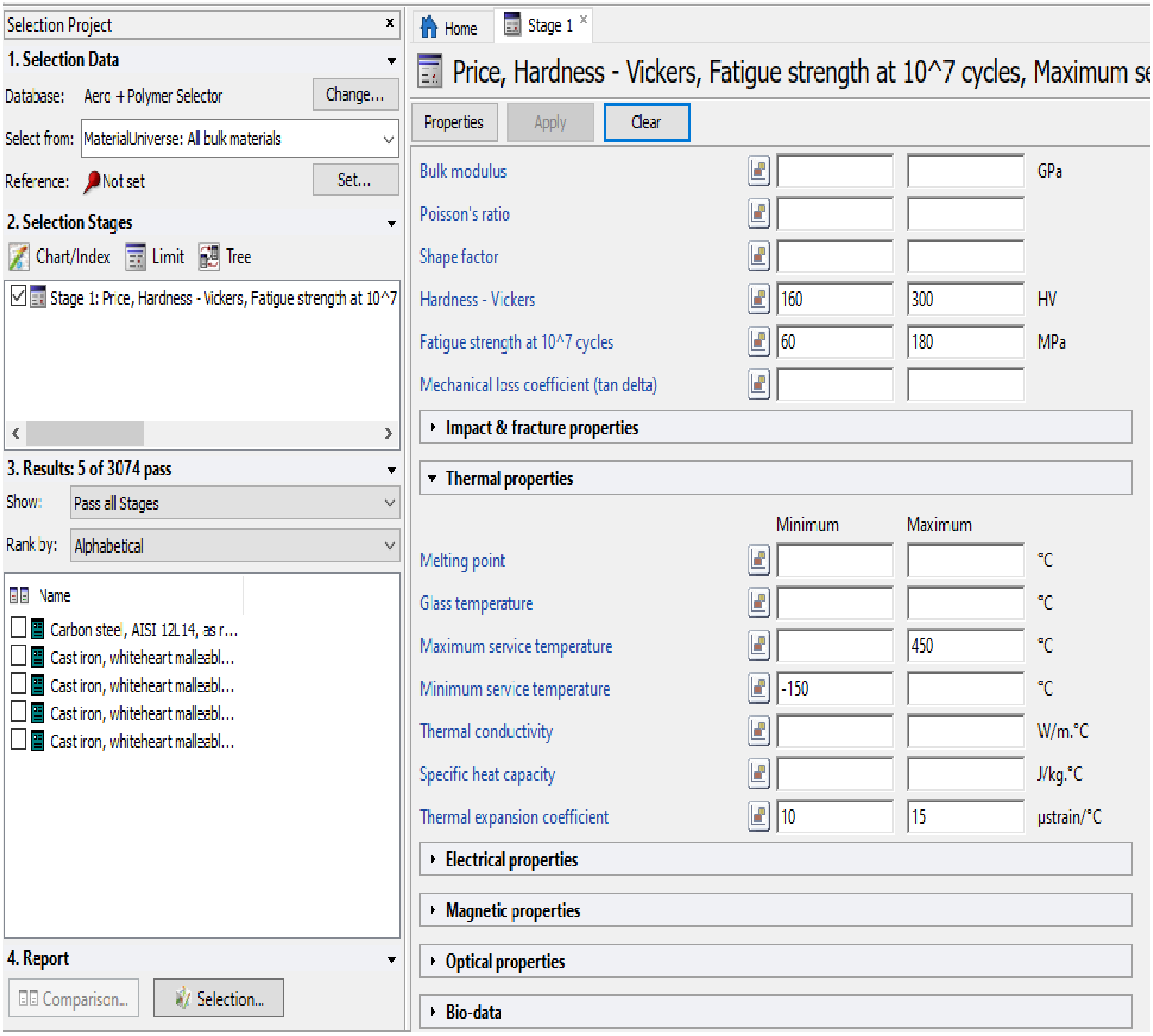

Database: Aero + Polymer Selector
Select from: MaterialUniverse: All bulk materials
Reference: Not set
2. Selection Stages
☑ Stage 1: Limit
3. Results: 3074 of 3074 pass
Show: Pass all Stages
Rank by: Alphabetical
Name
☐ 2024, T3 aluminum/aramid fibe...
☐ 2024, T3 aluminum/aramid fibe...
☐ 250 maraging steel, maraged ...
☐ 7075, T761 aluminum/aramid fi...
☐ 7075, T761 aluminum/aramid fi...
☐ ABS (10% carbon fiber, EMI s...
☐ ABS (10% carbon fiber, EMI s...
☐ ABS (10% stainless steel fiber)
☐ ABS (15% carbon fiber, EMI s...
☐ ABS (20% carbon fiber, EMI s...
☐ ABS (20% carbon fiber, EMI s...
Click on the headings to show/hide selection criteria

Figure 3. Option as the candidate material type

As a result, CES contains cast iron as the most suitable material to be used for camshafts. Then, looking at the typical uses of the cast iron found, it will be seen that they are used in camshafts and the answer is confirmed.



1. Selection Data

Database: Aero + Polymer Selector

Select from: MaterialUniverse: All bulk materials

Reference: Not set

2. Selection Stages

☑ Stage 1: Price, Hardness - Vickers, Fatigue strength at 10^7

3. Results: 5 of 3074 pass

Show: Pass all Stages

Rank by: Alphabetical

Name
☐ Carbon steel, AISI 12L14, as r...
☐ Cast iron, whiteheart malleabl...
☐ Cast iron, whiteheart malleabl...
☐ Cast iron, whiteheart malleabl...
☐ Cast iron, whiteheart malleabl...

4. Report

Price, Hardness - Vickers, Fatigue strength at 10^7 cycles, Maximum se

	Minimum	Maximum	
Bulk modulus			GPa
Poisson's ratio			
Shape factor			
Hardness - Vickers	160	300	HV
Fatigue strength at 10^7 cycles	60	180	MPa
Mechanical loss coefficient (tan delta)			

Thermal properties

	Minimum	Maximum	
Melting point			°C
Glass temperature			°C
Maximum service temperature		450	°C
Minimum service temperature	-150		°C
Thermal conductivity			W/m.°C
Specific heat capacity			J/kg.°C
Thermal expansion coefficient	10	15	µstrain/°C

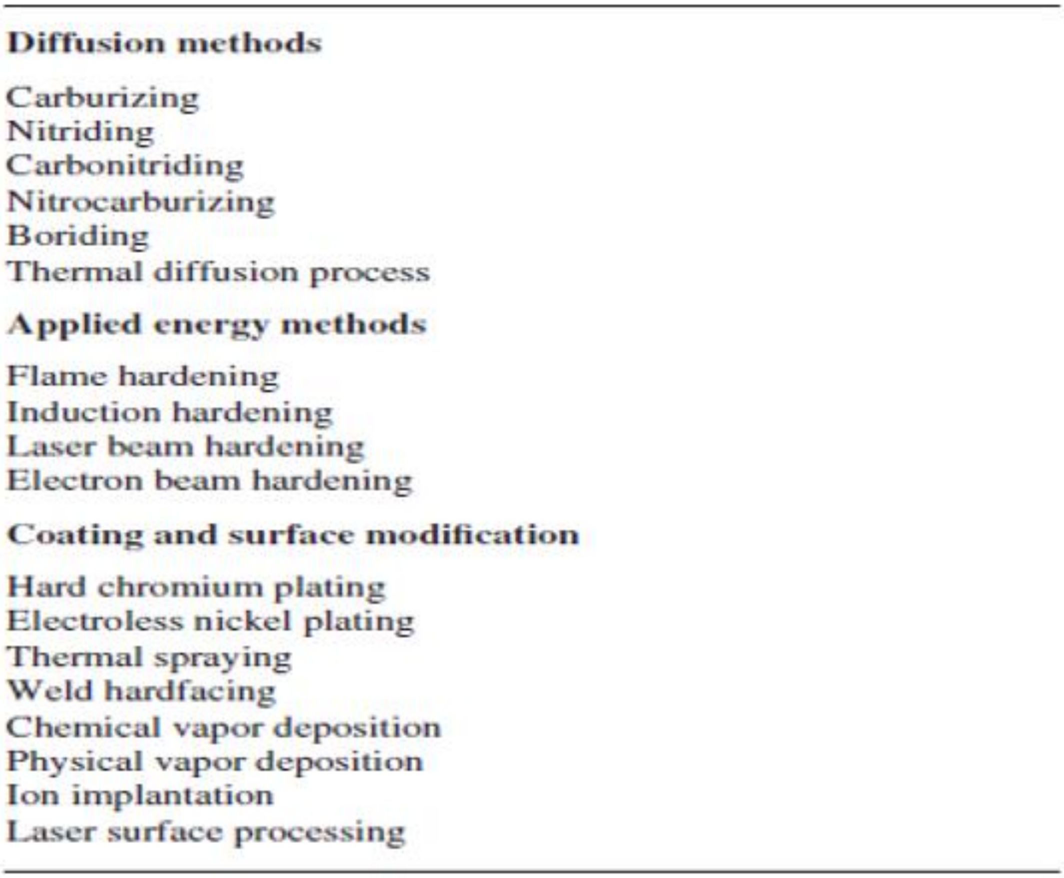
Figure 4. Material selection results

4. Results and discussion

4.1. Mechanical properties

Surface hardening heat treatment (Table 5) is utilized to increase the wear resistance of the surfaces of portions deprived of distressing the softer inner of the fragment. This arrangement of hard surface and impact resistance is beneficial in fragments for example cam or ring gears that must have a hard wear-resistant surface. Also, surface hardening of the steel has a benefit over direct hardening, a smaller amount costly for low and medium carbon steels.

Table 5. Surface hardening techniques for steels [5,7]



Diffusion methods

Carburizing
Nitriding
Carbonitriding
Nitrocarburizing
Boriding
Thermal diffusion process

Applied energy methods

Flame hardening
Induction hardening
Laser beam hardening
Electron beam hardening

Coating and surface modification

Hard chromium plating
Electroless nickel plating
Thermal spraying
Weld hardfacing
Chemical vapor deposition
Physical vapor deposition
Ion implantation
Laser surface processing

4.2. Hardening of Surface

The difference of induction hardening from conventional furnace hardening is fast heating, diminutive austenitizing times and swift cooling, resulting in different micrographs. For hardening, the part is first austenitized. For this heat treatment, first, the austenite structure is obtained by keeping the steel at the austenitizing temperature in the austenite (γ) phase area (Figure 5) for a sufficient time.

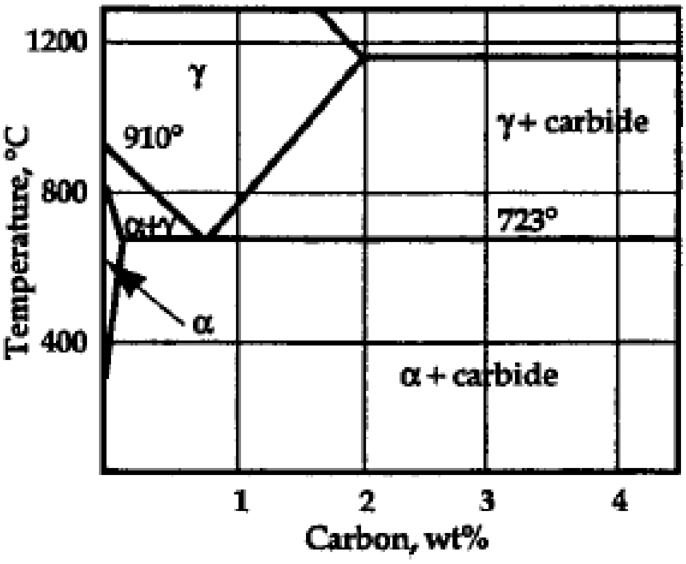


Figure 5. A part of the iron-carbon phase diagram.

It is extra valuable to study the austenite creation on incessant heating because this is similar to the actual heat treatment application. A TTT diagram for austenite creation in a steel under unceasing heating is exposed in Figure 4. It shows a characteristic warming curve for a fragment located in an oven at 900 °C. Uniform austenite is attained after about 1 hour (3600 s). Also shown in the figure is a curve branded R for a portion that is quickly heated by means of the induction method. If an inferior maximum austenitization temperature is utilized, undissolved carbides may remain in the structure. This reduces the hardenability of the steel.

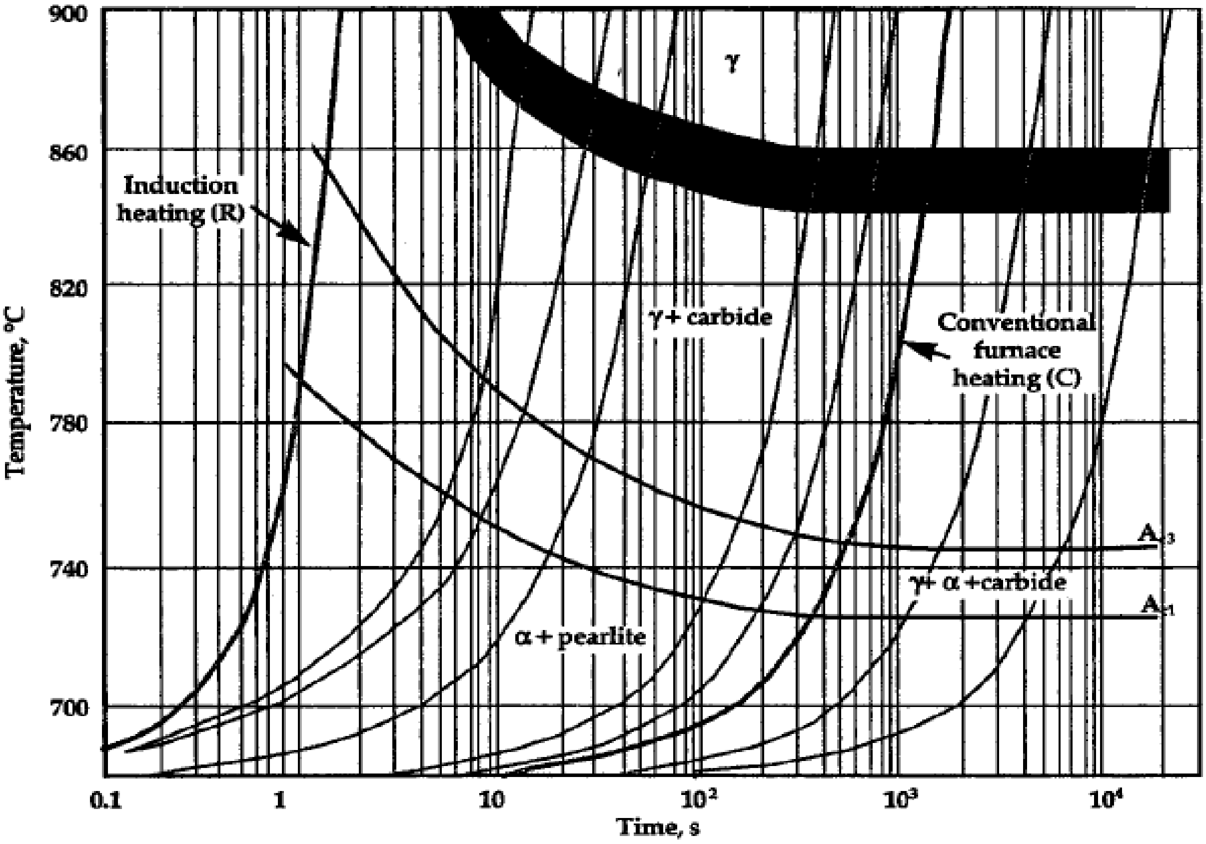


Figure 6. A TTT diagram for the creation of austenite. Likewise exposed are characteristic curves for furnace heating, C, and fast warming by induction [1,5]

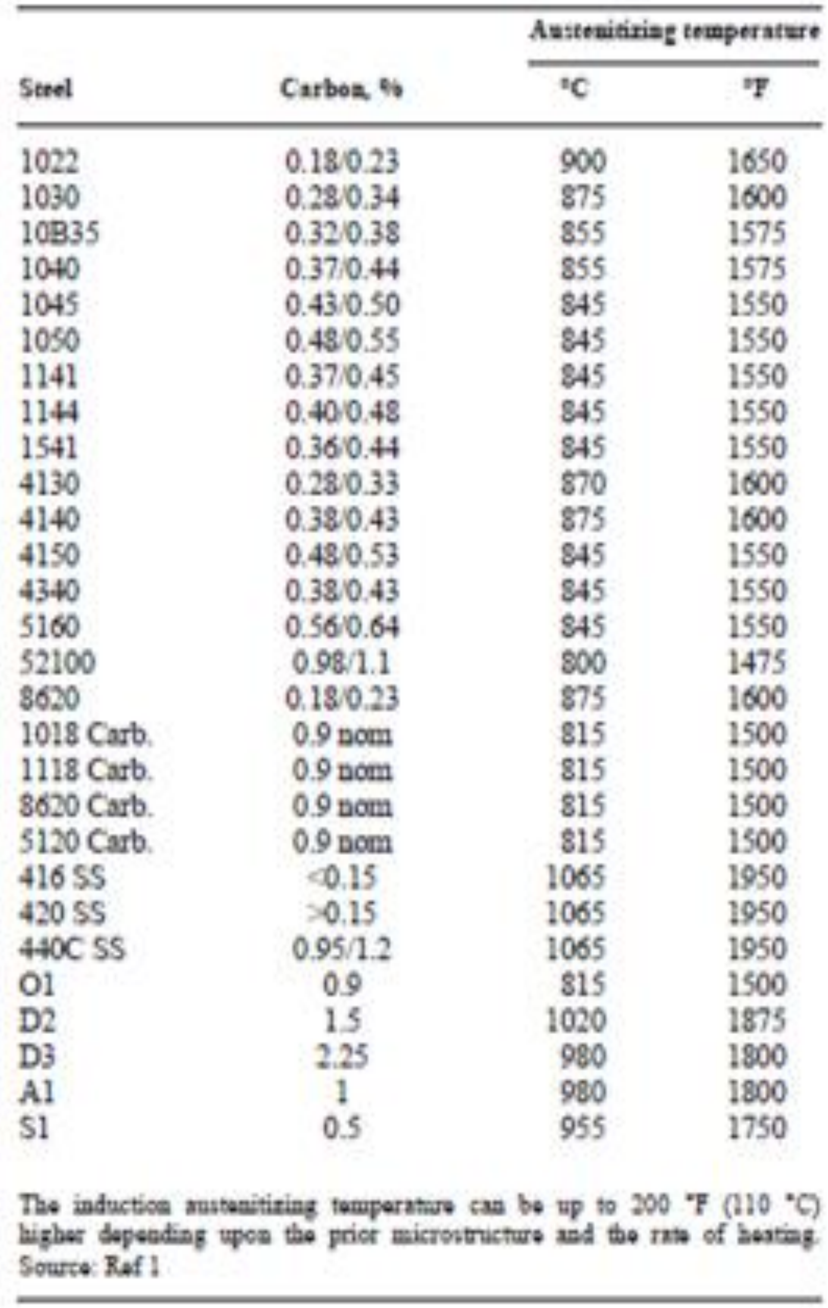
4.3. Induction Hardenable Steels

Induction hardening is practical for hardenable steels. Induction hardened steels include:

- Low carbon steels are used where toughness is required.
- Medium carbon steels are the communal induction hardened steels. These steels are utilized in mechanisms for example gears and drive shafts.
- High carbon steels are used for drills and other tool bits because of their great hardness.
- Alloy steels are utilized for possessions like bearings and machine tools.

Table 6 shows the induction steels and their austenitizing temperatures.

Table 6. Induction hardenable steels and their austenitization temperatures [1,5]



Steel	Carbon, %	Austenitizing temperature	
		°C	°F
1022	0.18/0.23	900	1650
1030	0.28/0.34	875	1600
10B35	0.32/0.38	855	1575
1040	0.37/0.44	855	1575
1045	0.43/0.50	845	1550
1050	0.48/0.55	845	1550
1141	0.37/0.45	845	1550
1144	0.40/0.48	845	1550
1541	0.36/0.44	845	1550
4130	0.28/0.33	870	1600
4140	0.38/0.43	875	1600
4150	0.48/0.53	845	1550
4340	0.38/0.43	845	1550
5160	0.56/0.64	845	1550
52100	0.98/1.1	800	1475
8620	0.18/0.23	875	1600
1018 Carb.	0.9 nom	815	1500
1118 Carb.	0.9 nom	815	1500
8620 Carb.	0.9 nom	815	1500
5120 Carb.	0.9 nom	815	1500
416 SS	<0.15	1065	1950
420 SS	>0.15	1065	1950
440C SS	0.95/1.2	1065	1950
O1	0.9	815	1500
D2	1.5	1020	1875
D3	2.25	980	1800
A1	1	980	1800
S1	0.5	955	1750

The induction austenitizing temperature can be up to 200 °F (110 °C) higher depending upon the prior microstructure and the rate of heating.
Source: Ref 1

4.4. Microstructural characterization

The heating and cooling times (Fig. 7') required for induction hardening will be in the order of seconds. The surface is heated to the austenite region at high temperatures and undergoes growth after austenite grains are formed. The subsurface regions heated to the austenite range may have lesser austenite grains (curve 2 within Figure 7). Additionally, there are sites that comprise mixtures of austenite and primary ferrite.

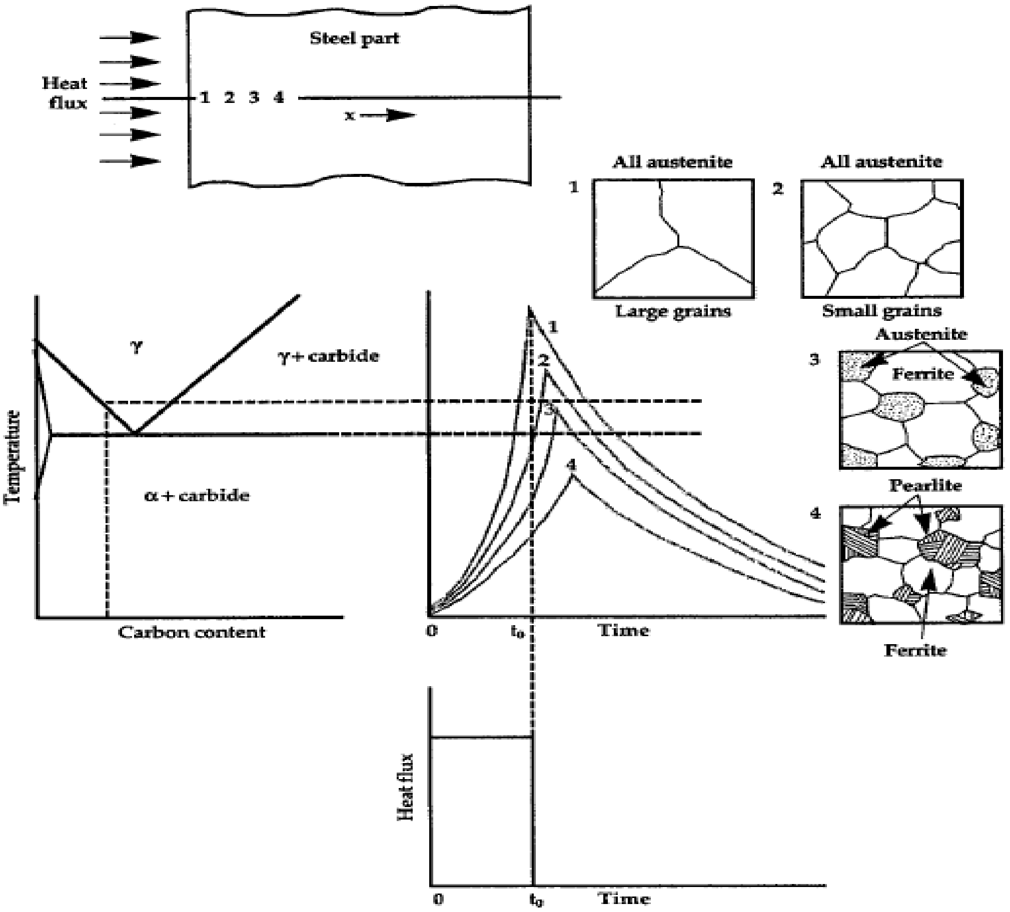


Figure 7. T-T (time-temperature) curves for induction surface hardening of a 0.4% C steel. Micrographs display austenite creation. Austenite grains at the surface are conditional on growing subsequently they form [5]

Since the cooling is very rapid in a few seconds on the surface, martensite forms (Figure 8). Closer to the interior, a region that is only partially austenite at high temperature is reached, and then martensite is formed by cooling of the structure.

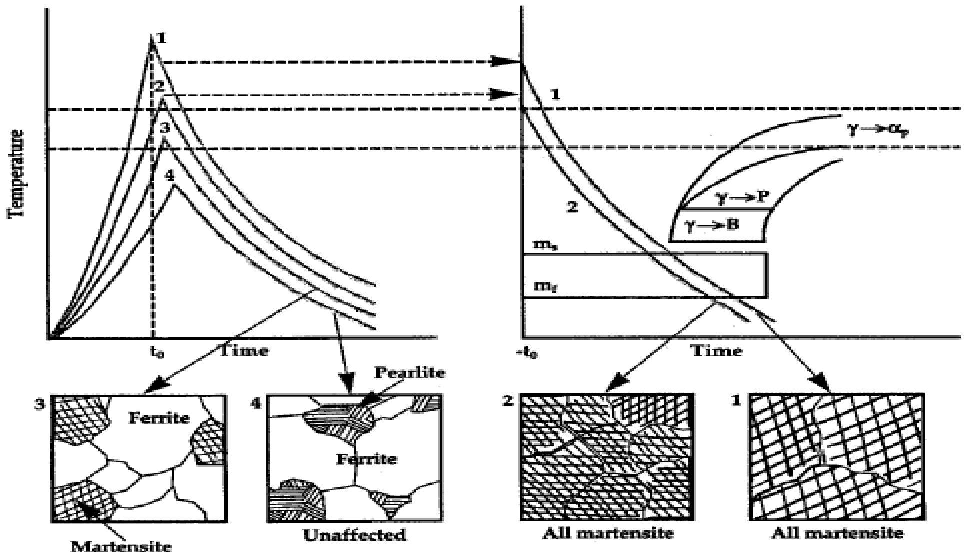


Figure 8. Alteration of austenite by cooling the surface heated 0.4% C steel. Numbers 1 to 4 denote to deepness positions in the steel portion (see Figure 13). Martensite typically occurs on the surface. (γ, austenite; P, pearlite; B, bainite; αp, primary ferrite) [5]

Cast iron, known as spheroidal graphite cast iron and denoted by DI (ductile iron), consists of small spheres dispersed in the iron matrix of graphite (Fig. 9). DI cast iron comprises spheroidal graphite and consequently has a greater elastic modulus than gray cast iron [1]. DI cast iron has decent castability as well as mechanical properties and is modest in charge.

Figure 10 shows the micrographs of the hardened and unhardened regions of SM53C. (A) It can be seen that the surface part of the hardened zone consists of a uniform detailed martensite structure. It is known that martensite has a coarser micrograph in case of slow cooling rate outside the hardening surface6. However, in the case of high frequency induction hardening, this undesirable tendency does not occur. Therefore, carbide amounts are reduced for austenite. Also, the observed proeutectoid ferrite was retained as shown in B and C. It forms perlite (lamellar) and ferrite (white) as original material, through the hardened and unhardened zone boundary in the centre (Figure 10(E)). Figure 10(F) displays a cross sectional plane subsequently etching. The dark division designates the heated hardened zone. The bright part specifies the uncured zone.

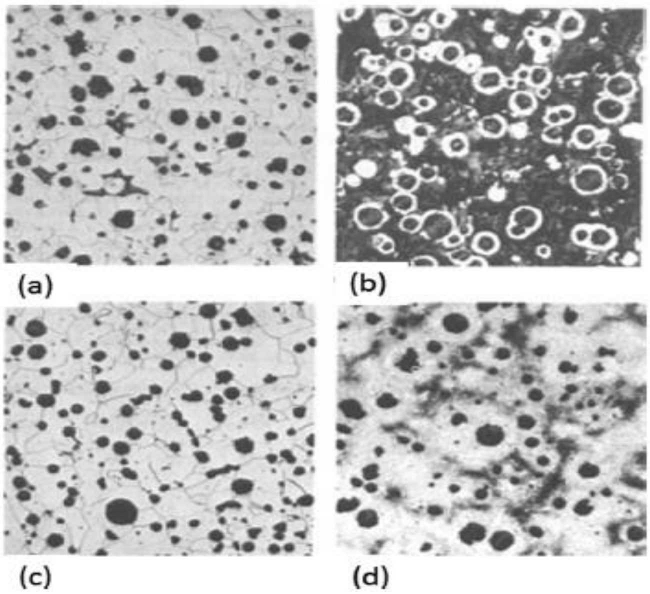
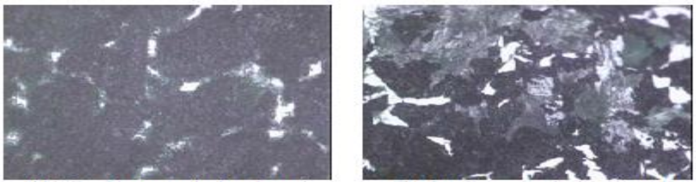
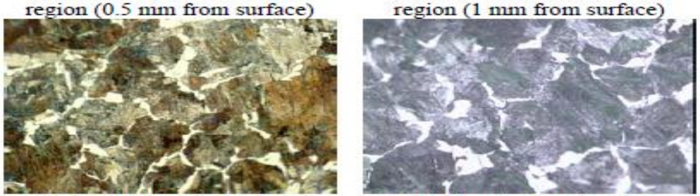


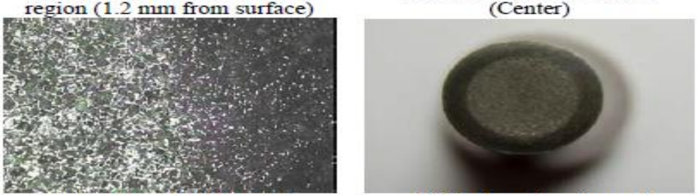
Figure 9 Micrographs of nodular iron. (a) As-cast ferritic. (b) As-cast pearlitic, 255 HB hardness. (c) Ferritic, annealed 3 h at 700ºC. (d) Pearlitic ductile iron, oil quenched and tempered to 255 HB (etched in 2% nital) [12]



(A) Surface part in hardened region (0.5 mm from surface) (B) Surface part in hardened region (1 mm from surface)



(C) Surface part in hardened region (1.2 mm from surface) (D) Non-hardened region (Center)



(E) Hardened region and non-hardened region (F) Hardened region and non-hardened region

Figure 10. OM of SM53C hardened in ECD 1.1 mm (×1000) [13]

4.5. Hardness Assessment

Hardness depends upon the micrograph. Figure 11 shows the hardness scattering subsequently induction heating of 0.8% C steel with pearlitic micrograph. Hardness curves are specified for the numerous maximum temperatures grasped at the surface of the steel.

On heating to 700 °C, hardness change did not occur as this temperature was underneath the eutectoid (723 °C); no austenite was shaped consequently (Fig. 5). By heating 0.8% C steel to 800 °C, a completely austenitic surface was obtained and the entire structure was transformed into martensite on this surface, resulting in a hardness of 63 HRC. For extreme surface temperatures greater than this, the hardness augmented to 65 HRC.

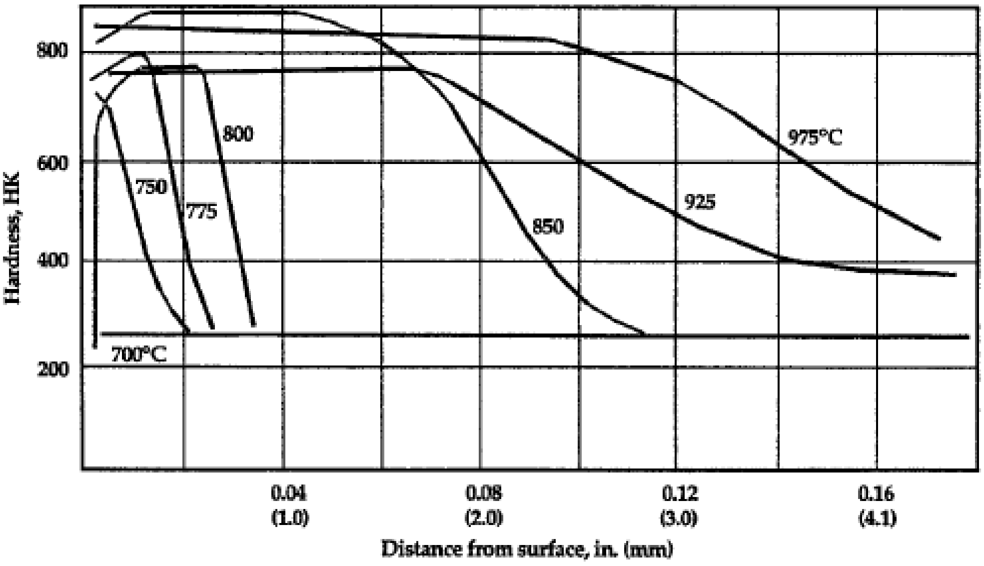


Figure 11. Hardness outlines for induction hardened 0.8% C pearlitic micrograph steel [1]

5. Conclusions

The camshaft is an object that converts rotational motion into reciprocating motion. Camshafts are used in internal combustion engines. Induction hardening is the method of hardening the surfaces by first heating the surfaces and then rapidly cooling them by quenching. Heating and curing belongings are confined and the deepness of cure can be controlled. The subsequent deductions can be acquired from the current research:

a) Camshafts are essential materials for internal combustion engines.
b) Several cast irons (EN GJL 100, 150, 200, 250, 300, 350) and steels (AISI 1117, 1015, 1030, 1137, 1080, 1144) can be used for the production of camshafts.
c) Induction and flame hardening as well as carburization and nitriding can be used for surface hardening of camshafts.
d) Conventional methods as well as computer-assisted software (CES) can be used for the camshaft materials.
e) Induction hardening is used in fragments for example cam or ring gears to develop the wear resistance of portions without disturbing the softer, harder inner of the fragment.
f) In induction hardening, the surface is longest in the austenite zone at elevated temperatures and therefore undergoes growth after austenite grains are formed. Martensite forms because the cooling at the surface is actual fast in a few seconds.
g) Hardness depends upon the micrograph. Heating 0.8% C steel to 800 °C produces a fully austenitic surface, which when cooled turns almost all martensite with a hardness of ~63 HRC.

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