The questions you had on quenching heat treatment you never asked!

- 1. What is immersion quenching?
- 2. What happens to the steel part when quenched?
- 3. What are TTT Diagrams?
- 4. What are CCT diagrams?
- 5. Is it correct to superimpose cooling curves on TTT diagrams?
- 6. What are cooling curves?
- 7. What are cooling rate curves?
- 8. Where can we use the TTT and CCT diagrams?
- 9. Why is cooling rate important?
- 10. Can we control the cooling rate during immersion quenching?
- 11. What controls the cooling rate?
- 12. What is the measure of heat removal capacity of a quenchant?
- 13. Can we measure the surface heat flux or the heat transfer coefficient during quenching?
- 14. Will the cooling rate be the same throughout the part?
- 15. What is quench bath maintenance?
- 16. How does polymer concentration affects cooling rates?
- 17. How does ammonia contamination in polymer quenchant affect cooling curves?
- 18. How does oil contamination in polymer quenchant affect cooling curves?
- 19. How does water contamination affect the performance of quench oil?
- 20. How does oxidation of oil affect quench oil performance?
- 21. How does bath agitation affect quenching?
- 22. What is the effect of salt concentration in brine?
- 23. Why do some heat treated components develop cracks?
- 24. Why do stresses develop during quenching?
- 25. How can residual stresses be minimized?
- 26. What is distortion of quenched component due to?
- 27. How to ensure distortion and crack free components?
- 28. Is there a way of calculating the required cooling rate for a given component?
- 29. Is there a simplified approach for guiding in the selection of proper quenchant?
- 30. How are the cooling curves obtained normally?
- 31. How are the cooling curves at the core and surface of the cylindrical surface obtained?
- 32. How different is QuenchProbe from others?

The questions you had on quenching heat treatment but you never asked !

What is immersion quenching?

Immersion quench heat treatment of steel refers to the process of heating steel component to the 2ustenitizing temperature (shaded region in the diagram above) and immersing it in a suitable fluid medium. The fluid medium is called the quenchant. Quenchants can be of many types; brine, various types of mineral oils, aqueous solutions of polymers, or even plain water.



Hardening temperature range

What happens to the steel part when quenched?

Quenching of a steel component results in hardening of the steel. Steel is principally an alloy of iron of with carbon. Other elements like manganese, silicon, chromium, vanadium, nickel etc are also present which makes steel, the most versatile material, for engineering applications.

Different combinations of these elements can be distinguished in a steel under a metallurgical microscope. They are known as 'phases'. The principle phases in steel are Austenite, Ferrite, Peralite, Bainite and Martensite. Of these phases, Ferrite is the softest and Martnesite is the hardest. Asutenite is not found, generally at room temperature (except some 'retained' austenite).

When a steel component is cooled from the 'austenetizing temperature' (around 850 C for most of the steels) the austenite transforms itself into various phases depending upon the cooling rate. If the cooling is very fast, like in quenching, more of martensite and bainite will form making the component hard. If the component is cooled in air, called normalizing, more of ferrite and pearlite will form making the steel softer.

The percentages of these phases in the heat treated component control the hardness. Again, how much of these phases form at a given cooling rate depends on the steel grade and chemistry.

What are TTT Diagrams?

A TTT (Time-Temperature-Transformation) diagram, also called I-T (Isothermal Transformation) diagram gives information about the product phases (ferrite, pearlite, bainite, martensite, austenite) when a steel component is HELD at CONSTANT temperatures for long enough times. That means the component is NOT COOLED ! It is a difficult diagram to understand and often mis-understood. But, in spite of the impracticalities of the TTT diagram, it is the starting point for understanding heat treatment.

Referring to the diagram above, which depicts the TTT Diagram of 4130 steel (TTT diagrams for each steel is different) on the X-axis is marked time in log scale and temperature is marked on the Y-axis in natural scale. There are principally a maximum of five curves on any TTT diagram: ferrite start, pearlite start (also ferrite end), pearlite end, bainite start and bainite end, depending upon the grade. In addition, there will be two lines at martensite start and martensite end.



TTT diagram of eutectoid steel



If you draw a horizontal line at any temperature, the line may (or may not) cut the curves at different time scales. For example, a line drawn at 800 C, cuts only the first curve, which is the ferrite start. It means: if the steel, heated initially to 850 C (austenetizing temperature) is SUDDENLY cooled to 800 C and KEPT at that temperature, then ferrite will start to form from the austenite in about 2 minutes (when the line at 800 C cuts the ferrite start curve) but, it will take infinite time for the transformation to complete !

If you now draw a line at 700 C, it says: ferrite will start in about 5 seconds, pearlite transformation commences at about 30 seconds (ferrite transformation completes at the same time) and pearlite completes transformation at about 100 seconds.

The DIRECT use of TTT diagram is thus limited as in practical quench heat treatment, the part is CONTINUOUSLY cooled at DIFFERENT RATES of cooling.

What are CCT diagrams?

CCT (Continuous Cooling Transformation) diagrams give the information of transformation products when austenite is COOLED continuously, which is nearer to practice. However, here also there is a hitch. The CCT diagram refers to the product phases when a steel is cooled continuously at CONSTANT COOLING RATES, which again is not practical. Calculations during quenching show that cooling rates can form 10 to 400 C/sec in the SAME PART at the same location. Hence, even CCT diagrams cannot be used directly except as MERE GUIDELINES



CCT Diagram of a steel under various cooling rates

Is it correct to superimpose cooling curves on TTT diagrams?

NO. For reasons explained above, we cannot derive any correct information DIRECTLY by superimposing the cooling curves on the TTT curves. It requires very complex calculations to interpret the product phases by combining TTT diagram and cooling curve.

QuenchProbe has special software to do this.

TTT diagrams can be used for obtaining one information, however : The minimum cooling rate that is necessary to obtain a fully martensitic structure which gives the hardest steel. The 'nose' of the curve is the shortest time for ferrite start which occurs

at different temperatures for different steels. If full martensite is desired, then the cooling curve should not cut the 'nose'.

What are cooling curves?

A cooling curve refers to a graph obtained by drawing time on X-axis and temperature on Y-axis, when a component is cooled. The temperature at any point in the component can be measured by inserting a thermocouple and using a data logger with computer interface.

Note that cooling curves can be different for different locations of the same component.



A typical cooling curve obtained during plant trial

What are cooling rate curves?

The cooling rate at any time or temperature is calculated form the cooling curve. It shows HOW FAST the temperature is changing. The formula for calculating the cooling rate is given by CR = (Temperature drop in a time interval)/(The time interval). Its unit is degree C/second. It is very important to understand the different between cooling curves and cooling rate curves.

Cooling rate curves can be drawn in two ways: (a) CR on X-axis and Temperature on Y-axis and (b) Time on X-axis and CR on Y-Axis. Of the two the first one is more important.

Obtaining the cooling curves of a component AT CRITICAL POINTS is the most important first step in the analysis of immersion quenching.

QuenchProbe does this elegantly by measuring the cooling curve at just one point in the specimen and calculating the cooling curves at other locations, by using special software.



Cooling rates at the surface and core in a 25 mm diameter probe quenched in unagitated bath

Where can we use the TTT and CCT diagrams?

Though TTT and CCT diagrams are highly impractical, they are very important, in fact the only tools for understanding the metallurgical transformation during heat treatment.

They are used in combination with measured cooling curves and very complex mathematical calculations, which has been the topic of research world over. The calculation involves non-linear heat transfer with temperature dependent boundary conditions, temperature dependent material properties, finite element analysis, inverse formulation etc. QuenchProbe has all these modules in place and it is a product of research work carried out in laboratories over the past 10-12 years.

Why is cooling rate important?

If you closely observe the TTT diagram you will realize that if the steel takes long time to cool, then softer phases like ferrite and pearlite will form giving rise to soft steel (curves D and E above). With medium time for cooling, harder phase like bainite may form (curve C) and with very fast cooling, martensite will form (curves A and B). It is obvious that one has to control the cooling rate to get the desired hardness in the component.



Can we control the cooling rate during immersion quenching?

It is not possible to 'control' the cooling rate during immersion quenching in the conventional sense. However, one can achieve the desired cooling rates by a careful selection of the quenchant. Referring to the same diagram above, brine gives maximum cooling rate followed by high speed oil, conventional oil and hot water in that order.

What controls the cooling rate?

The heat transfer during immersion quenching is very complex and it is not very well understood by scientists even to date. Quenching results in boiling of the quenchant and during boiling, the quenchant vaporizes carrying away the heat from the surface of the component. Thermal conductivity of the steel component, viscosity of the quenchant, chemical nature of the quenchant, temperature of the bath, agitation levels of the bath and a host of other factors affect the overall heat transfer rate. Of significant importance is the fact that the heat transfer mechanism in the quenchant can be distinctly different at different temperatures, giving rise to three important phenomena called (a) the vapor blanket (b) nucleate boiling and (c) convective phases.

What is the measure of heat removal capacity of a quenchant?

The heat removal capacity of a quenchant is measured by the surface heat flux, whose units are (W/m^2) . It is also expressed as a heat transfer coefficient given by W/m^2C .

Can we measure the surface heat flux or the heat transfer coefficient during quenching?

No. We cannot measure heat flux or the heat transfer coefficient. We can only compute them by mathematical calculations. One of the methods of computing the surface heat flux is known as Inverse Heat Conduction Method.

QuenchProbe computes the heat flux during quenching by Inverse Heat Conduction Method.

Will the cooling rate be the same throughout the part?

No. For any steel component, the cooling rates will be different at different locations. For example, the corners cool fastest while the core (mid-section) has the slowest cooling rates.

What is quench bath maintenance?

The immersion of hot parts into the quench tank will affect the chemical nature of the quenchants. Continuous usage of oil results in oxidation and thermal degradation giving rise to by-products, changing the very nature of the oil. Oil may get contaminated with water, polymer etc. Polymer degradation results in lowering the viscosity of the polymer film. Even brine also has to be tested periodically as the concentration of NaCl can change the quenchant characteristics over a period of time. Hence oil and polymer quenchants require periodic maintenance to ensure consistent process control.

How does polymer concentration affects cooling rates?

An increase of 5% polymer concentration decreases the cooling rate by about 10^0 C/sec. The temperature at which the maximum cooling rate occurs, however, remains more or less constant.



How does ammonia contamination in polymer quenchant affect cooling curves?

Ammonia contamination in an aqueous solution of polymer quenchant has a predominant effect on the vapor blanket phase of boiling curve. In the diagram above, uncontaminated quenchant has a rapid cooling rate from the very beginning, while, with a contamination level of 5% ammonia, there is an initial phase of slow cooling rate characterized by the initial sloping line. This characteristic feature shifts the temperature at which maximum cooling rate occurs to lower levels with increasing ammonia contamination.



How does oil contamination in polymer quenchant affect cooling curves?

Oil contamination in an aqueous solution of polymer quenchant also has identical effects on the vapor blanket phase of boiling curve as ammonia contamination. The temperature at which maximum cooling rate occurs shifts lower because of an initial slow cooling regime.



How does water contamination affect the performance of quench oil?

Water contamination in quench oil can drastically change the cooling power of oils. As shown above, as little as 0.2% water can increase the maximum cooling rate from 50 to 80° C/sec. Also, the temperature at which maximum cooling rate occurs will be lower with water contamination.

The higher cooling rates with contaminated oils will result in higher residual stresses resulting in cracks/distortions in parts where oil quenching is recommended.



How does oxidation of oil affect quench oil performance?

Repeated immersion of heated objects in an oil bath results in the oxidation of the oil. With continued use, the maximum cooling rate increases to nearly twice the level of fresh oils. The temperature at which the maximum cooling rate occurs also increases.



How does bath agitation affect quenching?

Bath agitation is very effective in 'smoothening' the effects of various regimes of heat transfer in an oil. As the diagram above shows, bath agitation decreases the distinction between the two peaks (solid line) at the same time increasing the maximum cooling rate (outermost line). This provides for more uniform heat extraction throughout cooling.



What is the effect of salt concentration in brine?

Sodium chloride dissolved in water (brine) is extremely potent in increasing the cooling rates, up to about 15% concentration. Beyond that, it will have a negative effect as shown above.

Thus, while the brine is fresh, it will have a very high cooling rate. As the bath ages, NaCl concentration may increase resulting in lowered cooling rate. If this goes unnoticed, trhe required hardness may not be obtained in the quenched components.



Why do some heat treated components develop cracks?

Intensely quenched components may develop cracks due the development of residual stresses inside the component during quenching.

Why do stresses develop during quenching?

Stresses develop inside a quenched component due to the temperature difference between in the inside and the surface of the component.

How can residual stresses be minimized?

Residual stresses can be minimized by ensuring uniform cooling at the core and the surface of the component.

What is distortion of quenched component due to?

Component distortion also is due to the generation of internal stresses during quenching. If the component is constrained from distortion (due to the shape of the component), then the internal stresses increase. Beyond a limit, the component may develop cracks.

How to ensure distortion and crack free components?

Distortion and cracks can be minimized in a heat treated component by choosing the right quenchant for the component. One of the most important things is that the cooling rate must be just adequate; neither too high nor too low. The correct cooling rate is decided by the steel composition, the section thickness, and the hardness required. Once the cooling rate is decided the proper quenchant is selected which gives the required cooling rate. The cooling rates of quenchants, in turn depend upon the type of quenchant (brine, water, oils, polymer solutions etc), whether they are new or old, clean or contaminated, level of agitation etc.

Is there a way of calculating the required cooling rate for a given component?

Yes, but it involves very detailed mathematical analysis. Some of the areas like boundary hat flux distribution on the component surface are still under research.

Is there a simplified approach for guiding in the selection of proper quenchant?

Yes. There is a simplified approach for the selection of the right quenchant for crack free components. The diagram below illustrates the point. It shows the cooling curves at TWO points in a 50 mm diameter cylindrical probe, at the center and at near the surface, when quenched in an oil. It also shows the TEMPERATURE DIFFERENCE between the center and the surface of the specimen.

As per the theory of stress development in quenched components, the quenchant which gives minimum temperature difference, but at the same time assuring the minimum cooling rate is the safest. For this approach, the probe material will have to be of the same grade of steel as that of the component and the diameter must be of the order of the maximum section thickness of the component.

How are the cooling curves obtained normally?

Normally cooling curves are obtained by recording the time temperature curve ehile quenching a cylindrical specimen with a thermocouple attached at the center of the specimen. The specimen is made of a variety of materials like silver, inconel, stainless steel etc. By this method, we get only one cooling curve at the center of the specimen. It is very difficult to relate the cooling curve thus obtained to what happens when the actual component made of alloy steel is quenched.

This cooling curve data has limited use in that they can be used to COMARE the performance of different quenchants qualitatively. WE CAN ONLY SAY WHICH QUENCHANT HAS A SUPERIOR QUENCHING POWER. Whether it is adequate or not for the component cannot be deduced.



Some of the commonly used probe designs are shown below.

How are the cooling curves at the core and surface of the cylindrical surface obtained?

QuenchProbe has a built-in software which will compute the cooling curve at any point inside the specimen. As a routine, quench probe computes the cooling rates EXACTLY on the SURFACE and the CORE of the specimen.

How different is QuenchProbe from others?

- <u>Cylindrical stainless steel probes</u> of any suitable dimension for qualitative assessment of quenching mediums
- <u>Cylindrical alloy steel prob</u>es of the same grade as the component being heat treated of any suitable dimension for measurement of actual heat transfer coefficient of the quenching medium in plant operating conditions
- Portable tubular furnace for heating the specimen <u>at the plant site</u>
- Highly accurate, 0.3 mm K type thermocouple wires, mineral insulated and sheathed in stainless steel tube of 1mm outer diameter, giving maximum accuracy
- Data acquisition system (USB Based, computer programmable with in-built memory) integrated with the probe assembly (patent pending) for easy portability
- Single thermocouple at the mid section of the probe for recording the thermal profile
- Measured data used as input for analysis of cooling rates at any location in the probe capable of differentiating the cooling rates at the surface and center of the probe
- Thermal analysis of the probe coupled with metallurgical transformation (in the case of alloy steel probe) for prediction of microstructure and hardness, FIRST TIME EVER.
- The measured heat transfer rates at actual plant conditions used for simulation of quenching heat treatment of industrial components
- Data base generated for different quenching mediums can be used of designing process sheets for new products selection of quenchant, quenching cycles, whether interrupted or continuous etc. for optimal quality in terms of hardness distribution, stress distribution, cracking susceptibility etc.
- All software modules indigenously developed and tested over the last 20 years
- Finite element analysis of non linear heat transfer for calculation of cooling curves and cooling rates at any location in the probe as well as the actual part
- Prediction of microstructure evolution and final microstructure distribution both in the probe and the product component
- Coupling of metallurgical transformation of austenite with the heat transfer analysis
- Non linear inverse analysis for computing the heat flux and the heat transfer coefficient during quenching
- Use of TTT data of the specific alloy steel for austenite transformation modeling
- Highly researched data used for thermo-physical properties (thermal conductivity, specific heat and latent heat) of individual

transformation product phases (ferrite, pearlite, bainite, martensite, austenite)