"REFERENCE QUENCHPROBE" - FEATURES AND BREAKTHROUGHS

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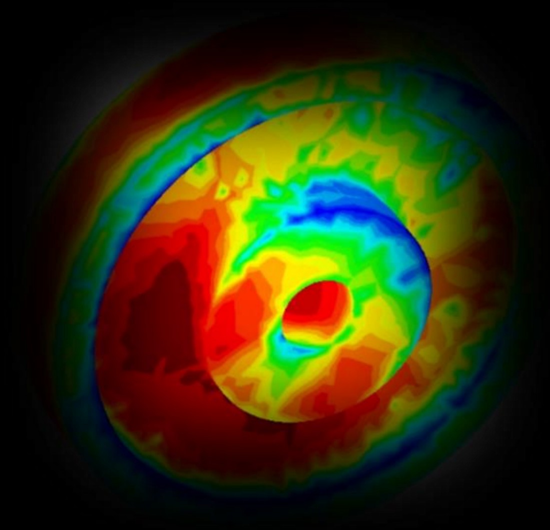
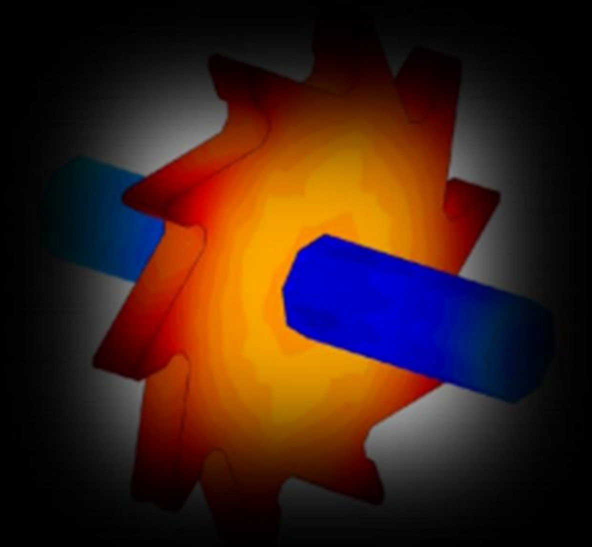
'Reference QuenchProbe' –

New Tool For *in-situ* Estimation of

Cooling Rates, Heat Flux and Hardenability during

Immersion Quenching of Steels





"REFERENCE QUENCHPROBE" – AN ANSWER TO ALL YOUR QUERIES ON QUENCHANTS

- Understanding your quenchant properties
- Developing process control charts
- Optimizing the required parameters
- Freeze the final parameters for optimal results

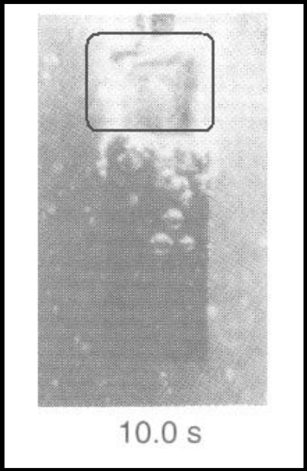
IMMERSION QUENCHING – AN INTRODUCTION

- Immersion Quenching is accompanied by boiling / vaporization of the fluid medium - one of the most complicated phenomenon to quantify

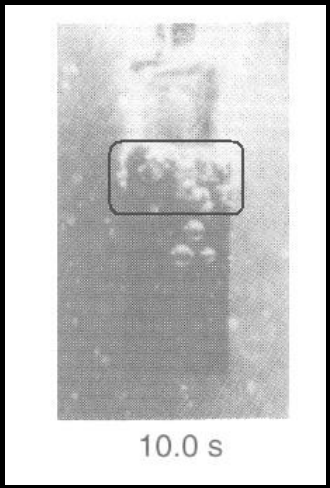
- Heat transfer during quenching of steel occurs in several stages
  - Vapor phase – a thin blanket of fluid vapor separates the component surface and the quenchant
  - Nucleate boiling – the vapor blanket breaks down and the fluid comes in direct contact with the component surface
  - Convective heat transfer –boiling ceases and the heat transfer is through the convective mechanism

- Every point on the component surface goes through the three stages, each stage lasting for different durations

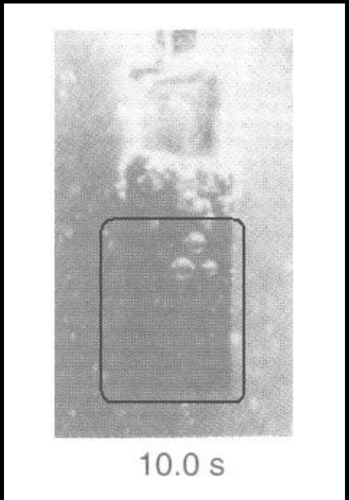
Heat Transfer during Quenching*



Film boiling phase: Heat transfer impeded by a vapor blanket



Nucleate boiling phase: Maximum heat transfer due to wetting

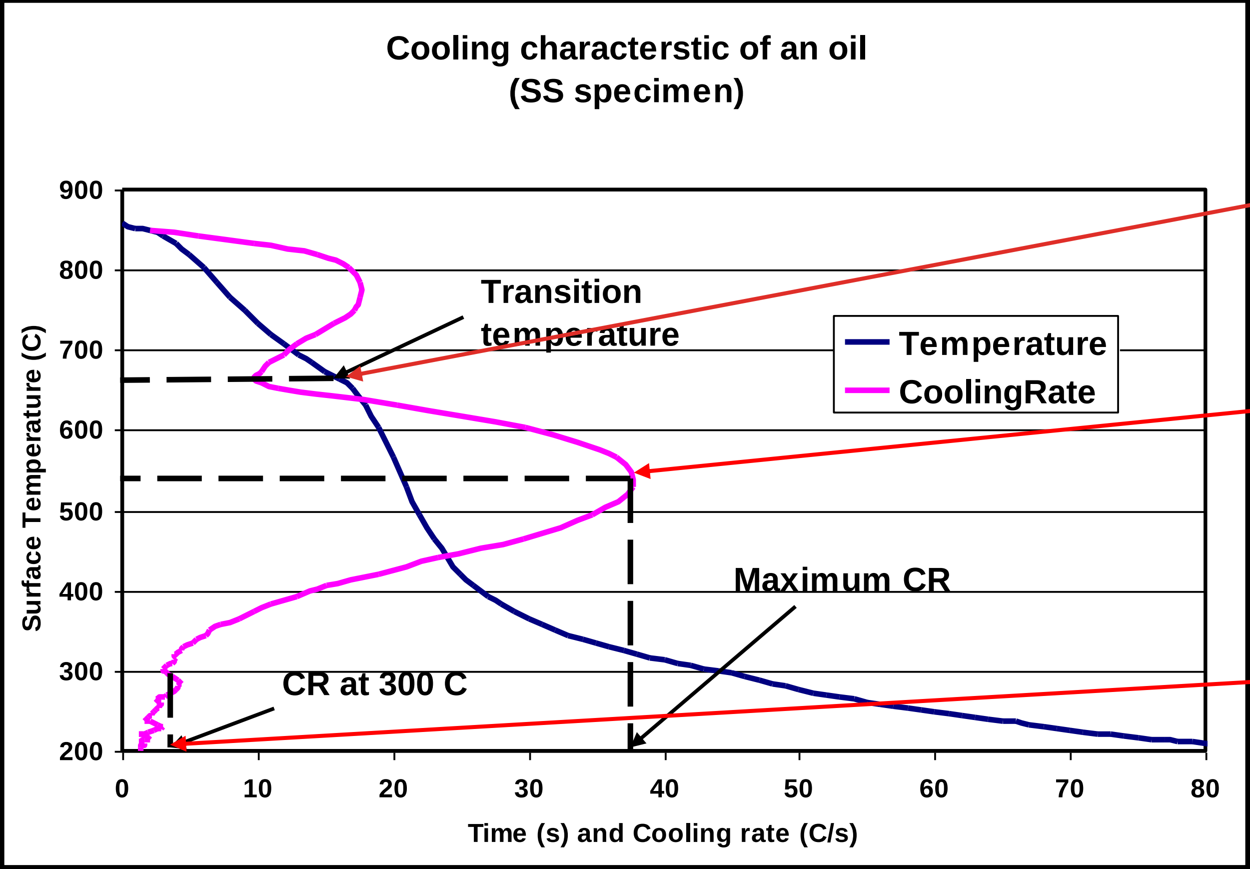


Convective Phase: Low heat transfer through convection

*"Handbook of Quenchants and Quenching Technology," 1993, Eds: G.E.Totten, C.E.Bates, N.A.Clinton, ASM

Reference Quench Probe

ANALYSIS OF COOLING CURVES

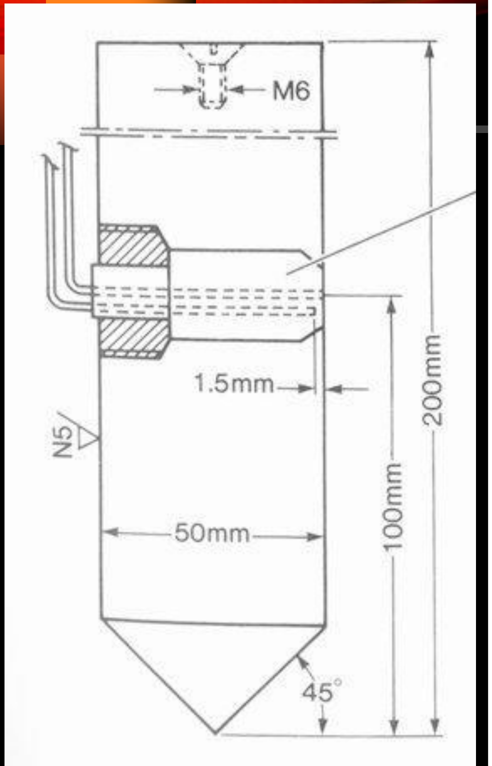


Vapor blanket to film boiling

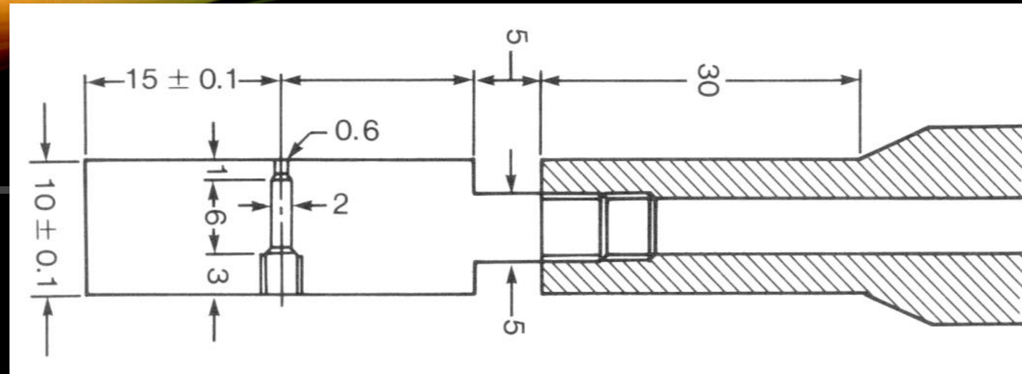
Must be sufficiently high to minimize ferrite and pearlite transformation

Indicates probability of distortion and cracking

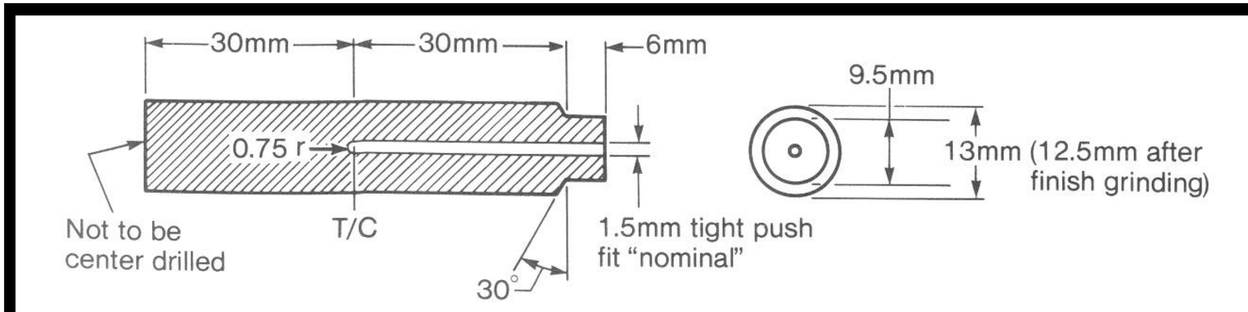
Reference Quench Probe



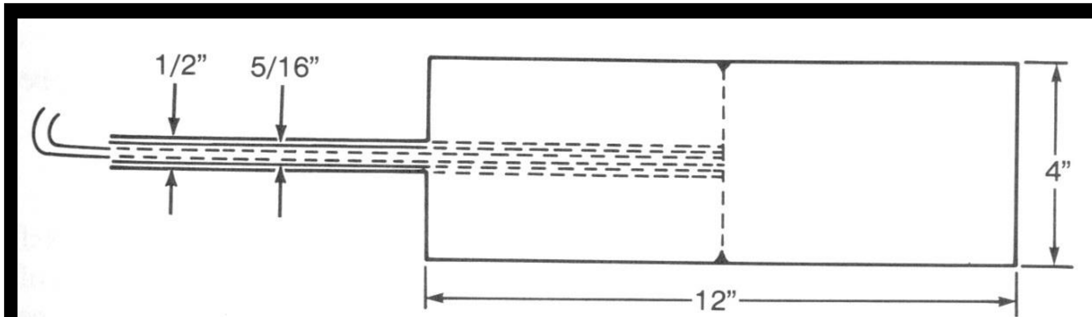
Liscic NANMAC Probe for measuring heat flux – Austenitic steel specimen



Silver probe for surface temperature measurement



Wolfson Inconel probe (Single cooling curve)



The Grossman probe –SAE 5145 (Single cooling curve)

Reference Quench Probe

CONVENTIONAL PROBES - LIMITATIONS

- Grossman probe, JIS Silver probe, French Probe, Wolfson Inconel probe, Cylindrical Silver Probe, Allen Plate Probe
- How to interpret the results – material is different – test conditions are different
- What does a change in the cooling curve actually mean – how to map it on to my material and my plant conditions?
- Should one continue with the existing bath, top it up or replace – what should be the basis?

THE ASTM STANDARDS FOR QUENCHANT TESTING - D6200-01(2012)

Interpretation of Results

- Cooling curves and cooling rate curves are obtained for
  - Comparing one oil with other
  - Comparing one oil with control sample
  - Compare with previous performances

- The test may show the effect of
  - Oxidation
  - Presence of additives
  - Contamination

Reference Quench Probe

STANDARD PARAMETERS FOR TESTING QUENCHING OIL AS PER ASTM

- Viscosity, Specific Gravity, Contamination
- Water Content, Flash Point

Parameter	Min. % of Ref.	Max % of Ref.
Max Cooling Rate C/sec	90	110
Temp @ Max Cooling Rate C	95	105
Cooling Rate @ 300 C C/sec	70	130
Time to Reach 600 C sec	85	115
Time to Reach 400 C sec	90	110
Time to Reach 200 C sec	90	110

THE ASTM STANDARDS FOR QUENCHANT TESTING - D6200-01(2012)

Limitations

- Designed to evaluate quenching oils in a non -agitated system.
- No correlation between these test results and the results obtained in agitated systems.
- No correlation between the test results and results with different grades of steel

PARAMETERS AFFECTING COOLING CURVES DURING QUENCHING

- Cooling curves are affected by bath conditions
  - Bath temperature, Agitation, Quenchant type, Section size, Steel Composition
- Cooling curves are also affected by bath degradation
  - Continuous usage of oil results in oxidation and
  - Contamination of oil with water, polymer etc.
  - Concentration of Polymer
  - The concentration and temperature of NaCl can affect the quenchant characteristics

ADDRESSING THE LIMITATIONS OF THE STANDARD PROBES USING QUENCHPROBE

- Specimen material same as of component to be taken
- Fix thermocouple at 4mm below surface
- Heat to soaking temperature
- Quench in plant conditions

FEATURES OF "REFERENCE QUENCHPROBE"

- Cylindrical specimen (25 dia x 100 long) -
  - Same grade as component: For material-quenchant-plant specific cooling curves
- Single temperature measured at 4mm from the surface; Mineral insulated Inconel sheathed 'K' type thermocouple
- Patented design for fixing the thermocouple for positive contact
- Unique USB based data logger for portability; Integrated design
- Portable electric resistance furnace for heating the specimen

Reference Quench Probe

Integrated design; the handle with a view port receives the data logger which is thus physically protected for plant use; body fabricated of stainless steel with bright finish; weight of the probe finely balanced

HARDENING POWER – GROSSMAN NUMBER

- Grossman number - a measure of cooling capacity of quenchant

  H = htc/2*(th.cond)

- htc varies continuously during quenching

- Single value of H cannot be attributed to a steel and quenchant combination

- Still, widely accepted by heat treaters:
  - Slow oil – no agitation 0.20
  - Good oil – moderate agitation 0.35
  - Poor water – no agitation 1.00
  - Very good water – strong agitation 1.50
  - Brine – no agitation 2.00
  - Brine – violent agitation 5.00

Reference Quench Probe

HARDENING POWER – HEAT FLUX RATE

- Liscic Probe

- Heat flux at surface measured by two TCs by gradient method
  - Assumes linear dT/dx
  - Actual surface temperature cannot be measured directly as this method claims

- Austenitic stainless steel probe
  - Results cannot be applied to other materials

- Microstructure and hardness in alloy steel cannot be computed based on SS heat flux

TO SUMMARIZE …..

Acquisition of cooling curve and subsequent analysis should ensure:

- Specificity of material – quenchant combination
- Tests done under plant conditions – to replicate practical issues
- Use experimental data (TTT and hardness data)
- Develop mathematical models to relate plant conditions to data base
- Easy and hassle free test procedure

The new "Reference QuenchProbe" addresses these issues

THEORY OF "QUENCHPROBE" - TTT (IT) DIAGRAMS

- Give information about the product phases (ferrite, pearlite, bainite, martensite, austenite); sometimes, the hardness of the resulting phases also is given
- Steel component is held at the temperature of transformation for long enough times – not cooled !
- They are 'read' only along the isotherms
- Very limited direct application
- Interpreted through mathematical models

THEORY OF "QUENCHPROBE" - CCT DIAGRAMS

- Give the information of transformation products when a steel is cooled continuously at variable cooling rates

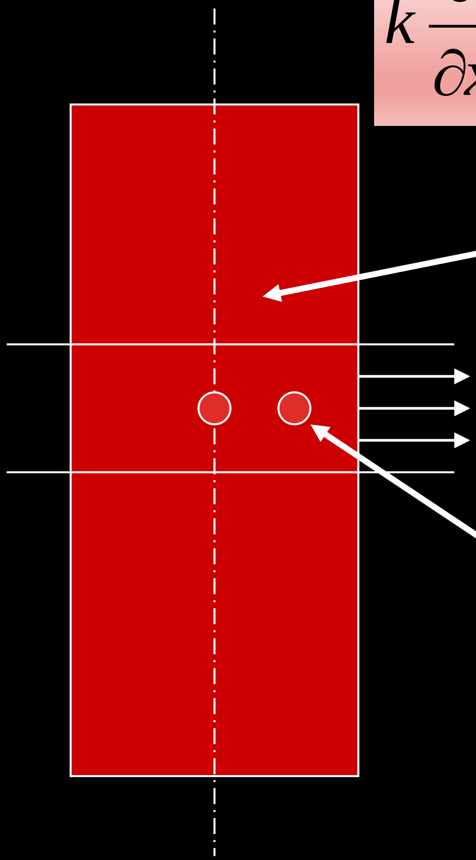
- Many ways of construction
  - Based on following different cooling paths
  - Based on cooling rates at a temperature
  - Based on different diameter specimens in different quenchants
  - Based on time to cool between two temperatures

- Used as guidelines by superimposition

- Proper interpretation through mathematical modeling

THEORY OF "QUENCHPROBE" – INVERSE HEAT TRANSFER

$$k\frac{\partial}{\partial x}\left(\frac{\partial T(x,y,t)}{\partial x}\right)+k\frac{\partial}{\partial y}\left(\frac{\partial T(x,y,t)}{\partial y}\right)+\dot{q}=\rho c\frac{\partial T(x,y,t)}{\partial t}$$



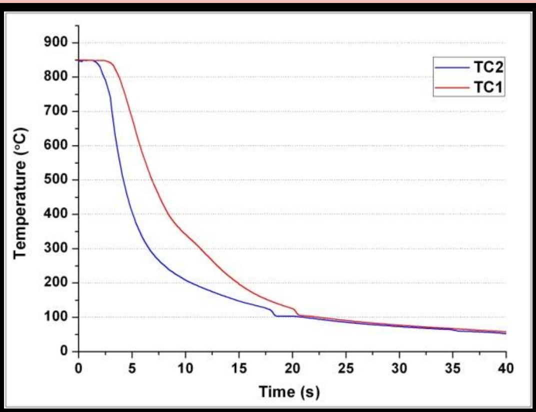
IC:

$$T(x,y)=T_{soaking}$$

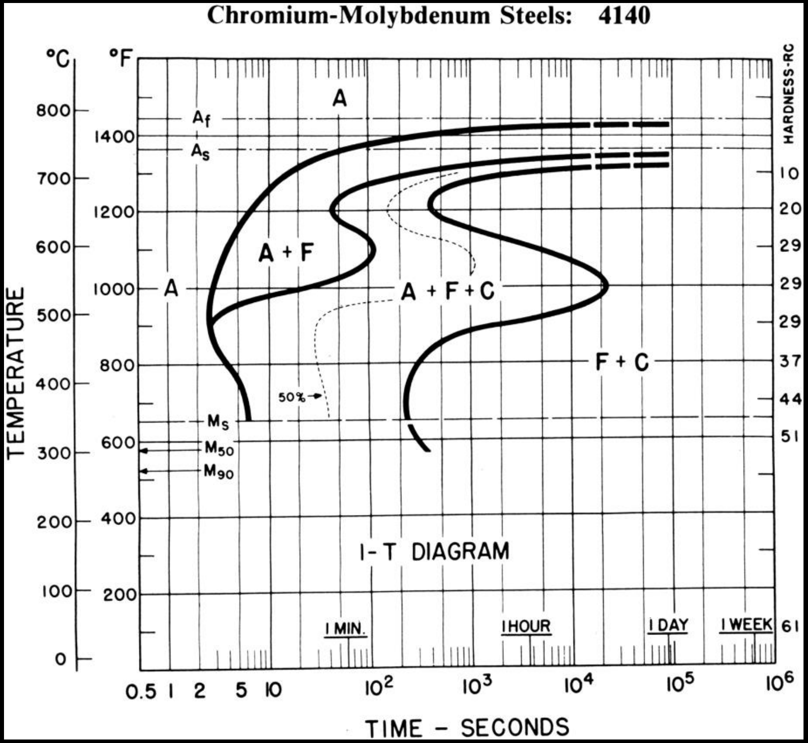
BC:

$$-k\left(\frac{\partial T}{\partial x}n_x+\frac{\partial T}{\partial y}n_y\right)=q=?$$

Input:



THEORY OF "QUENCHPROBE" – METALLURGICAL MODEL



Austenite – Ferrite/Pearlite/Bainite

$$X_i^{\,j} = 1 - \exp[-b(T_j)\, t_j^{\,n(T_j)}]$$

$$n(T_j) = \frac{\ln[\ln(1-X_s)/\ln(1-X_f)]}{\ln(\tau_s/\tau_f)}$$

$$b(T_j) = -\frac{\ln(1-X_s)}{t_s^{\,n}}$$

Austenite - Martensite

$$X_m = 1 - \exp[-0.011(M_s - T)]$$

THEORY OF "QUENCHPROBE" – FINITE ELEMENT ANALYSIS

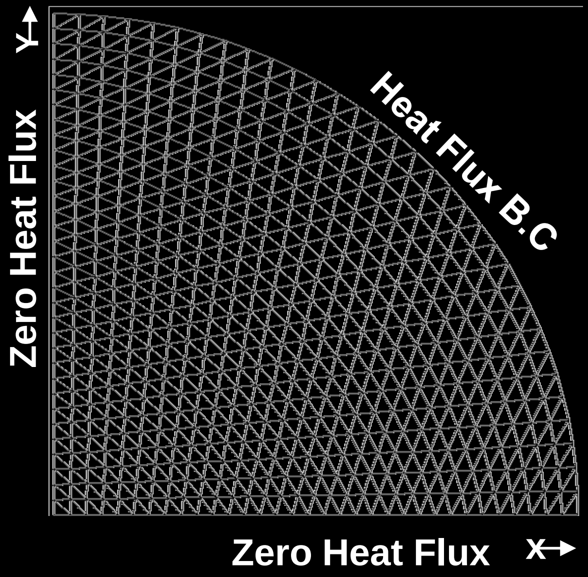
Iterative FE formulation within time step for non linear problems:

$$\left(\Delta t\theta[K]_{n+1}^{l+1}+[C]_n\right)\{T\}_{n+1}=\left([C]_n-\Delta t(1-\theta)[K]_n\right)\{T\}_n+\Delta t(1-\theta)\{F\}_n+\Delta t\theta\{F\}_{n+1}^{l+1}$$

$$C_{ij}=\int_{\Omega^e}\left[\rho c-\rho\Delta H\left(\frac{\Delta f}{\Delta T}\right)\right]\psi_i\psi_j d\Omega$$

$$K_{ij}=\int_{\Omega^e}\left[k\frac{\partial\psi_i}{\partial x}\frac{\partial\psi_j}{\partial x}+k\frac{\partial\psi_i}{\partial y}\frac{\partial\psi_j}{\partial y}\right]d\Omega$$

$$F_i=-\oint_{\Gamma_2}q\psi_i d\Gamma$$



Objective function:

$$S=\sum_{i=1}^{r}\left(Y_{m+i-1}-\hat{T}^{+}{}_{m+i-1}\right)^2$$

Flux computed from:

$$(\Delta q)_m=\frac{\sum_{i=1}^{r}\left[Y_{m+i-1}-\hat{T}_{m+i-1}\right]\phi_i}{\sum_{i=1}^{r}(\phi_i)^2}$$

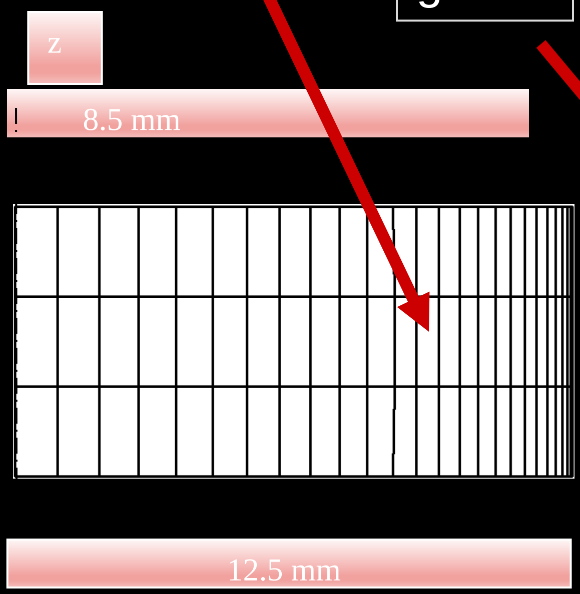
Using Sensitivity Coefficient:

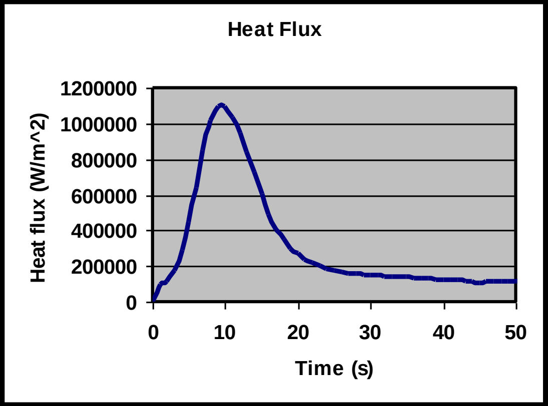
$$\phi_i=\frac{\left(\hat{T}^{+}{}_i-\hat{T}_i\right)}{\Delta q_i}$$

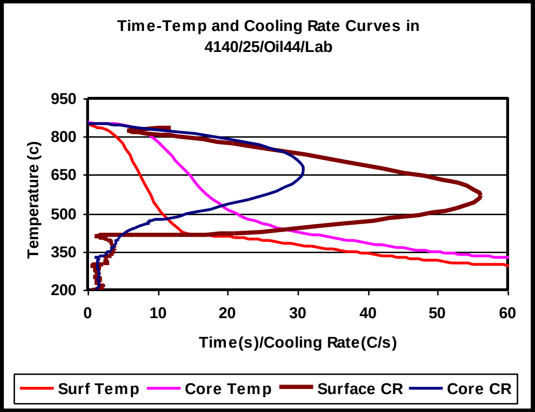
COUPLED MATHEMATICAL MODELING – INPUT/OUTPUT

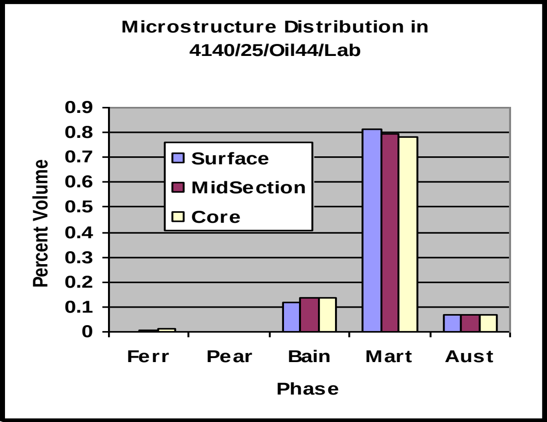
With a single measurement here

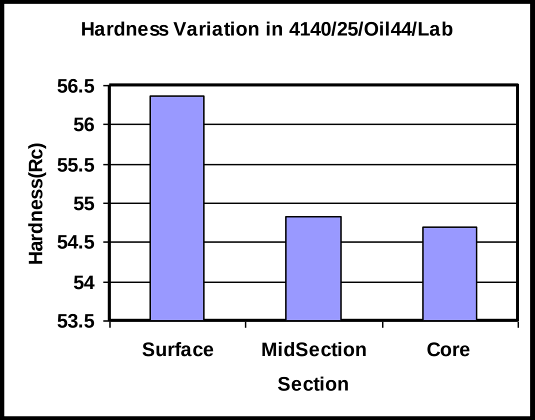
We get





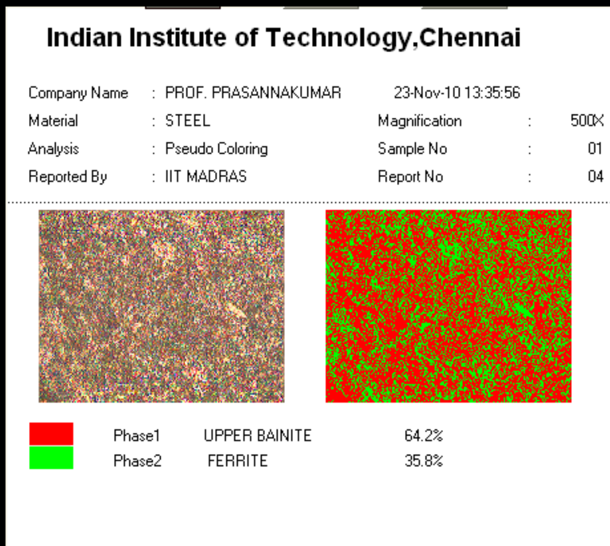


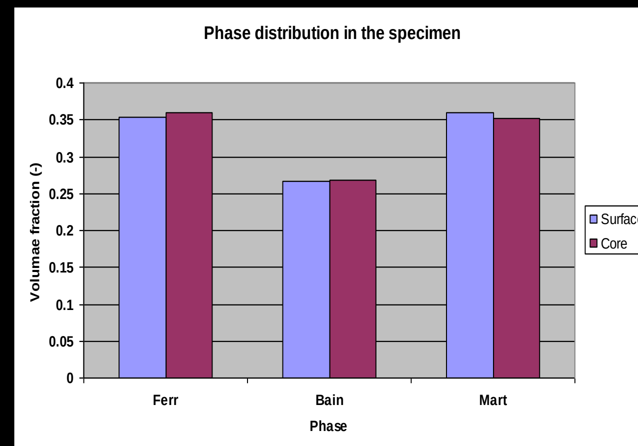


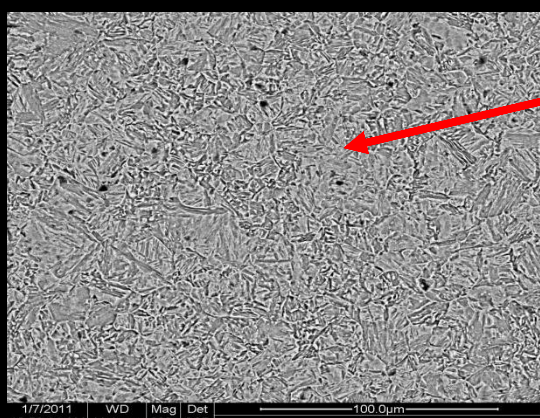


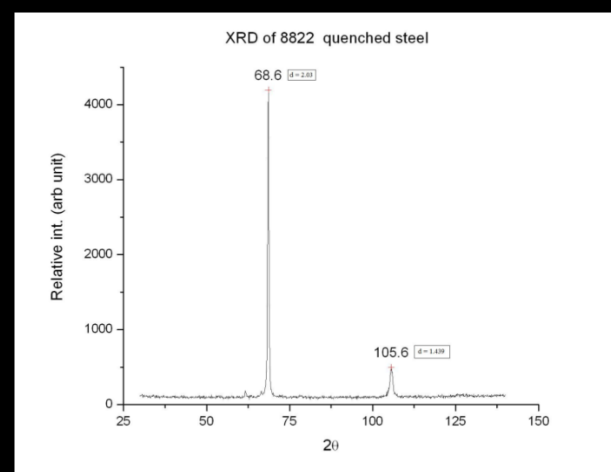
Reference Quench Probe

VALIDATION –OIL QUENCHED – AISI 8822H





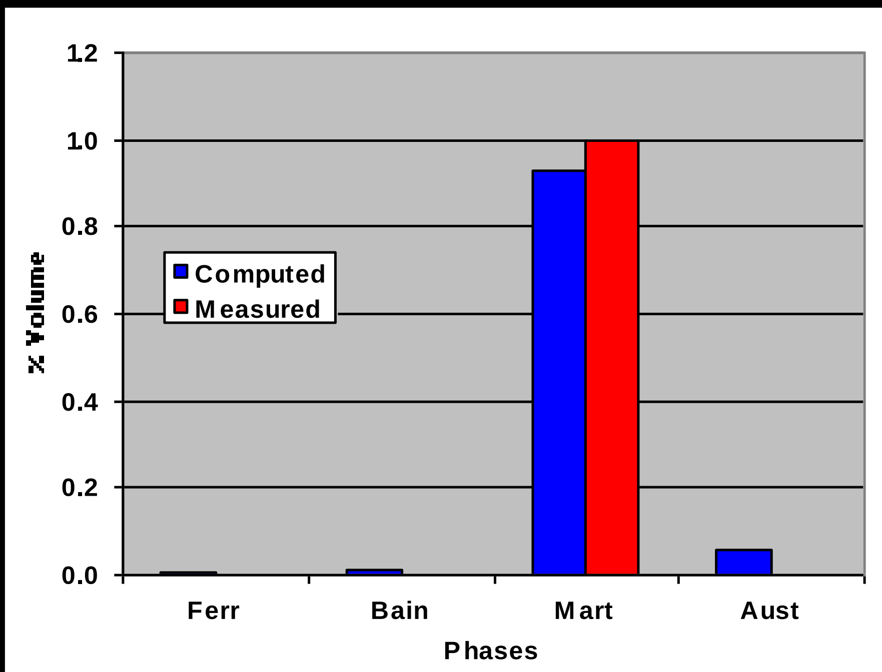


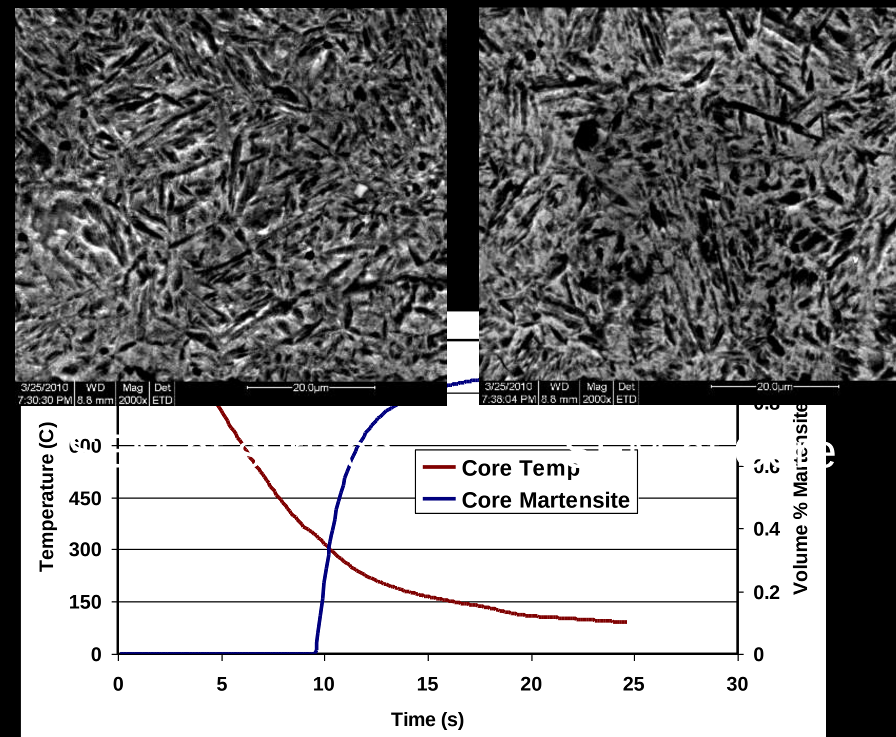


SEM at surface

Reference Quench Probe

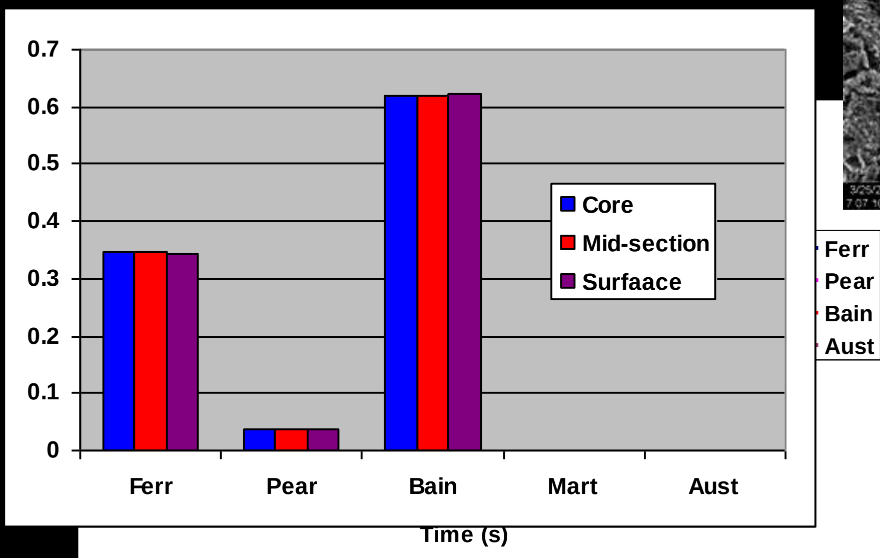
VALIDATION –WATER QUENCHED – AISI 4140

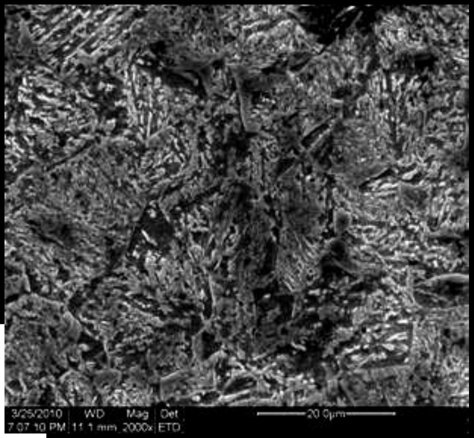




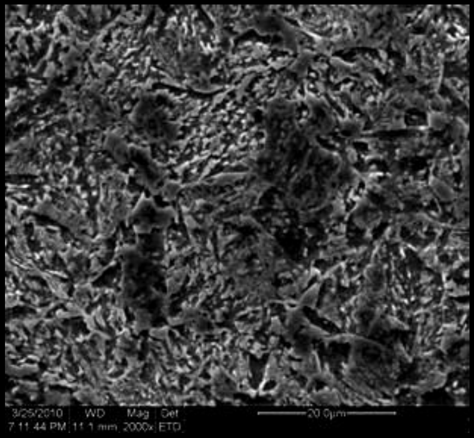
Reference Quench Probe

VALIDATION -AIR COOLED - 4140





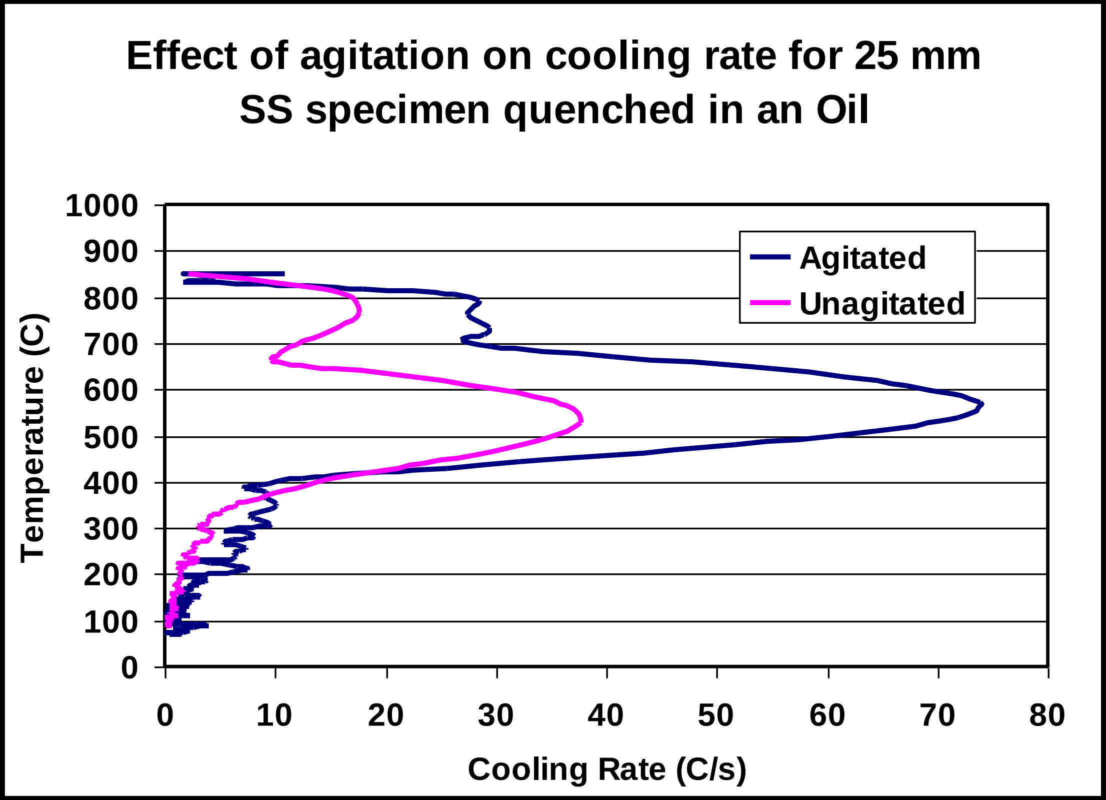
SEM at surface



SEM at Core

Reference Quench Probe

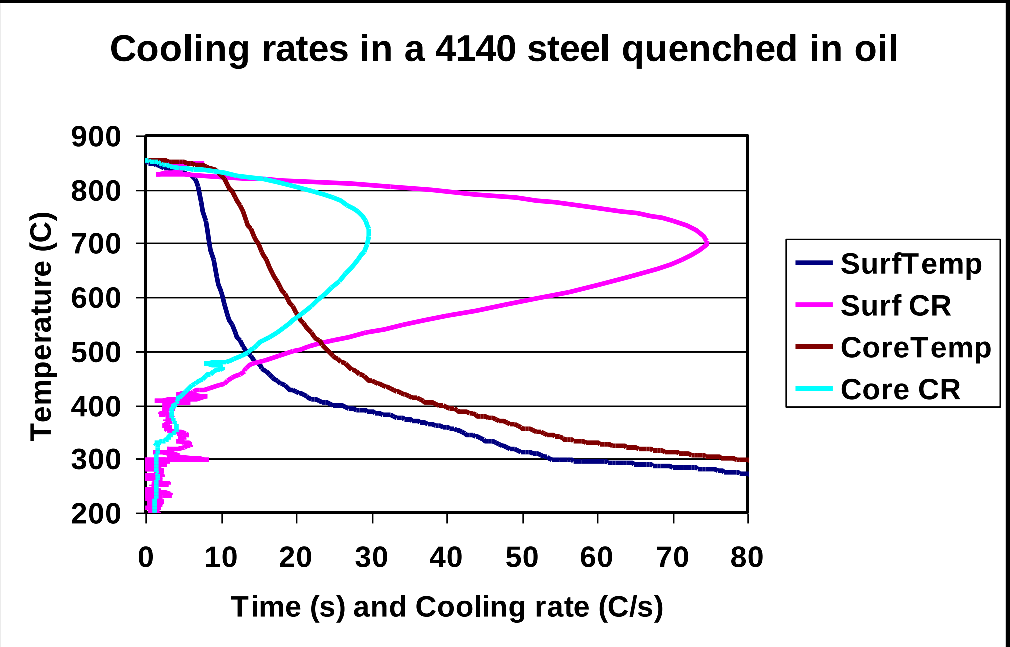
"QUENCHPROBE" – CHECK EFFECT OF AGITATION ON COOLING RATE (OIL)

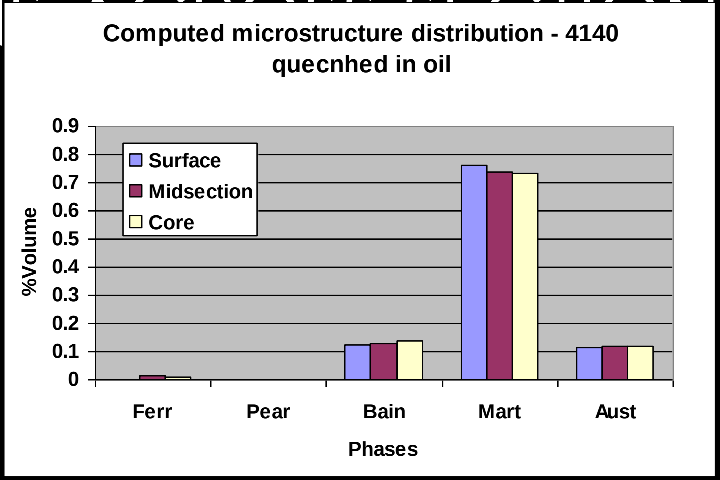


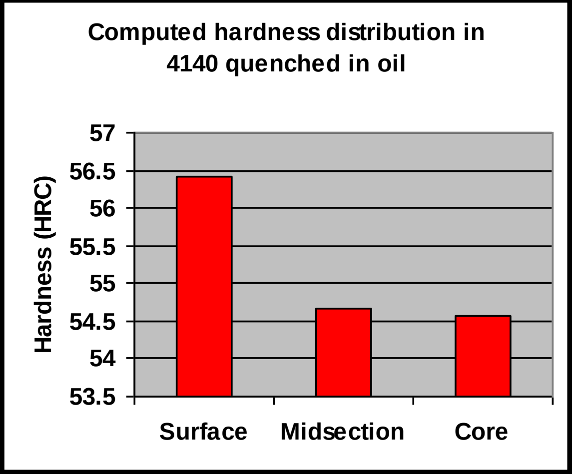
Higher heat flux due to agitation

Reference Quench Probe

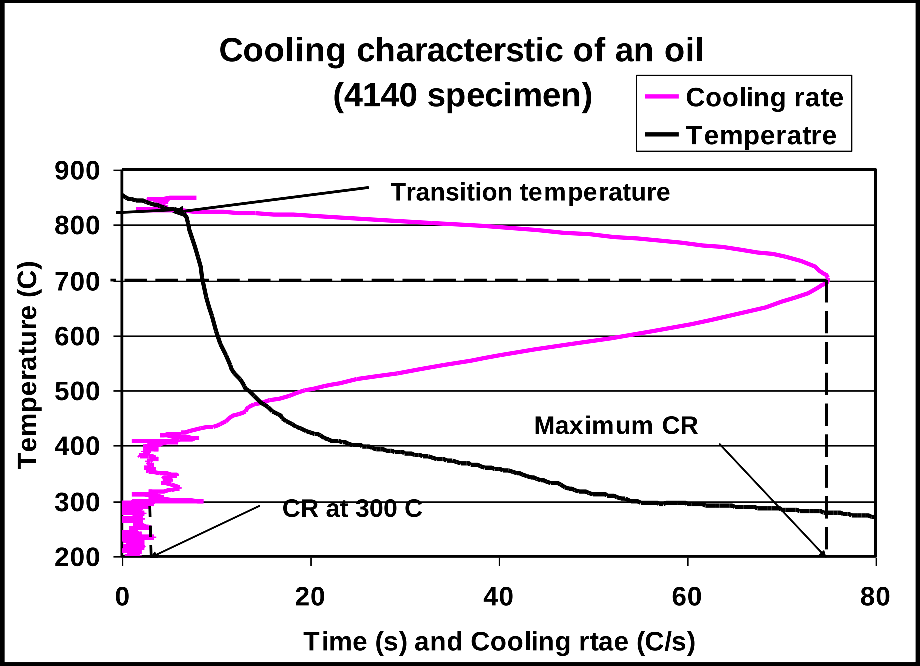
"QUENCHPROBE"– COMPUTATION OF PROPERTY VARIATIONS ACROSS SECTIONS

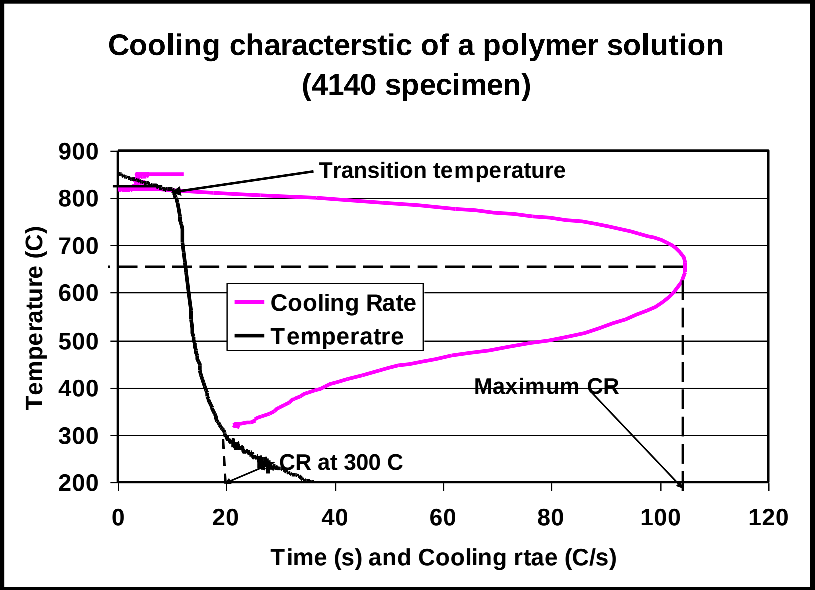






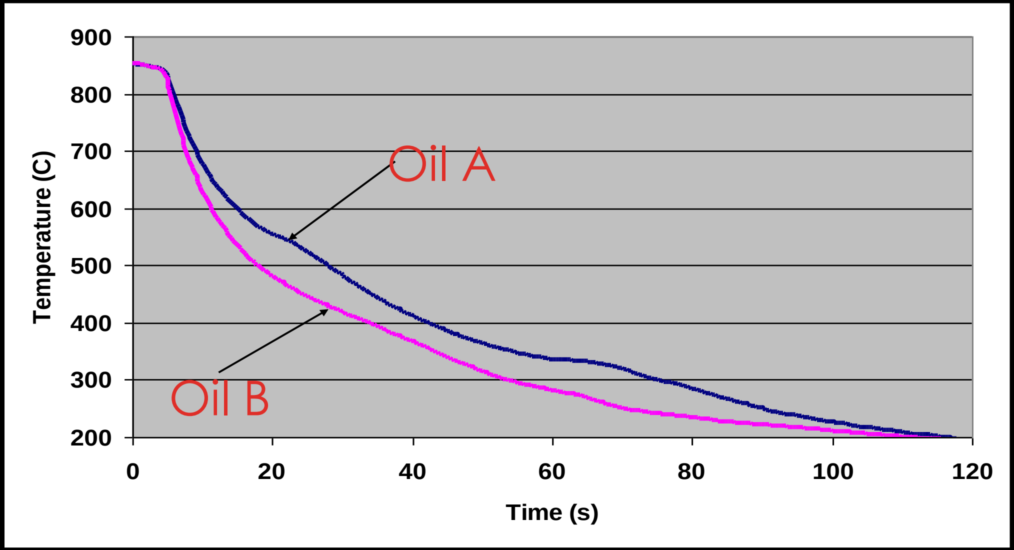
"QUENCHPROBE"– COMPUTATION OF COOLING CHARACTERISTICS OF QUENCHANTS





Reference Quench Probe

PERFORMANCE OF DIFFERENT OILS IN PLANT CONDITIONS



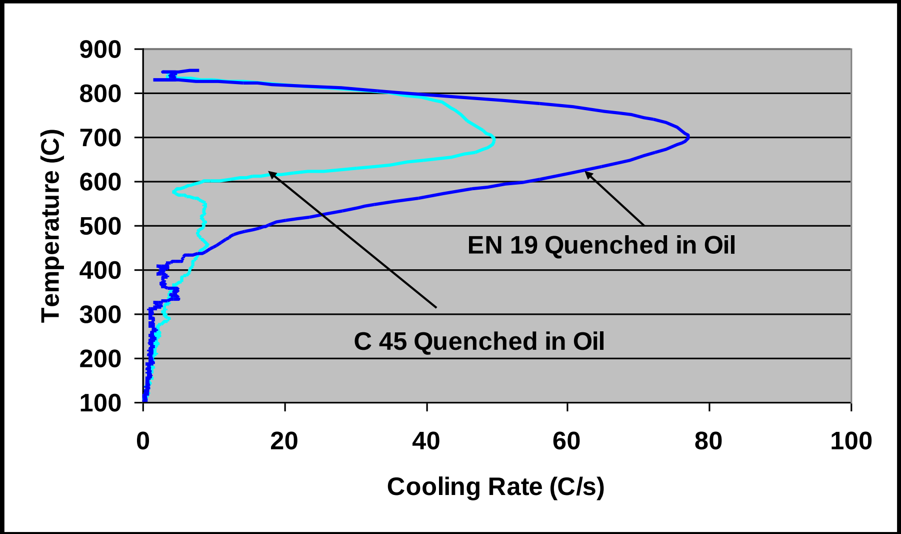
Cooing curves obtained with **100Cr6** steel :

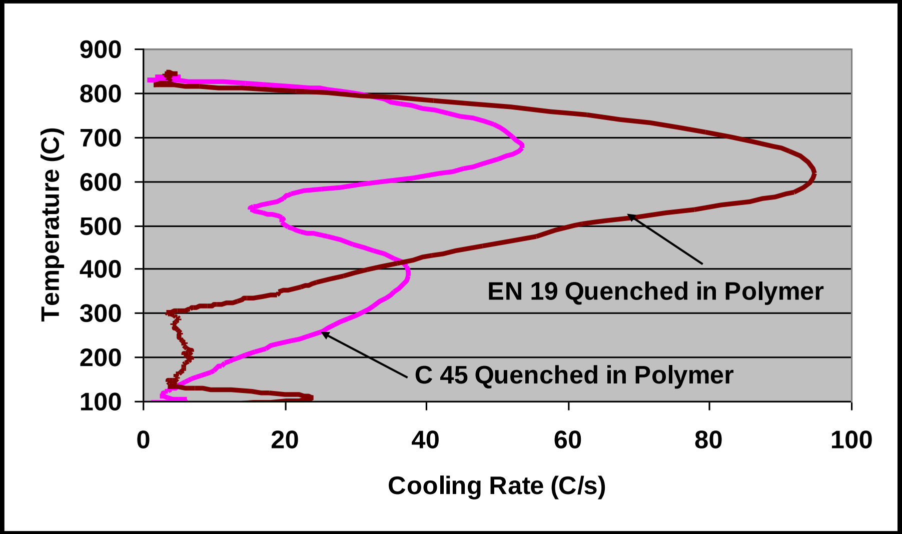
C: 1.04%; Mn:0.33%; Si:0.26%; Cr:1.53%; Cu:0.20%; Ni:0.31%; P:0.023%; S:0.006%

Oil A: Nippon Hot Quench Oil 303; **Oil B**: Castrol Iloquench 798 Hot Quenching Oil

Reference Quench Probe

COOLING RATE CURVES FOR ALLOY STEELS





Computed surface cooling rates for steel specimens of **different grades** quenched in identical **mineral oils**

Computed surface cooling rates for steel specimens of **different grades** quenched in identical aqueous **solutions of polymer**

Reference Quench Probe

"QUENCHPROBE" BREAKTHROUGHS

- The effect of oil degradation due to all conceivable factors on heat removal is directly measured in quench tanks
- The cooling rates are calculated for the specific steel and quenchant combinations
- Single thermocouple at midsection, giving multiple cooling curves at center and core. Advanced heat transfer calculations differentiates cooling across the cross section.
- Thermal analysis of the probe coupled with metallurgical transformation for prediction of microstructure and hardness, first time ever.
- Gives heat removal rates under plant operating conditions of agitation etc. Tests are done in-situ with a portable probe

Reference Quench Probe

APPLICATIONS OF "QUENCHPROBE"

- *In-situ* measurement of quenching capacity of different quenching mediums
- Check the 'health' of quenchants with continued use
- Check the effect of agitation level/flow rate/quenching position in the tank
- Check the effect of contamination in quenchants (water in oil; polymer in oil etc.)
- Inspection of quenchants in as-received condition
- Estimate the cooling rates at the surface and core of specimen

APPLICATIONS OF "QUENCHPROBE"

- Predict microstructure / hardness at the surface and core of alloy steel specimen for a quenchant
- Generate data for
  - mathematical modeling of heat flux for a specific plant condition
  - calculating stresses in quenched component by Finite Element Analysis
- Select the most suitable quenchant for a given component to achieve the required hardness range
- Reduce rejections and ensure consistent quality

Reference Quench Probe

ABOUT "QUENCHPROBE"

- 'QuenchProbe' is a result of research conducted at IIT Madras in the past 12 years.
- Six research theses; four research projects (sponsored by the Indian Space and Fusion Energy Projects and others)
- Eleven International Refereed Journal papers
- Eighteen International and National Conference / Symposium / Workshop papers have been published so far, related to the technology of QuenchProbe.

"QUENCHPROBE" – INDUSTRIAL TESTS

Sl No	Company
1	Automotive Axles Ltd, Mysore, India
2	Bharath Earth Movers Ltd., KGF, India
3	Bharath Forge Ltd., Pune, India
4	HAL, Bangalore, India
5	L&T, Hazira, India
6	LVM, Bangalore, India
7	Mahindra Forge Ltd., Pune, India
8	NBC Bearings, Jaipur, India
9	SKF Bearings, Pune, India
10	SSS Springs, Siriperambudur, India

Steels tested:

C45, 41Cr4, 100Cr6, 8822H, SA 542, 52100, 4140, SUP 9

Quenchants tested

Servo 707, Castrol 798, Nippon 303, Hardcastle Polymer solutions (4.5%, 6.0%, 13.5%, 14.0%) **All in agitated tanks**

TO SUM UP…..

- Reference quench Probe is a portable and handy equipment which is being robotized for deployment in the plant considering the safety of personnel

- It obtains steel-quenchant-plant specific cooling curves which is a kind of process signature

- The cooling curve obtained at 4 mm below the surface enables accurate heat flux estimation – the only probe of this type

TO SUM UP.....

- Cooling rates at the specimen surface and the core can be differentiated.

- Different diameters, user specific specimens can be used.

- All software indigenously developed - ensures continuous development and tuning

- Heat flux data is an important input for heat treatment

Thanks for your attention