Surface Engineering for Corrosion and Wear Resistance Application
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Lecture – 24
Flame Hardening and Induction Hardening

Welcome to the 24th lecture of Surface Engineering. We already have started discussing the specific techniques for various approaches of surface engineering of engineering solids. And we began discussing the techniques which are concerned with applying controlled amount of surface deformation onto the surface, principally with the name to create residual compressive stress to improve the fatigue resistance or certain other kinds of resistance against surface failures.

The principle mechanism of that approach was to create strain plastic strain and increased dislocation density onto the surface so, that eventually we create residual compressive stress.

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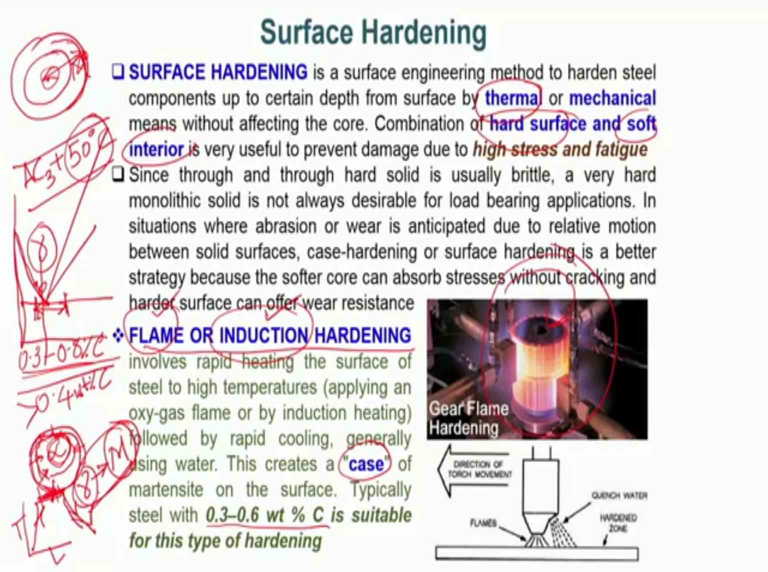

Surface Hardening

- ☐ **SURFACE HARDENING** is a surface engineering method to harden steel components up to certain depth from surface by **thermal** or **mechanical** means without affecting the core. Combination of **hard surface and soft interior** is very useful to prevent damage due to ***high stress and fatigue***
- ☐ Since through and through hard solid is usually brittle, a very hard monolithic solid is not always desirable for load bearing applications. In situations where abrasion or wear is anticipated due to relative motion between solid surfaces, case-hardening or surface hardening is a better strategy because the softer core can absorb stresses without cracking and harder surface can offer wear resistance

❖ **FLAME OR INDUCTION HARDENING** involves rapid heating the surface of steel to high temperatures (applying an oxy-gas flame or by induction heating) followed by rapid cooling, generally using water. This creates a "**case**" of martensite on the surface. Typically steel with ***0.3–0.6 wt % C is suitable for this type of hardening***

Today we are going to discuss surface hardening which is a thermally activated process with the same aim that we want to harden the surface. And we are essentially when we talk of surface hardening in particular we are talking about all the discussions are concerned with steel the interstitial solid solution of carbon in alpha iron.

So, in steel we all are aware if you look into the first view graph, if you just consider the solid state part of the iron carbon diagram so, this is the so called eutectoid portion and so, in this surface hardening approach we are concerned with a composition range which is somewhat in this range. So, somewhere around let us say typically about 0.3 to about 0.8 or maybe even less amount of carbon.

So, this is the level of carbon content and we are talking about primarily plain carbon steel, but this is certainly applicable to alloy steel as well. But we require typically somewhere around 0.3 I would say optimally 0.4 and above 0.4 weight percent of carbon or above this is what we need.

Now, why we need this carbon content I will come that come to that in a minute, but the most important thing that we need to realize is that we essentially in this kind of a treatment, if we are talking about a component the cross section of which is let us say of this diameter. We would like to harden the surface only up to a certain depth from the surface and not through and through.

So, the core will be left in ferritic state the surface because of transient heating is supposed to; so, essentially the surface should experience a heating cycle which is so, this is temperature and this is time. So, we want the surface to reach fairly high temperature hence the so called high temperature what we mean should be somewhere around here.

So, if this is AC 3 the ferrite austenite transition line, we would expect a temperature typically which should be AC 3 plus about 50 degrees centigrade. So, this is the austenitizing range; so, depending upon the carbon content whether it is 0.6 or 0.4 or 0.3, we just find out what is the corresponding temperature at the AC line. And then add up around 50 degree or slightly more to take care of the possible thermal fluctuations during the heating process.

So, the temperature here is somewhere in that range AC 3 plus 50 to 100 degree centigrade and then subsequently we cool. We actually cool by way of some accelerated cooling by way of quenching which could be by application of certain fluids we will also discuss that in a minute.

So, the whole idea is to use steel whose composition is between this range and then subjected to transient heating to a temperature which is in the single phase austenitic zone. And then subsequently we quench using some kind of a quench and to bring it to room temperature. And in the process we expect the surface zone up to a certain depth to undergo a phase transition from austenite to marten site.

So, the strengthening is because of marten site as compared to the previous surface deformation induced processes like shock peening or shock peening or laser shock peening, where we introduce plastic strain and dislocation density and that is how we created residual compressive stress. Here the process involves a solid state phase transformation where in austenite transforms to marten site.

So, as I said this is primarily a thermal treatment, we want a hard surface and the soft core because the core for example, this ferrite here will actually be able to absorb energy including impact or high strain rate energy. Whereas, the surface will be able to resist deformation due to wear abrasion erosion or any other kinds of surface damages.

So, it is important that we actually create a graded microstructure, what we mean is that if this is the cross section we want gradation such that we are very fine acicular ferrite onto the acicular marten site onto the surface, and then in the core we can actually we can afford to have polyhedral ferritic or ferito perlitic microstructure. So, in the process we actually see a gradation from pure martensitic to marten site plus perlite and then eventually martin ferrite perlite combination.

So, this is obtained or achieved through a thermal activation by way of one of the two, we are going to discuss so called flame hardening and induction hardening. So, the heating is done either by flame or by electromagnetic induction. And in the process the hard surface that we create is called case and typically the case depth could be millimeter or less even a few millimeters in some cases.

So, here is a real time picture; so, this is a very large gear which is subjected to flame from multiple sides and this assembly is rotating at a particular speed. So, that the surface by turn the entire surface by turn is exposed to high temperature and this is a kind of heating cycle the surface actually experiences. So, we heat we actually allow certain residence time, but this is transient heating so; obviously, this is very short time and then subsequently we quench using some kind of a quench end.

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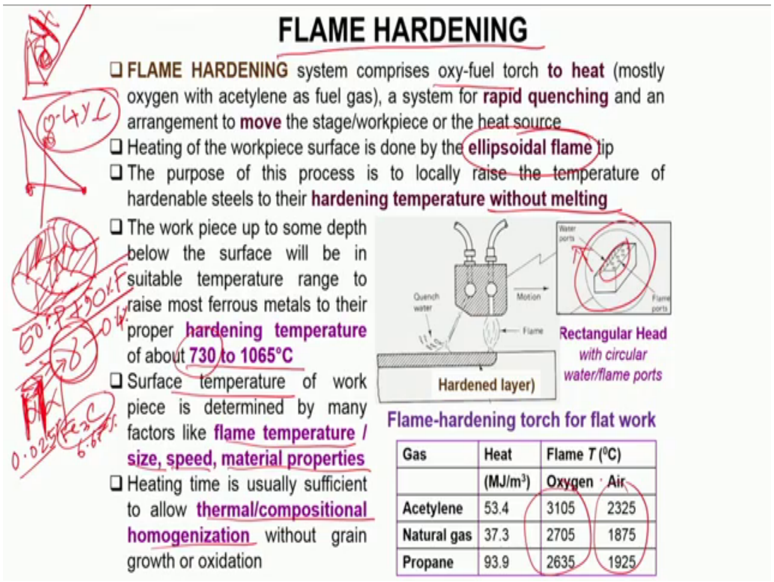

FLAME HARDENING

- ❑ **FLAME HARDENING** system comprises oxy-fuel torch **to heat** (mostly oxygen with acetylene as fuel gas), a system for **rapid quenching** and an arrangement to **move** the stage/workpiece or the heat source
- ❑ Heating of the workpiece surface is done by the **ellipsoidal flame** tip
- ❑ The purpose of this process is to locally raise the temperature of hardenable steels to their **hardening temperature without melting**
- ❑ The work piece up to some depth below the surface will be in suitable temperature range to raise most ferrous metals to their proper **hardening temperature** of about **730 to 1065°C**
- ❑ Surface temperature of work piece is determined by many factors like **flame temperature / size, speed, material properties**
- ❑ Heating time is usually sufficient to allow **thermal/compositional homogenization** without grain growth or oxidation

Rectangular Head *with circular water/flame ports*

Flame-hardening torch for flat work

Gas	Heat	Flame T (°C)	
	(MJ/m³)	Oxygen	Air
Acetylene	53.4	3105	2325
Natural gas	37.3	2705	1875
Propane	93.9	2635	1925

So, first let us pick up the flame hardening where we actually use it could be simply an oxy acetylene or some other form of flame. So, we use a burner so, this is a typical burner with several orifices. So, we actually can; so, this top portion is primarily to create through the oxygen and acetylene combination and by combustion of this gas mixture, we get very high temperature at the tip. The tip typically takes up the ellipsoidal form and then subsequently from the sides of the burner nozzle, we also have orifices or openings through which we can throw water.

So, when this flame is off and the stock of the surface of the stock has reached the required temperature. Then we want immediate quenching and that is obtained by throwing water or various kinds of coolants mixture of water and salt or maybe water and some kind of polymers and so on or oil, and then that that fluid flow basically extracts heat from the surface and causes very fast quenching of the surface.

So, one thing what we must remember is if you recall I kind of just now showed that we are we are only talking about the solid state part of the phase diagram. We are not referring to the portion which actually is related to the peritectic. So, this is the liquidus line we never cross the liquidus line so, we are well within the single phase austenitic zone. So, there is no melting, the typical hardening temperatures would be about 730 to 7 6 1065 degree centigrade.

This essentially depends upon if this is AC 3 and depending upon the temperature depending upon the composition that you are talking about it can be on the higher side for about 0.3 percent carbon. You actually go to our temperature which is close to 1000 or little over 1000 degree centigrade, but if the composition is 0. 6 or close to eutectoid temperature eutectoid point then you are talking about 727 plus about 50 degree.

So, something like 700 and any anywhere between 730 to 780 or that kind of a temperature range. So, typically the temperature that we generate on to the surface now this is what we are talking about the temperature of the stocks, but the flame temperature certainly would be little higher because you are actually heating up through radiation from the flame.

So, the temperature at the surface will be determined by the flame temperature, the size and shape of the flame, the speed at which the work pieces is moving either rotating or translating away from the plain flame and of course, the material properties which means, the conductivity the density the specific heat melting temperatures and so on and so forth.

The heating time should be sufficient for thermal and compositional homogenization. Now, we are talking about let us say 0.4 percent carbon steel. So, if we are talking about 0.4 percent carbon at room temperature, we expect point four percent carbon seal typically a mild steel should have a microstructure which will be a both pearlite and some amount of ferrite. So, we will have pearlitic zone and maybe some fanatic regions left in between.

So, typically we expect sort of 50 percent perlite and 50 percent ferrite, this is the kind of micro structural aggregate that we expect from a 0.4 percent carbon steel at room temperature. So, when an aggregate with both ferrite and pearlite is subjected to rapid heating to a temperature above the AC 3; so, we expect this aggregate to turn into single phase austenite or gamma that takes time, because you have to dissolve Fe 3 C. So, you have alternate sequence of Fe 3 C and alpha and this Fe 3 C has to has a composition of 6.67 percent carbon. On the other hand ferrite composition is somewhere here which is typically let us say 0.0258 percent of carbon.

So, you have to swing, you have to allow compositional homogenization within a very short distance though. So, typically this is about a micron or micrometer or a few micrometer apart so, 6.67, 6.67 and in between 0.025. So, within about let us say 2 or 3 micrometer. So, whatever is the heating temperature you must also allow sufficient time for first of all thermal homogenization which is faster because the thermal conductivity is always higher than the diffusion coefficient. But, you also should have sufficient time given, so that compositionally the whole region when it converts to gamma this gamma should have a uniform composition of 0.4 percent carbon throughout.

So, compositional homogenization is also important. These are the various kinds of the gas mixtures that we use. So, if you use combination of oxygen air with oxygen or air with acetylene or natural gas or propane. So, this is the kind of flame temperatures that you can develop. So, if its oxygen, so this is the range of temperatures you can generate or with air the temperature range would be slightly lower. So, one has to control the flow of gases at the tip of the flame so, that the right kind of temperature mix is maintained.

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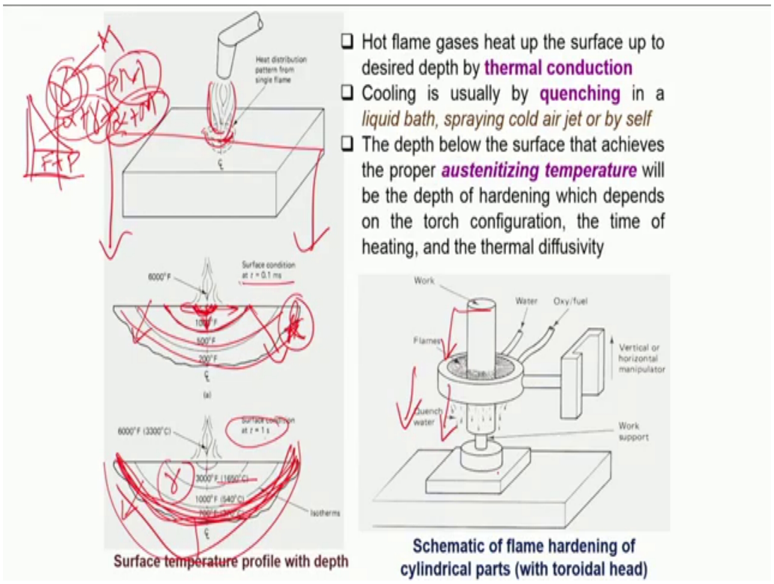

- ☐ Hot flame gases heat up the surface up to desired depth by **thermal conduction**
- ☐ Cooling is usually by **quenching** in a *liquid bath, spraying cold air jet or by self*
- ☐ The depth below the surface that achieves the proper ***austenitizing temperature*** will be the depth of hardening which depends on the torch configuration, the time of heating, and the thermal diffusivity

Surface temperature profile with depth

Schematic of flame hardening of cylindrical parts (with toroidal head)

So, when you heat; so, this is how the flame which is typically assumes the shape like this, and this is going to heat up the surface. So, let us say this is the heated zone and if you now take a section, if you take a section like this and on this section you see the isothermal contours. So, for example, these are in Fahrenheit so, approximately the temperatures would be kind of little over half of this.

So, the temperature at the surface or the meniscus at the surface, this is where you have the maximum heat and the temperatures will be the highest. As you go down you;

obviously, the heat has to flow and that is primarily determined by the conductivity K and this is how the temperature flows into the interior.

But the isothermal, iso-temperature contours meaning, this is the line throughout which will be maintaining the same temperature or this is the trajectory of the same temperature points. Now, why is it semicircular it is because heating right below is maximum and similarly heat flows not only in the perpendicular direction or right below, but it also propagates laterally.

So, because of heat propagation in all directions a in at least in into the vertically downward as well as laterally to x and y directions the contour surface temperature contour is going to be semicircular like this and as we go to lower and lower higher and higher depth below the surface the temperature decreases gradually.

So, if you and this temperature also there is a transient heating; so, with time this isothermal contours change. So, this is what you expect at 0.1 millisecond region, but after one second; that means, 100 times more than that if the if the heating continues for 100 times more than that. So, 0.1 millisecond becomes 1 second, then the temperature which earlier was about 1000 Fahrenheit or maybe 550 or so, degree centigrade has now reached easily 1650 and so on.

So, this is only limited to a very shallow depth. So, the surface actually should not be exposed to very high temperature, but on the other hand the temperature the surface should be high enough. So, that up to the desired depth you actually expose the material to the minimum possible temperature or minimum desirable temperature which is which should be above the eutectoid temperature.

But of course, there will be a region which is called the heat affected zone. So, this region; so, let us say this is the boundary unto which you are able to heat to a temperature above AC 3. So, are you into the single phase gamma region you are able to convert everything into gamma, but there will be also a region below which will be experiencing a temperature which will be between in the in the two phase region of ferrite plus gamma.

So, this is single phase gamma and they will be also a region which will actually remain as ferrite plus pearlite. So, if this is the composition from the surface a portion below the surface will go into single phase gamma, a portion below will be below that will be ferrite plus austenite and then finally, you will also have a rich a certain depth which will be only remain as ferrite pearlite combination.

This portion which is gamma pure gamma or the portion which is partly ferrite and partly austenite these two austenitic range; the regions or these two regions having austenite will directly convert into marten site. So, we are going to see fully martenstic and ferrite plus the marten site combination. So, this is typically the configuration for example, for our shaft with a circular section.

So, you are heating it from all sides and the heating ring actually can move to upper down; vertically upper down and as a result you start let us say heating from here and then you go all the way down to; so, you are able to actually heat treat the whole surface. The important point is that heating temperature should not cross the fusion temperature or the so called solidus temperature.

So, that some liquid forms we do not want that should happen at all. So, heating should be confined below the solidus temperature and the heat flows through thermal conduction and once the temperature has reached the required level, then we also are able to throw water through other orifices and immediately quench the material quench the surface to room temperature.

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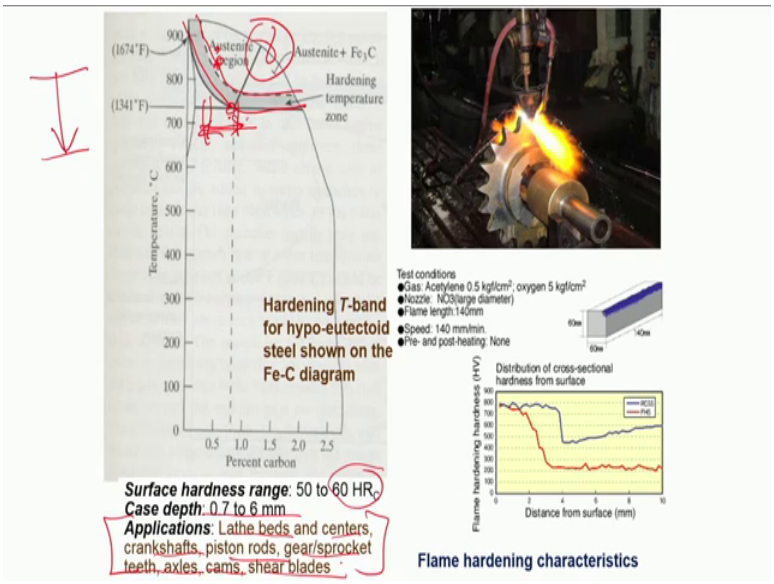

Hardening *T*-band for hypo-eutectoid steel shown on the Fe-C diagram

Surface hardness range: 50 to 60 HR_C
Case depth: 0.7 to 6 mm
Applications: Lathe beds and centers, crankshafts, piston rods, gear/sprocket teeth, axles, cams, shear blades

Test conditions
- Gas: Acetylene 0.5 kgf/cm^2; oxygen 5 kgf/cm^2
- Nozzle: NO3(large diameter)
- Flame length:140mm
- Speed: 140 mm/min.
- Pre- and post-heating: None

Distribution of cross-sectional hardness from surface

Flame hardening characteristics

So, the cycle will be room temperature to austenitizing temperature and then subsequently quenching back to room temperature. So, this is the typically the temperature band that we actually target; so, this is the eutectoid point and we are talking about typically steel of this composition range. So, this is the level of this is the kind of temperature that we heat up to, but since it is a transient heating very difficult to maintain precise temperature, and it is not going to be an isothermal condition, there will be a gradation of temperature from the surface to the bottom or to the interior.

So, as I already said that we expose to high temperature where why we have single phase austenite and then we quench. And in the process we expect the surface to create at the very surface region, we expect very high hardness over 60 rock well hardness scale; rock well C hardness scale and the typical case depth the harden depth can be anything from about 0.7 or 0.5 to as high as 6 millimeters. So, we are talking about more than I mean a substantial amount of depth from the surface.

So, typical applications the components which are amenable to such surface hardening by flame would be the lathe beds, the centers, the crankshafts, the piston rods gears and sprockets teeth of the gear, x axles, cams shear blades and so on and so forth. These are all steel products and this whole process is applicable primarily to steel and as I said which should have minimum of 0.3, 0.4 percent carbon content.

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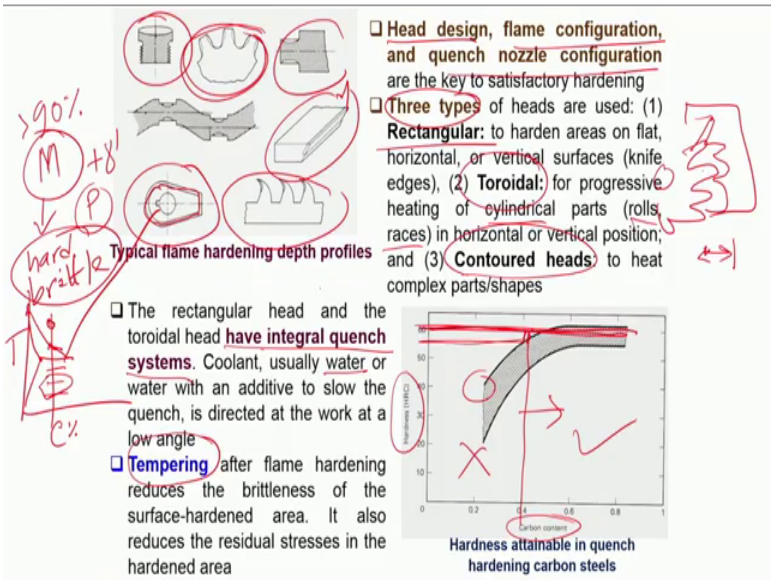

Typical flame hardening depth profiles

- ❑ **Head design, flame configuration, and quench nozzle configuration** are the key to satisfactory hardening
- ❑ Three types of heads are used: (1) **Rectangular:** to harden areas on flat, horizontal, or vertical surfaces (knife edges), (2) **Toroidal:** for progressive heating of cylindrical parts (rolls, races) in horizontal or vertical position; and (3) **Contoured heads:** to heat complex parts/shapes
- ❑ The rectangular head and the toroidal head **have integral quench systems**. Coolant, usually water or water with an additive to slow the quench, is directed at the work at a low angle
- ❑ **Tempering** after flame hardening reduces the brittleness of the surface-hardened area. It also reduces the residual stresses in the hardened area

Hardness attainable in quench hardening carbon steels

Now, so, these are the various geometries which actually can be subjected to a shear blade or a gear teeth or again another gear teeth, very cams and various kinds of shafts or screws and nuts and so on, where the surface always should have higher hardness and higher wear resistance. But the core we would purposely leave as ferritic or ferito perlitic. So, that it can absorb energy and of mechanical deformation and provide toughness.

So, the important considerations are the head design, the flame configuration, the nozzle quench nozzle configuration and the velocity with which we throw the coolant and so on. So, we are we basically can have three types of heads one is a rectangular head so, for materials which are rectangular in nature maybe a blade or a sheer blade like that or a cutting tip. So, which are rectangular or square or thin sheets and so on?

So, we use a rectangular head for heating, we can use a toroidal head which basically is applicable to cylindrical or circular parts like rolls and races or we can use a contoured head. So, for example, we have typical we have a very complex shape of a component like this. So, for treating such an such a surface or a component, we would like to also have a nozzle which actually will mimic the shape of this kind of a component. So, that the distance from the tip of the nozzle to the surface is maintained constant.

. So, these are the design aspects of various nozzles that we use for heating. We actually can have all these heating devices should also have an system of integral should integrate with a quench quenching system. The coolant usually is water or it can be water with some mixtures of may be polymers or salt or something or it can even oil, if it is a usually if we are employing a hardened steel or sorry an alloy steel, then we do not need very drastic quenching. So, instead of water we can use in that case oil.

After the process is over; that means, after the flame hardening is over, we actually may need a follow up tempering process. Because a material which is thrown through hardened and having let us say predominantly maybe 90 percent marten site or so, the remaining portion of course, is likely to be retained austenite or in some cases maybe pearlite. But if you have more than 90 percent marten site, the surface will be extremely hard and also brittle and because of this combination you cannot machine them, and there will be certain amount of distortion which may happen subsequently.

So, in order to make the surface amenable to subsequent machining or shaping or some other treatment, we may like to also follow up with the tempering process which is a reading process. So, essentially we can use the same flame to heat to a temperature way below the eutectoid transition point. So; that means, now when we when we talked about so, this is temperature and this is carbon content.

So, when we are talking about tempering, so for flame hardening we aimed a temperature zone somewhere here for a composition like this. But if we want tempering to follow the hardening process, then we would go somewhere around 500 or not even 500 somewhere around let us say 250 to 350 at the most four 100 degree centigrade or so, so this would be the typical zone ok.

And, what is important is that, why are we doing all these exercises because we want to harden the surface and by way of bringing in marten site. So, we want a predominantly martensitic surface, then the ultimate aim is to see a hardness level which is typically about 60 in the rock well c scale. Now, this is possible no matter how efficiently we do whether we are able to do it efficiently or not, this is typically possible for the composition range which is 0.4 percent carbon and above. So, this is the carbon content the homogeneous carbon content of the steel; so, if you have a steel which is less than 0.4 percent carbon steel, even if you conduct the process very efficiently you may not be able to reach the requisite hardness. So, the hardness level could be as low as 40 RC so, this is no good.

So, the important guideline here is that we want this range of composition to be subjected to flame hardening and not this range, because a requisite amount of carbon is necessary in the stock during heating process in order to get the desired level of hardness. If you recall during the discourse on martensitic transformation I did mention that one of the biggest reason of seeing marten site as the hardest solid solution phase is because of the fact that a marten site, actually is derives its strength from primarily from super saturation.

So, it is essentially a supersaturated solid solution and the super saturation if it is less than due to less than 0.3 percent carbon then that is not sufficient for creating the desired hardness after marten site formation.

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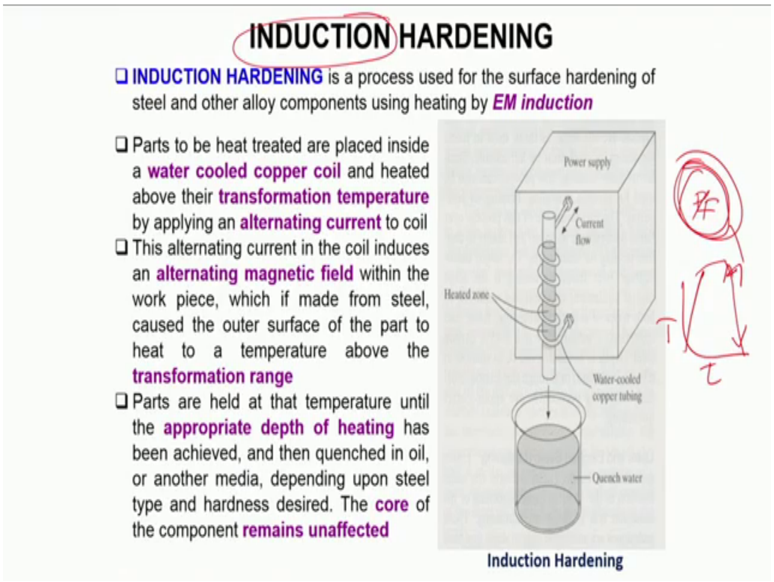

INDUCTION HARDENING

- **INDUCTION HARDENING** is a process used for the surface hardening of steel and other alloy components using heating by ***EM induction***
- Parts to be heat treated are placed inside a **water cooled copper coil** and heated above their **transformation temperature** by applying an **alternating current** to coil
- This alternating current in the coil induces an **alternating magnetic field** within the work piece, which if made from steel, caused the outer surface of the part to heat to a temperature above the **transformation range**
- Parts are held at that temperature until the **appropriate depth of heating** has been achieved, and then quenched in oil, or another media, depending upon steel type and hardness desired. The **core** of the component **remains unaffected**

Induction Hardening

Now, there is another method which is equally important and in fact, instead of flame here the thermal activation are so called the heating effect is given by electromagnetic induction. So just like flame, what we have here say for example, this is a typical shaft or a rod which we want; so, this is the cross section and we want as the surface up to a certain depth to get hardened and the core should remain perlitic or ferritic, but the surface should be martensitic.

So, with that intention we simply have a toroidal coil electromagnetic induction coil through which this rod can be inserted and we apply a very high frequency current. So, that electromagnetic fluxes are created and the fluxes intersect the surface and in the process through eddy heating they create heating onto the surface. So, the temperature again so, we exactly see temperature time profile which will be like this and then will be subsequently quenched by either dropping into a quenchent or at some other invent by throwing compressed air and so on.

So, we need water cooled copper coil for in magnetic induction, we need to reach the required transformation temperature and this temperature is reached because the alternative current that we sent to the coil. So, when we send alternating current, current to the coil we create alternating magnetic field, and this magnetic field interacts the fluxes interact with the surface and creates certain thermal state, and we it that takes the stock to a temperature above the austenite formation range.

So, we can control more precisely here the exact depth of heating the core remains unaffected, but the surface goes to temperature above ostracizing and then subsequently when quench in oil or maybe some other media.

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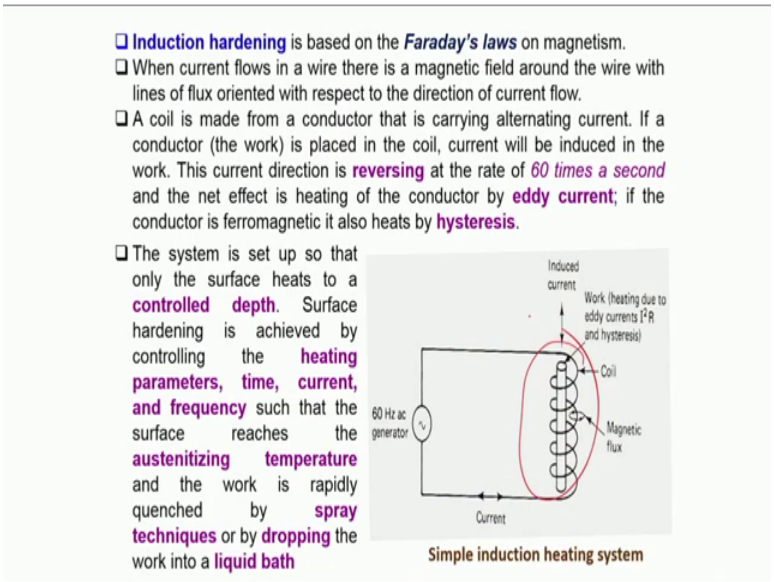

- **Induction hardening** is based on the ***Faraday's laws*** on magnetism.
- When current flows in a wire there is a magnetic field around the wire with lines of flux oriented with respect to the direction of current flow.
- A coil is made from a conductor that is carrying alternating current. If a conductor (the work) is placed in the coil, current will be induced in the work. This current direction is **reversing** at the rate of *60 times a second* and the net effect is heating of the conductor by **eddy current**; if the conductor is ferromagnetic it also heats by **hysteresis**.
- The system is set up so that only the surface heats to a **controlled depth**. Surface hardening is achieved by controlling the **heating parameters, time, current, and frequency** such that the surface reaches the **austenitizing temperature** and the work is rapidly quenched by **spray techniques** or by **dropping** the work into a **liquid bath**

Simple induction heating system

So, this is exactly the arrangement that I was talking about, and we actually what we must realize is that this induction hardening follows exactly the Faraday's law and which means that if we apply alternating current reversing at a very high frequency let us say 60 Hertz or so, then this is going to lead to very generation of very high eddy current. So, the heating will be through this eddy current also in addition there could be alternating cycles of magnetization demagnetization. So, there will be a hysteresis and the area under the loop will also lead to hysteresis heating.

We can as I mentioned we can maintain control the depth very precisely and this depth of heating will primarily depend upon the parameters, the heating parameters, the time of heating, the current, the frequency. So that we reach the correct hospitalizing temperature and then subsequently we quench by either spray or by dipping or dropping into a liquid bath.

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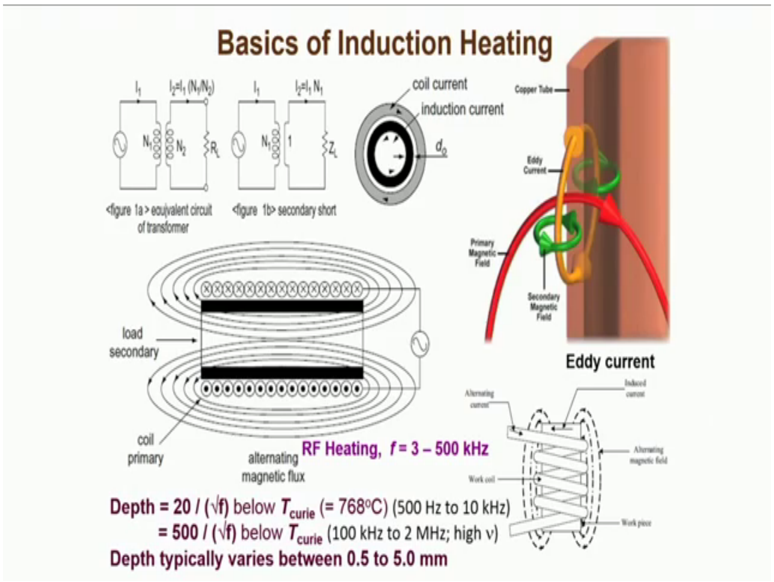

Basics of Induction Heating

RF Heating, $f = 3 - 500$ kHz

Depth = $20 / (\sqrt{f})$ below T_{curie} (= 768°C) (500 Hz to 10 kHz)
= $500 / (\sqrt{f})$ below T_{curie} (100 kHz to 2 MHz; high ν)
Depth typically varies between 0.5 to 5.0 mm

So, this is the depth this is the circular section so, this is the coil current and this coil induces current into the stock circular section of which you are seeing here. So, particularly the eddy current that we generate actually is responsible for heating, and this is the overall picture of electromagnetic induction so, these are the fluxes which are created from these induction coils.

And so, the coils are perpendicular to the stalk and this is how the flux is generated the left hand thumb rule and then these fluxes intersect the surface. And if the material is magnetic, then actually we get even better heat or a faster heating and that is very true for materials ferromagnetic materials like steel.

The, what is important is for us to know that why I was mentioning that the we can control the depth more precisely, the depth is an inverse function of the square of the square root of the frequency of induction. So, accordingly by applying the frequency, we actually can heat up to a temperature above the Curie temperature, but subsequently when its quenched it undergoes the martensitic transformation.

But, the degree to which we heat will primarily depend upon the range of frequency that we apply for inducing current. For electromagnetic induction if the if the frequency is less than 10 kilo Hertz then this is the relationship that we follow or if the frequency applied is higher say for example, from few hundred kilohertz to even megahertz then we apply the second relationship.

But what is important is the depth from the surface that for example, if this is a stalk then this is the depth from either side that we are subjecting too. So, this depth can be very precisely controlled a by way of controlling this frequency of induction and typically the depth can be anything from less than a millimeter to a few millimeters.

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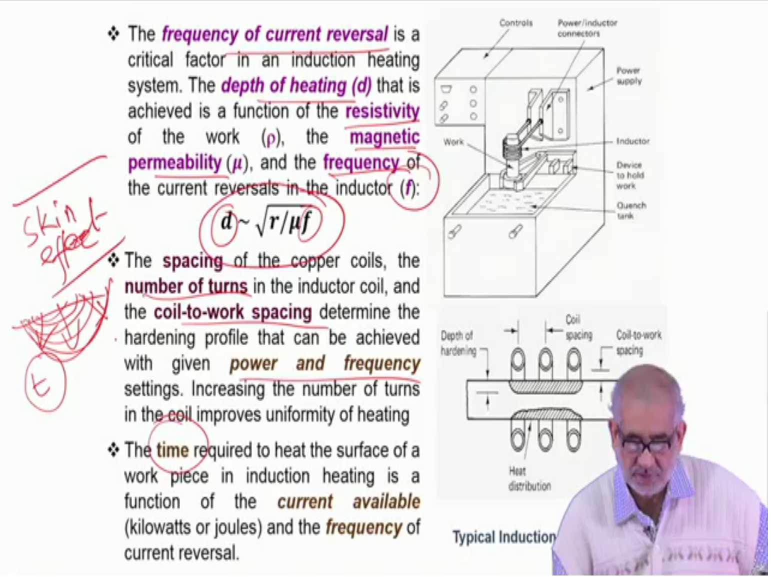

- The ***frequency of current reversal*** is a critical factor in an induction heating system. The ***depth of heating (d)*** that is achieved is a function of the **resistivity** of the work (ρ), the **magnetic permeability** (*μ*), and the **frequency** of the current reversals in the inductor (*f*):

$$d \sim \sqrt{r/\mu f}$$

- The **spacing** of the copper coils, the **number of turns** in the inductor coil, and the **coil-to-work spacing** determine the hardening profile that can be achieved with given ***power and frequency*** settings. Increasing the number of turns in the coil improves uniformity of heating
- The **time** required to heat the surface of a work piece in induction heating is a function of the ***current available*** (kilowatts or joules) and the ***frequency*** of current reversal.

skin effect

t

Typical Induction

So, this is the relationship I was referring to and it is because of this the depth is inversely proportional to the frequency square of the frequency, and this is what essentially leads to what is typically referred to in the literature and skin effect. So, you actually can harden or heat the surface to above the eutectoid and the ostracizing temperature by way of controlling the frequency.

So, the frequency of current reversal is an important factor and the depth will depend upon the resistivity of the material, the magnetic permeability, the frequency of as I said the frequency. So, what is also important is that the copper coil which is generally used water cooled copper coil which is generally used for induction, the number of turns the distance from the work piece and of course, the power and frequency all these are important process parameters.

Time is also very important because the residence time at high temperature determines to what extent from the surface you are able to penetrate the temperature. And we already saw that no matter whether its flame or induction we do generate such isothermal contours from the surface as heating profiles, and this changes with time because this is transient heating.

So, what is important is that we not only maintain the external parameters like frequency and the current and so on; we also apply such induction effect for a limited time for a control time. So, that the maximum temperature that we reach remains within the solid state and does not go into the liquid state all right.

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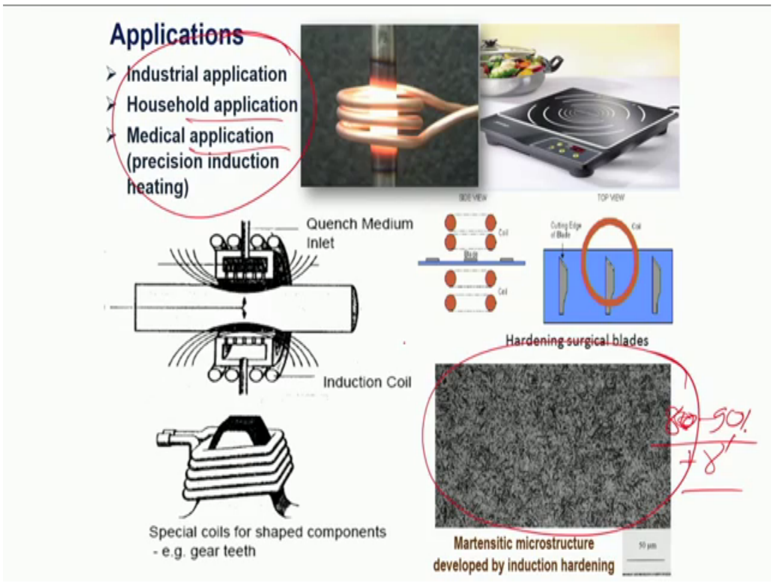

Applications

- Industrial application
- Household application
- Medical application (precision induction heating)

So, these are various applications not many industrial applications for various manufacturing processes, the various household appliances, then medical appliances and so on and this is the microstructure that we target at the surface. So, predominantly martensitic, when I say predominantly I do not mean 100 percent, but anywhere typically 80 to 90 percent of marten site onto the surface, and the remaining portion of course, will be the retained austenite.

So, this is typically a configuration where in you have seen that these are the induction coil and this is the shaft which is being fed into it or if it is a gear teeth this is; so, you actually will have a configuration which is going to be. So, this is the rotating part and you will have various number of such teeth of the gear like this. And so, if you are targeting one of these teeth like this then the coil should be properly designed the geometry of the coil should be; so, designed that it actually can fit in exactly to this. So, now you are in a position to harden that only the surface of the teeth to the desired depth.

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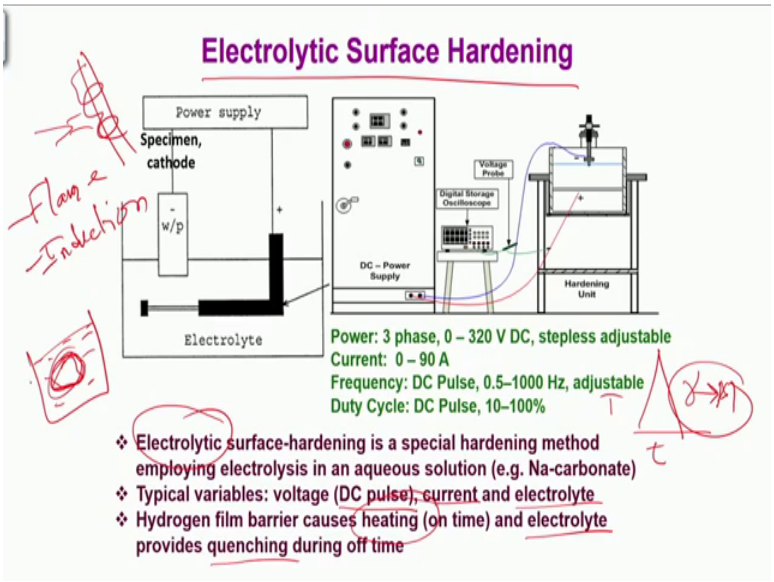

Electrolytic Surface Hardening

Power: 3 phase, 0 – 320 V DC, stepless adjustable
Current: 0 – 90 A
Frequency: DC Pulse, 0.5–1000 Hz, adjustable
Duty Cycle: DC Pulse, 10–100%

- Electrolytic surface-hardening is a special hardening method employing electrolysis in an aqueous solution (e.g. Na-carbonate)
- Typical variables: voltage (DC pulse), current and electrolyte
- Hydrogen film barrier causes heating (on time) and electrolyte provides quenching during off time

This one last thing I wanted to mention is that the heating so far we have done is either by flame or by induction. There is another way of doing this and this has very limited application, but is nevertheless quite effective is when you use an electrolyte. So, you actually are using an aqueous bath electrolytic bath wherein by applying DC pulse not EC and controlling the current and the composition of the electrolyte. You actually can create a hydrogen film onto the surface and because of the resistance created by this hydrogen film you can do heating onto the surface.

So, it is a correct electrolyte that you need to select and during off time the electrolyte extracts heat from the solid stock, and that is how you can actually allow heating and cooling cycle and as a result of which you can do hardening. So, you can take it to oscillating state and then subsequently convert this to marten site onto the surface.

So, this is the biggest utility of electrolytic surface heating is related to the fact that if you have a bath and if you have a stock here, inside the electrolytic bath then you can do heating uniformly or you can harden the entire stock in one shot uniformly which is not going to be possible when you are using a nozzle for heating or an induction coil for hardening the surface, you cannot do for the entire link together. But here in electrolytic heating you can do that for the entire stock because whole thing is immersed in the electrolyte.

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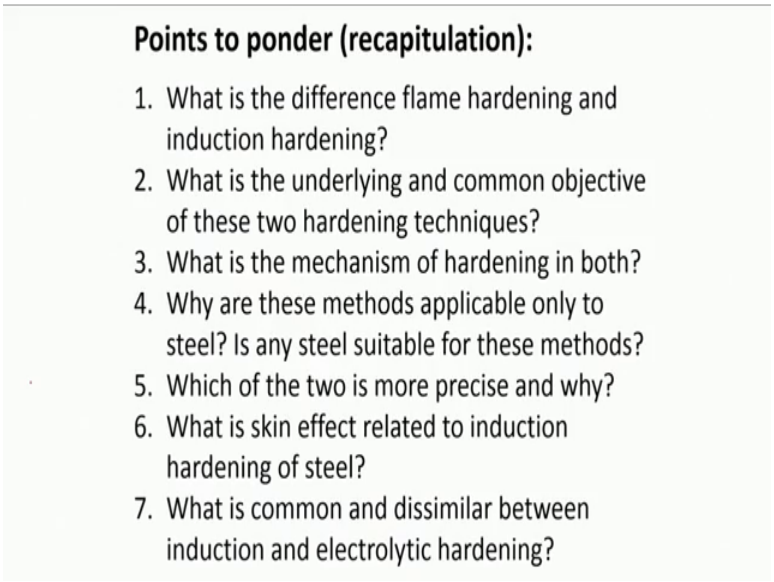

Points to ponder (recapitulation):

1. What is the difference flame hardening and induction hardening?
2. What is the underlying and common objective of these two hardening techniques?
3. What is the mechanism of hardening in both?
4. Why are these methods applicable only to steel? Is any steel suitable for these methods?
5. Which of the two is more precise and why?
6. What is skin effect related to induction hardening of steel?
7. What is common and dissimilar between induction and electrolytic hardening?

So, its now time to recapitulate what all we have discussed. So, we talked about flame hardening and induction hardening. And by now we should be able to understand what is the difference, certain difference between them the underlying technique is heating and cooling in of course, after heating there has to be quenching so, that is the common thing the most important thing is that in both the cases we expect the stock to have sufficient carbon. So, typically over 0.3, 0.4 percent carbon and then it goes to austenite and subsequently get quenched. So, that we get marten site and hence that is how we create a hardened surface.

So, it is essentially a solid state hardening process through martensitic transformation, and we request steel which can be plain carbon steel, but with at least 0.4 percent carbon or maybe alloy steel with sufficient amount of harden ability of it. Of course, between the two induction harm is more precise because of the so called skin effect.

We just heard which is the depth of heating being inversely proportional to the square of the frequency of alternation, alteration, alternation of current and last thing we talked about was the electrolytic heating and what is important is that you are able to use or heat, and convert the surface up to the limited depth. Uniformly, throughout the surface no matter what their shape and geometry of the solid component is.

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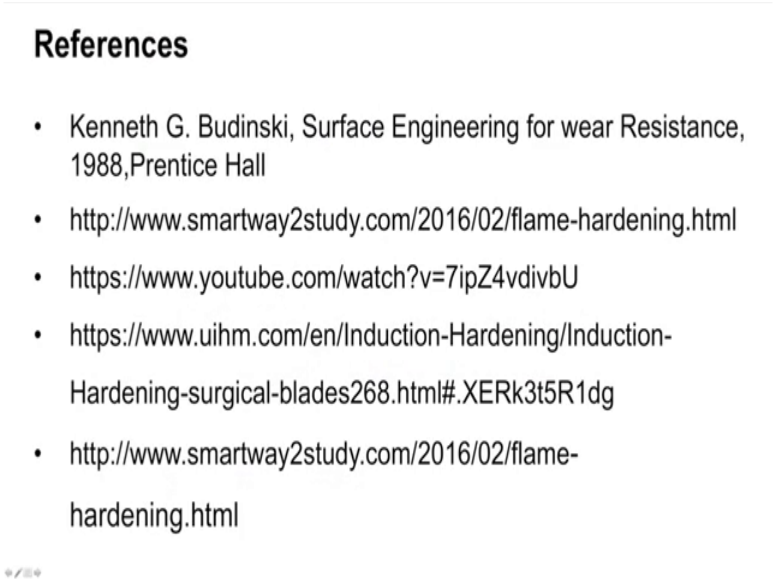

References

- Kenneth G. Budinski, Surface Engineering for wear Resistance, 1988,Prentice Hall
- http://www.smartway2study.com/2016/02/flame-hardening.html
- https://www.youtube.com/watch?v=7ipZ4vdivbU
- https://www.uihm.com/en/Induction-Hardening/Induction-Hardening-surgical-blades268.html#.XERk3t5R1dg
- http://www.smartway2study.com/2016/02/flame-hardening.html

So, I think that is all for the time being.

Thank you very much.