Continuous Cooling Transformation (CCT) Diagrams

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Continuous cooling transformation (CCT) diagram

Definition: Stability of phases during continuous cooling of austenite

There are two types of CCT diagrams

I) Plot of (for each type of transformation) transformation start, specific fraction of transformation and transformation finish temperature against transformation time on each cooling curve

II) Plot of (for each type of transformation) transformation start, specific fraction of transformation and transformation finish temperature against cooling rate or bar diameter for each type of cooling medium

Determination of CCT diagram type I

CCT diagrams are determined by measuring some physical properties during continuous cooling. Normally these are specific volume and magnetic permeability. However, the majority of the work has been done through specific volume change by dilatometric method. This method is supplemented by metallography and hardness measurement.

In dilatometry the test sample (**Fig. 1**) is austenitised in a specially designed furnace (**Fig. 2**) and then controlled cooled. Sample dilation is measured by dial gauge/sensor. Slowest cooling is controlled by furnace cooling but higher cooling rate can be controlled by gas quenching.

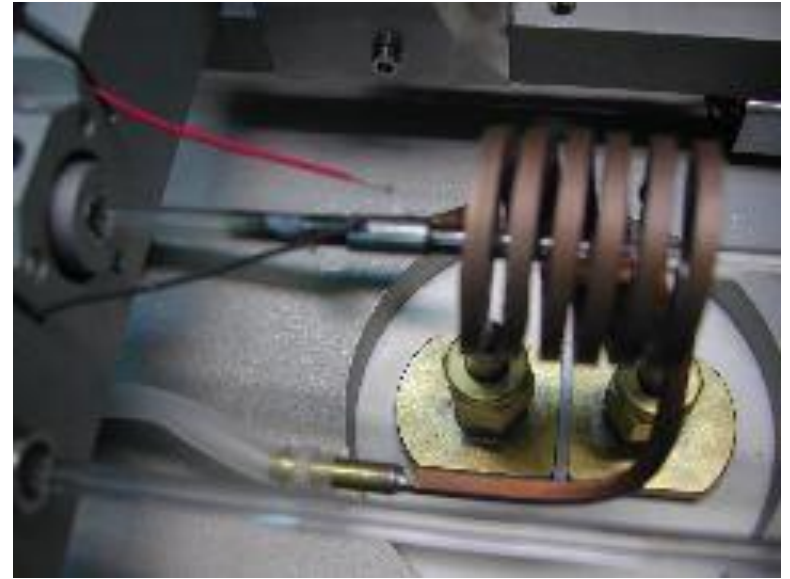Fig. 1: Sample and fixtures for dilatometric measurements

Fig. 2 : Dilatometer equipment

Cooling data are plotted as temperature versus time (**Fig. 3**). Dilation is recorded against temperature (Fig. 4). Any slope change indicates phase transformation. Fraction of transformation roughly can be calculated based on the dilation data as explained below.
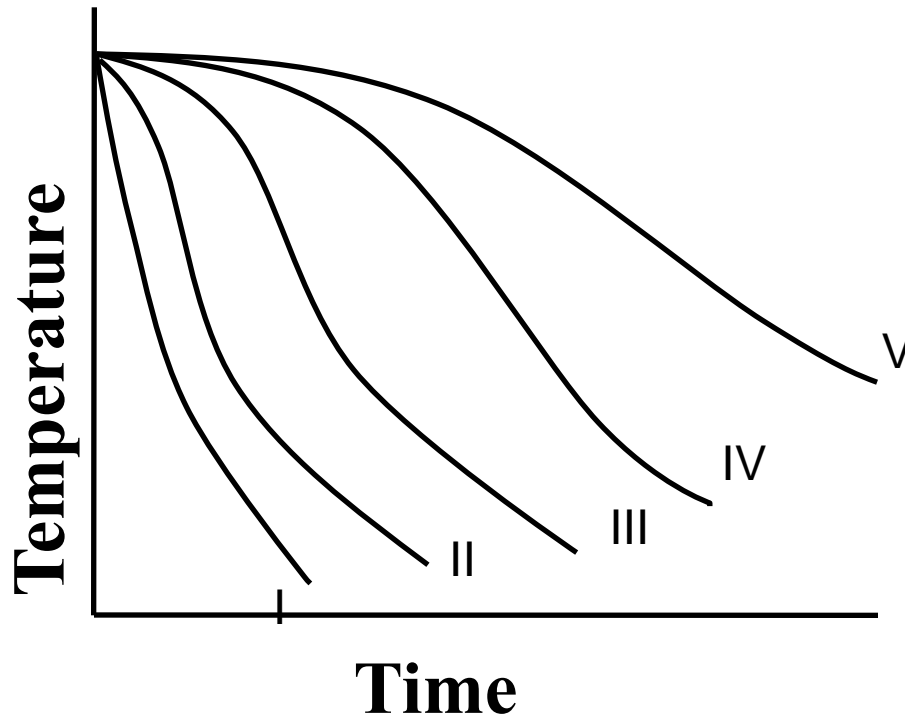
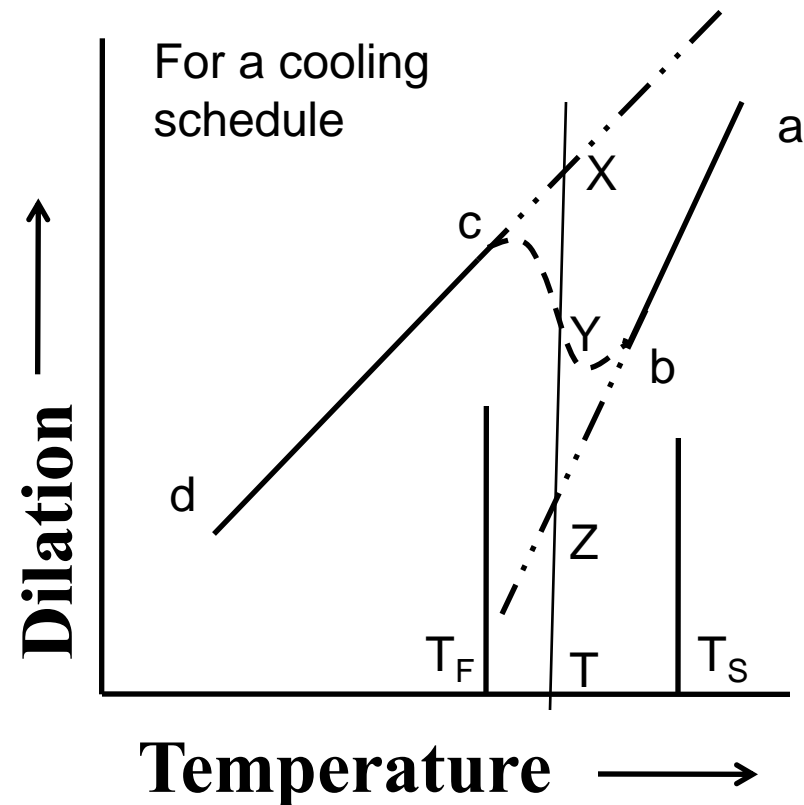

Fig. 3: Schematic cooling curves

Fig. 4: Dilation-temperature plot for a cooling curve

In **Fig. 3** curves I to V indicate cooling curves at higher cooling rate to lower cooling rate respectively. **Fig. 4** gives the dilation at different temperatures for a given cooling rate/schedule. In general slope of dilation curve remains unchanged while amount of phase or the relative amount of phases in a phase mixture does not change during cooling (or heating) however sample shrink or expand i.e. dilation takes place purely due to thermal specific volume change because of change in temperature. Therefore in **Fig. 4** dilation from a to b is due to specific volume change of high temperature phase austenite. But at T_S slope of the curve changes. Therefore transformation starts at T_S. Again slope of the curve from c to d is constant but is different from the slope of the curve from a to b. This indicates there is no phase transformation between the temperature from c to d but the phase/phase mixture is different from the phase at a to b.

Slope of the dilation curve from b to c is variable with temperature. This indicates the change in relative amount of phase due to cooling. The expansion is due to the formation of low density phase(s). Some part of dilation is compensated by purely thermal change due to cooling. Therefore dilation curve takes complex shape. i.e first slope reduces and reaches to a minimum value and then increases to the characteristic value of the phase mixture at c.

Therefore phase transformation start at b i.e. at temperature T_S and transformation ends or finishes at c or temperature T_F. The nature of transformation has to be determined by metallography. When austenite fully transforms to a single product then amount of transformation is directly proportional to the relative change in length. For a mixture of products the percentage of austenite transformed may not be strictly proportional to change in length, however, it is reasonable and generally is being used.

Cumulative percentage of transformation at in between temperature T is equal to YZ/XZ*100 where X, Y and Z are intersection point of temperature T line to extended constant slope curve of austenite (ba), transformation curve (bc) and extended constant slope curve of low temperature phase (cd) respectively.

So at each cooling rate transformation start and finish temperature and transformation temperature for specific amount (10 %, 20%, 30% etc.) can also be determined. For every type of transformation, locus of start points, isopercentage points and finish points give the transformation start line, isopercentage lines and finish line respectively and that result CCT diagram. Normally at the end of each cooling curve hardness value of resultant product at room temperature and type of phases obtained are shown.

- **Fig. 5** shows the five different cooling curves a to e employed to a hypoeutectoid steel. **Fig. 5**(a) to (e) show the type of corresponding dilatometric plots drawn against dilation versus temperature. **Fig. 6** shows the corresponding transformation temperature and time in a temperature versus log time plot against each corresponding cooling rate. At the end of each cooling rate curve normally hardness value and type of phases obtained at room temperature are shown. Symbols F, P, B, M stand for ferrite, pearlite, bainite and martensite respectively. Subscripts 'S and 'F' stand for reaction start and reaction finish respectively. In cooling 'a' schedule martensite starts at M_S and finishes at M_F and therefore 100% martensite results. While in cooling schedule 'b' bainite starts at B_S but reaction does not complete and retained austenite enriched in carbon transforms at lower M_S but completes at lower M_F. Cooling schedule 'b' results bainite and martensite.
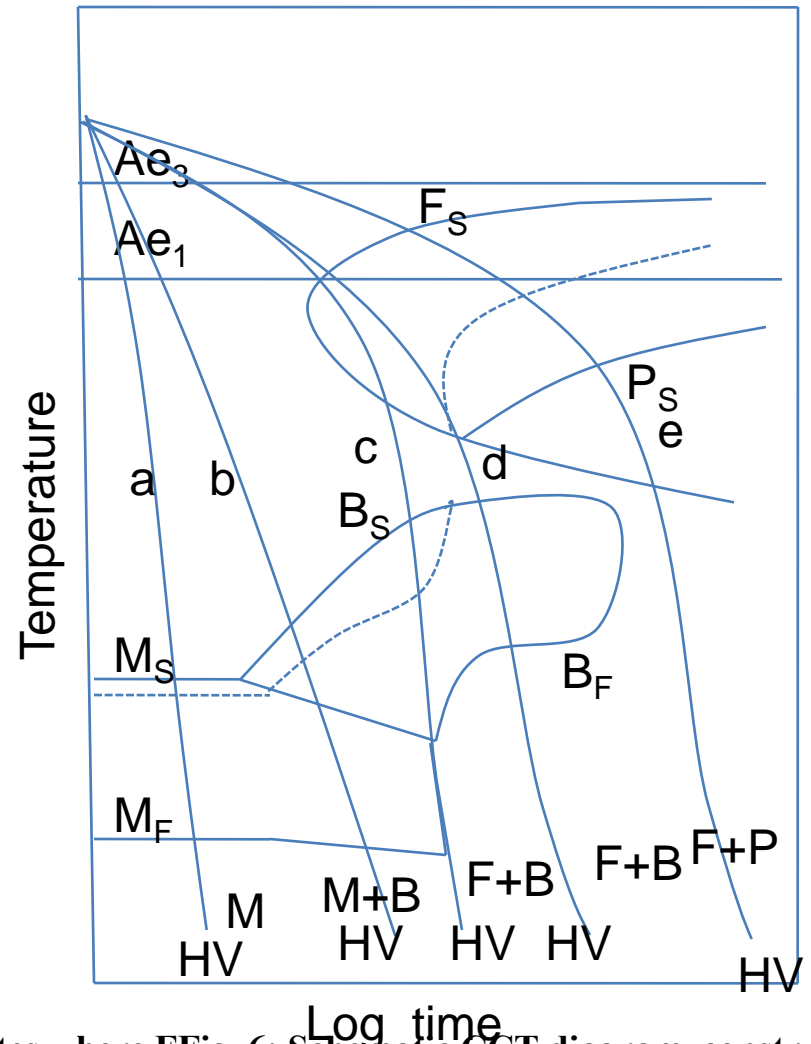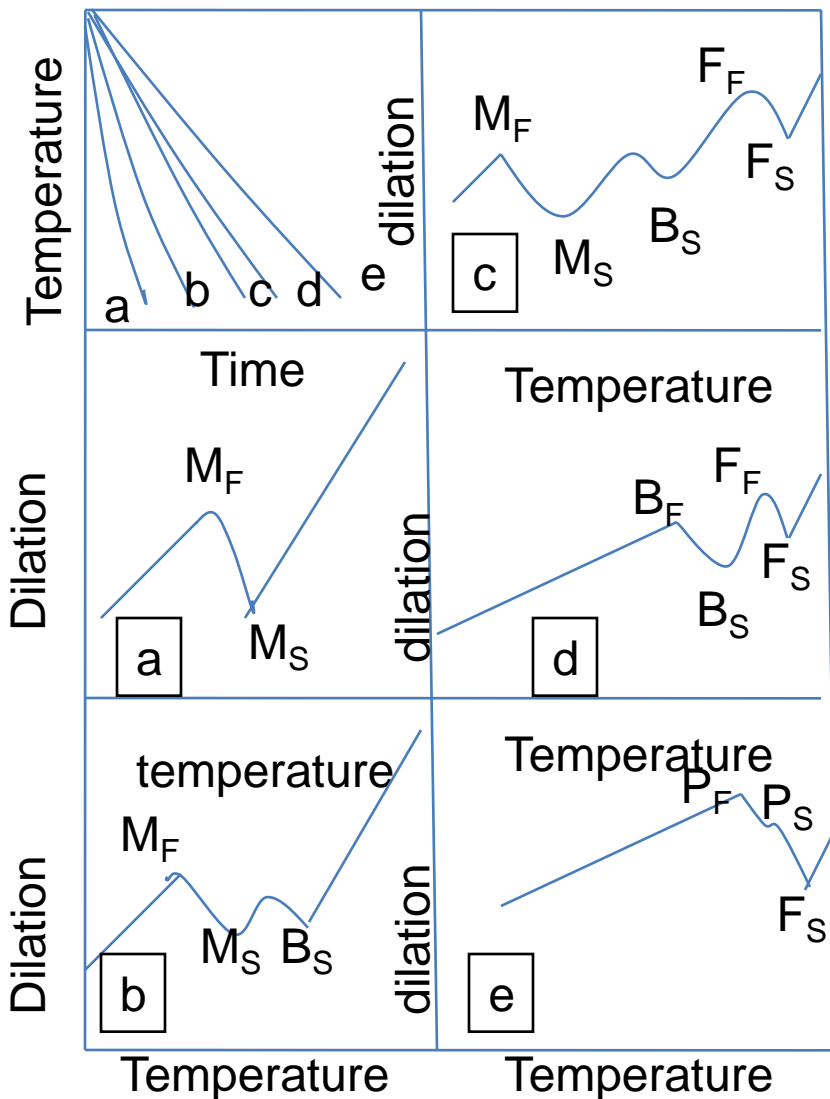
Fig. 5: Schematic dilatometric plots for five different cooling rates where F, P, B and M stands for ferrite, pearlite, bainite and martensite respectively and subscript S and F stands for transformation start and transformation finish for respective products for a hypoeutectoid steel

Fig. 6: Schematic CCT diagram constructed from data of Fig 3(for the hypoeutectoid steel). Dotted line is 25% of total transformation.

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In cooling schedule 'c' ferrite starts at F_S and finishes at F_F. Quantity of ferrite is about 15% but rest of austenite enriched in carbon transforms to bainite at B_S and just finishes at B_F. Therefore cooling 'c' results ferrite and bainite at room temperature. Similarly cooling schedule 'd' results increased ferrite and rest bainite. During cooling schedule 'e' ferrite start at F_S and pearlite starts at P_S but pearlite reaction finishes at P_F. Therefore cooling schedule 'e' results increased ferrite and rest pearlite. The locus of all start points and finish points result the CCT diagram. This diagram is not a unique diagram like TTT diagram for a material. It depends on type of cooling. This diagram can predict phase transformation information if similar cooling curves had been used during its determination or if equivalent cooling schedule are used during process of production.

The two cooling curves are considered equivalent if

(i) the times to cool from A_{e3} to 500°C are same.

(ii) the times to cool from A_{e3} to a temperature halfway between Ae_3 and room temperature , are same.

(iii) the cooling rates are same.

(iv) the instant cooling rates at 700°C are same.

Therefore to make it useful different types of CCT diagrams need to be made following any one of the above schedule that matches with heat treatment cooling schedule.

End-quench test method for type I CCT diagram

A number of Jominy end quench samples are first end- quenched (**Fig.7**) for a series of different times and then each of them (whole sample) is quenched by complete immersion in water to freeze the already transformed structures. Cooling curves are generated putting thermocouple at different locations and recording temperature against cooling time during end quenching. Microstructures at the point where cooling curves are known, are subsequently examined and measured by quantitative metallography. Hardness measurement is done at each investigated point. Based on metallographic information on investigated point the transformation start and finish temperature and time are determined. The transformation temperature and time are also determined for specific amount of transformation. These are located on cooling curves plotted in a temperature versus time diagram. The locus of transformation start, finish or specific percentage of transformation generate CCT diagram (**Fig. 8**).

1⅛"(29 mm) diameter

⅛"(3.2 mm)

½"(12.7 mm)

1¹⁄₃₂"(26.2 mm)

4"(102 mm) long

1"(25.4 mm) diameter

2½"(64 mm)

Free height of water jet
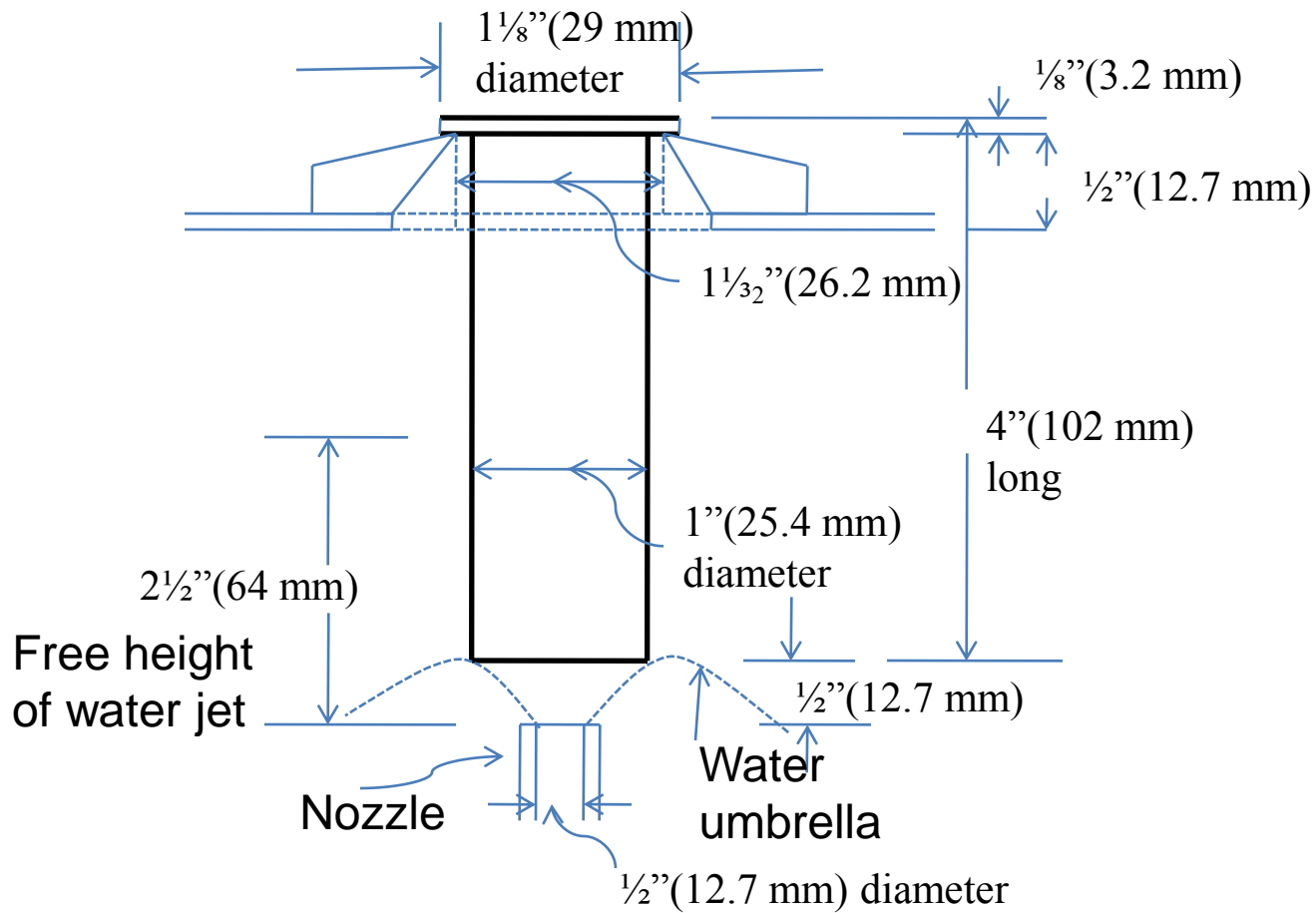
½"(12.7 mm)

Nozzle

Water umbrella

½"(12.7 mm) diameter
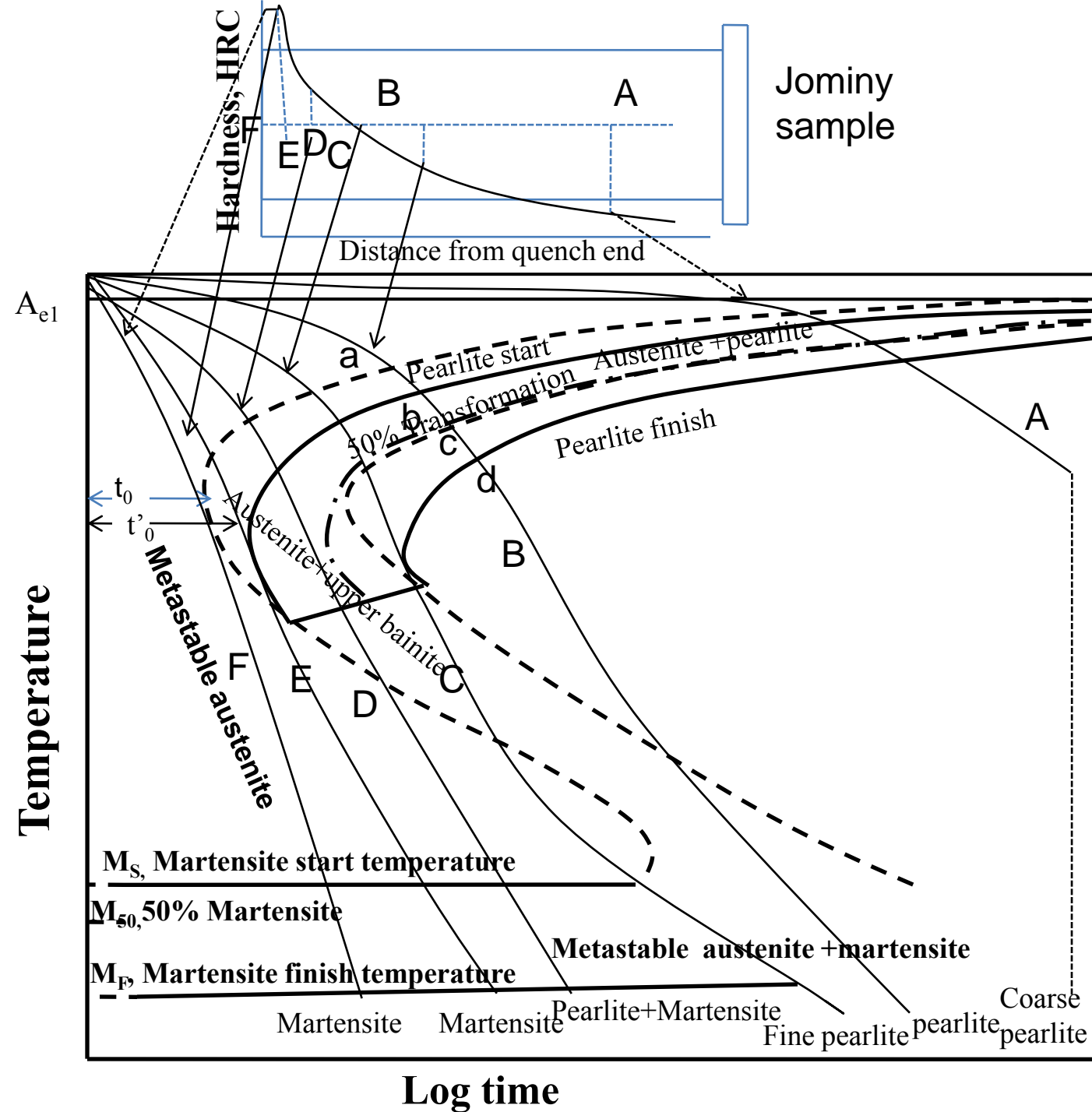
Fig 7(a): Jominy sample with fixture and water jet

Fig.7: Figures show (b) experimental set up, (c) furnace for austenitisation, (d) end quenching process. Courtesy of *DOITPoMS of Cambridge University.*

Fig. 8: CCT diagram (—) projected on TTT diagram (- -) of eutectoid steel

t_o=Minimum incubation period at the nose of the TTT diagram,
t'_o=minimum incubation period at the nose of the CCT diagram

Jominy sample

Hardness, HRC

Distance from quench end

Temperature

Log time

A_{e1}

t_0

t'_0

Metastable austenite

Pearlite start

Austenite +pearlite

50% Transformation

Pearlite finish

Austenite+upper bainite

M_S, Martensite start temperature

M_{50}, 50% Martensite

M_F, Martensite finish temperature

Metastable austenite +martensite

Martensite   Martensite   Pearlite+Martensite   Fine pearlite   pearlite   Coarse pearlite

a
b
c
d

A
B
C
D
E
F

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Fig. 7. shows the Jominy test set up and **Fig. 6** shows a schematic CCT diagram. CCT diagram is projected on corresponding TTT diagram.

A, B, C, D, E, F are six different locations on the Jominy sample shown at **Fig.8** that gives six different cooling rates. The cooling rates A, B, C, D, E, F are in increasing order. The corresponding cooling curves are shown on the temperature log time plot. At the end of the cooling curve phases are shown at room temperature. Variation in hardness with distance from Jominy end is also shown in the diagram.

For cooling curve B, at T_1 temperature minimum t_1 timing is required to nucleate pearlite as per TTT diagram in **Fig. 8**. But material has spent t_1 timing at higher than T_1 temperature in case of continuous cooling and incubation period at higher temperature is much more than t_1. The nucleation condition under continuous cooling can be explained by the concept of progressive nucleation theory of Scheil.

Scheil's concept of fractional nucleation/progressive nucleation

Scheil presented a method for calculating the transformation temperature at which transformation begins during continuous cooling. The method considers that (1) continuous cooling occurs through a series of isothermal steps and the time spent at each of these steps depends on the rate of cooling. The difference between successive isothermal steps can be considered to approach zero.

(2) The transformation at a temperature is not independent to cooling above it.

(3) Incubation for the transformation occurs progressively as the steel cools and at each isothermal step the incubation of transformation can be expressed as the ratio of cooling time for the temperature interval to the incubation period given by TTT diagram. This ratio is called the fractional nucleation time.

Scheil and others suggested that the fractional nucleation time are additive and that transformation begins when the sum of such fractional nucleation time attains the value of unity.

The criteria for transformation can be expressed

$$\Delta t_1/Z_1 + \Delta t_2/Z_2 + \Delta t_3/Z_3 + \ldots\ldots + \Delta t_n/Z_n = 1$$

Where Δt_n is the time of isothermal hold at Temperature T_n where incubation period is Z_n. This is called additive reaction rule of Scheil (1935). The reactions for which the additive rule is justifiied are called isokinetic, implying that the fraction transform at any temperature depends only on time and a single function of temperature. This is experimentally verified by Krainer for pearlitic transformation.

Therefore though nucleation has progressed to some fraction of the event but time is not sufficient for pearlite nucleation at a. If time is allowed in continuous cooling while summation of fractional nucleation time becomes unity (at b), pearlite is to nucleate but by that time temperature drops down as it is continuously cooling.

This concept of progressive nucleation is not strictly valid for bainite transformation where austenite get enriched with carbon at higher temperature. As transformation at higher temperature enriches the austenite by carbon, the transformation characteristic changes. i.e. transformation slows down at lower temperature.

By continuous cooling transformation temperature moves towards down and incubation moves toward right. Similar is the case for pearlite finish temperature and time. Pearlitic region takes the shape as shown in the diagram. The bainitic region moves so right that entire region is sheltered by the pearlitic curve.

So there is no chance of bainitic tranformation in eutectoid plain carbon steel under continuous cooling condition. There is untransformed region where earlier was bainitic region. Under such circumtances split transformation occurs. However martensitic region remain unaffected.

Various cooling rates give various combination of phases. Cooling A indicates very slow cooling rate equivalent to furnace cooling of full annealing process and that results coarse pearlite. Cooling B is faster cooling can be obtained by air cooling. This type of cooling can be obtained by normalising and that results finer pearlite. Cooling C: just touches the finishing end of nose that gives fully fine pearlite.

Cooling D is faster cooling that can be obtained by oil quenching. This is a hardening heat treatment process and that produces fine pearlite and untransformed austenite transforms to martensite below M_S.

Cooling curve E just touches the nose of CCT diagram and that produces almost fully martensite.

Cooling curve F avoid nose of C curve in CCT but touches the nose of TTT gives entirely martensite. Notice the critical cooling rate to avoid nose of CCT diagram i.e. diffusional transformations is lower than that to TTT diagram.

General features of CCT diagrams

1. CCT diagram depends on composition of steel, nature of cooling, austenite grain size, extent of austenite homogenising, as well as austenitising temperature and time.

2. Similar to TTT diagrams there are different regions for different transformation (i.e. cementite/ferrite, pearlite, bainite and martensite). There are transformation start and transformation finish line and isopercentage lines. However depending on factors mentioned earlier some of the transformation may be absent or some transformation may be incomplete.

3. In general for ferrite, pearlite and bainite transformation start and finish temperature moves towards lower temperature and transformation time towards higher timing in comparison to isothermal transformation. Transformation curve moves down and right.

4. The bainite reaction can be sufficiently retarded such that transformation takes shelter completely under pearlitic transformation in case of eutectoid plain carbon steel and therefore bainite region vanishes. However in other steel it may be partially sheltered. Therefore bainitic region observed in non eutectoid plain carbon steel or alloy steels.

5. C curves nose move to lower temperature and longer time. So actual critical cooling rate required to avoid diffusional transformation during continuous cooling is less than as prescribed by TTT diagram. Actual hardenability is higher than that predicted by TTT.

6. M_S temperature is unaffected by the conventional cooling rate,however, it can be lowered at lower cooling rate if cooling curves such that austenite enriches with carbon due to bainite or ferrite formation (in hypoeutectoid steel). On the other hand M_S can go up for lower cooling rate such that austenite become lean in carbon due to carbide separation (in hypereutectiod steel).

7. Large variety of microstructure like ferrite/cementite/carbide +pearlite+bainite+martensite can be obtained in suitable cooling rate. It is not feasible or limited in case of isothermal transformation.

Determination of type II CCT diagram

This procedure was developed by Atkins. In this process round samples of different diameters were quenched in three different media air, oil and water. The cooling curves were recorded at the centre of each bar. Later these cooling curves were simulated in dilatometer test in order to identify the transformation temperature, microstructure and hardness. The transformation information is plotted against temperature and bar diameter cooled in specific medium. These are bar diameter cooled in air, quenched in oil and quenched in water. A scale cooling rate (usually at 700°C) in °C/min is added.

At the bottom of the same diagram another plot is added for hardness (in HRC) and with same cooling rate axis/bardiameter.

These diagrams have to be read along vertical lines (from top to bottom), denoting different cooling rates. **Fig. 9** shows a schematic CCT diagram for hypoeutectoid plain carbon steel.
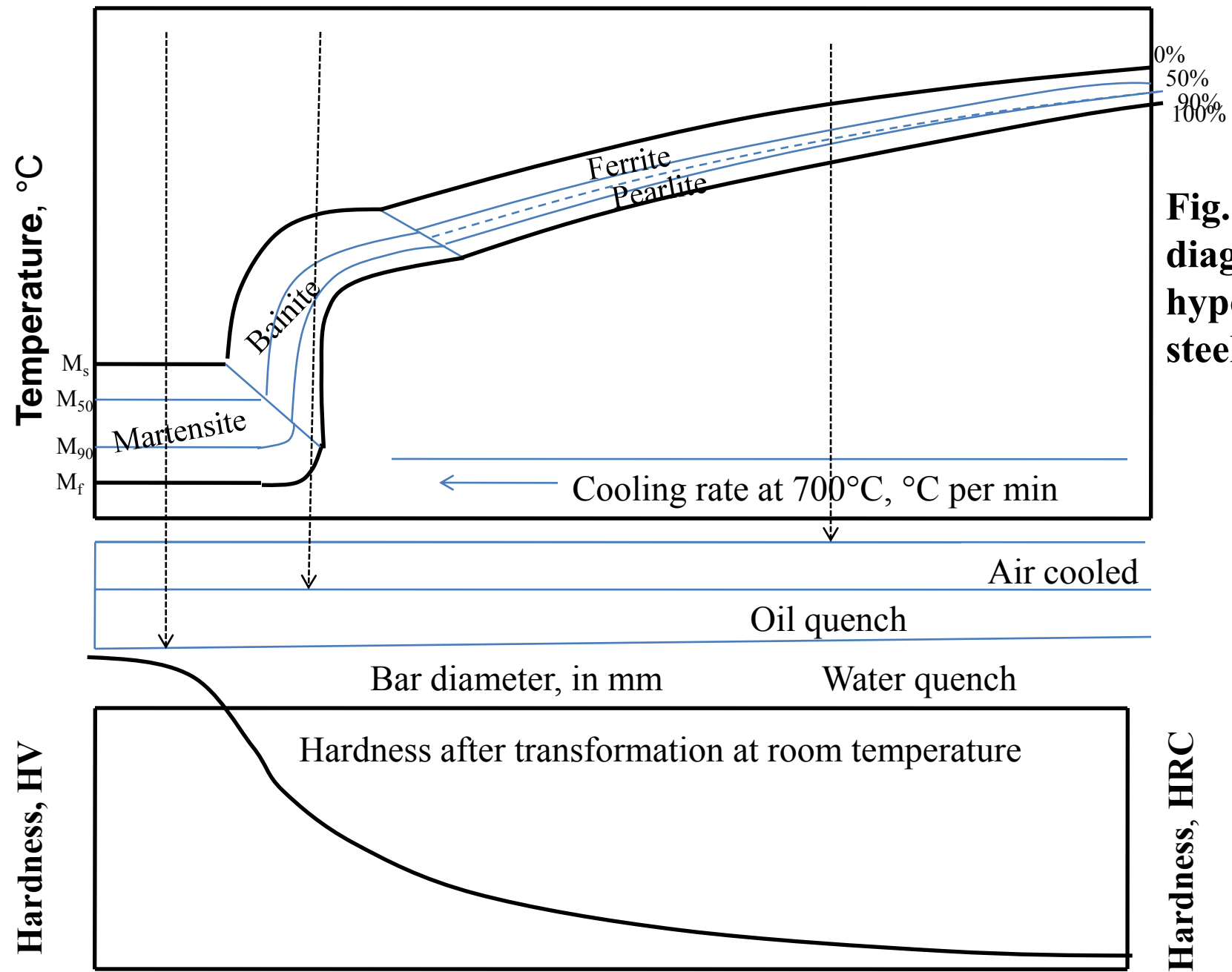
Fig. 9: CCT diagram for hypoeutectoid steel

Conversion of TTT to CCT diagram, Scheil's method (1935)

Scheil's method is based on the assumption that the continuous cooling curve is a combination of sufficiently large number of isothermal reaction steps. Incubation for the transformation occurs progressively as the steel continuously cools. Transformation begins when the sum of fractional nucleation time attains the value of unity.

The criteria for transformation can be expressed

$$\Delta t_1/Z_1 + \Delta t_2/Z_2 + \Delta t_3/Z_3 + \ldots\ldots + \Delta t_n/Z_n = 1$$

Where Δt_n is the time of isothermal hold at temperature T_n where incubation period is Z_n. The rule can be justified if reaction rate solely depends on volume fraction and temperature.

Conversion of TTT to CCT, Grange and Kiefer Method (1941)

During continuous cooling along a given cooling curve which intercepts the TTT start curve at temperature T_1, the transformation will start at temperature T_2, such that the time of cooling between T_1 and T_2 is equal to the time for the start of transformation during isothermal holding at temperature $T_3 = (T_1 + T_2)/2$ (as shown in **Fig. 10**).

$t_3 = t_2 - t_1$

Similar rule can be applied for a isopercentage curve and finish curves.

Assumptions are not strictly valid, however, the method gives reasonable result. The method is particularly suitable for ferrite-pearlite region
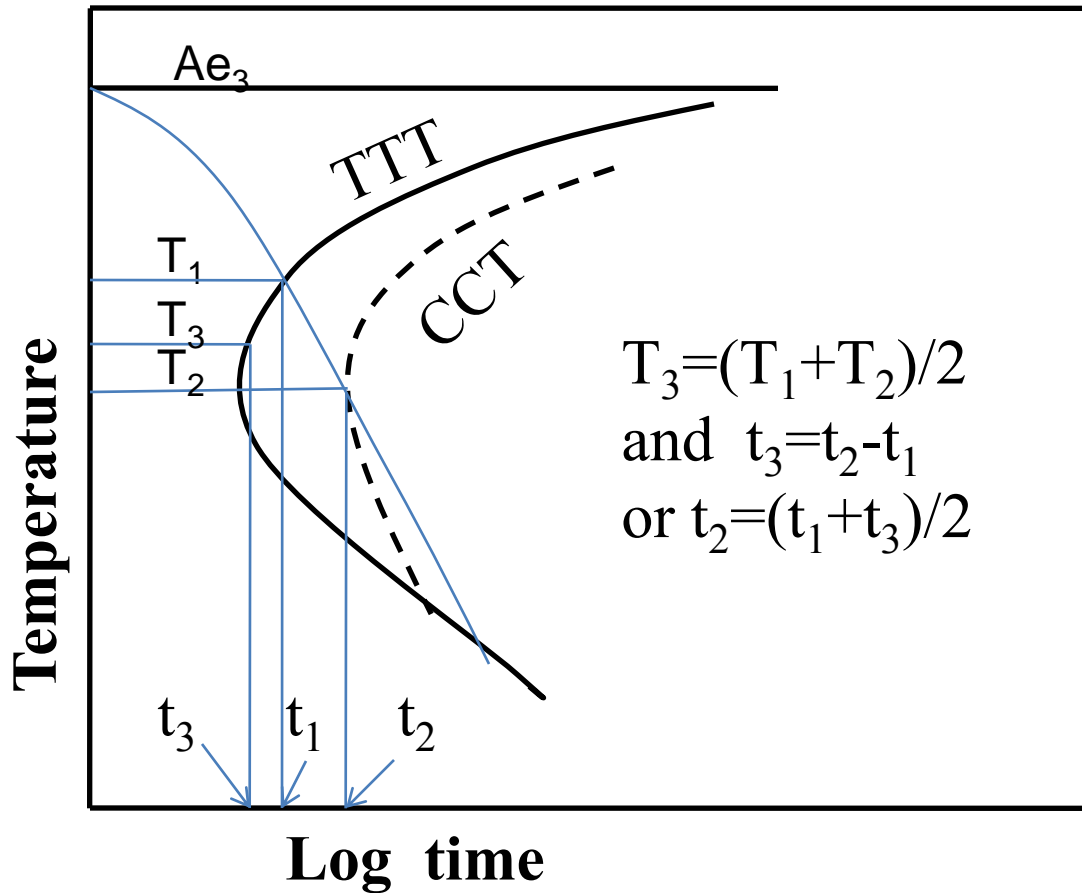
Fig. 10: Graphic method of converting TTT diagram to CCT diagram [Grange and Kiefer method]

Conversion of TTT to CCT, Avrami method (1939)

Let $\tau_{TTT}(T)$ be time required to obtain a given percentage of transformation, X at temperature T during isothermal transformation.

Then time required(τ_{CCT}) to obtain the same percentage of transformation, X, on continuous cooling at T_{CCT} is given by the condition

$X = \int_{Ae_3}^{T}{}_{CCT}\, dX = \int_{Ae_3}^{TCCT} dX/dt.dt = \int_{Ae_3}^{TCCT} g\text{-}dt\text{-------}1$

g-=time average transformation rate (at any temperature T)=$X/\tau_{IT}(T)$.

Substituting this in equation 1

We get $\int_{Ae_3}^{TCCT} dt/\, \tau_{TTT}(T) = 1\text{--------}2$,

By rewriting equation 2 we get

$\int_{Ae_3}^{TCCT} dT/(\tau_{TTT}(T)\, dT/dt) = 1\text{---------}3$

Both these integrals are called Avrami integral. Any one of these integrals has to be evaluated for each cooling curve to get the τ_{CCT} at T_{CCT}

Conversion of CCT to TTT diagram, Kirkaldy and Sharma method (1982)

Let $\tau_{CCT}(T_{CCT})$ be the time required to obtain a given percentage of transformation, X at temperature T_{CCT} during continuous cooling. If it is assumed that CCT diagram was constructed using constant cooling rate(linear cooling),

Then

$$dT/dt = -(A_{e3} - T_{CCT})/(\tau_{CCT}(T_{CCT}) ----4$$

Substituting equation 4 in equation 3, cross multiplying and differentiating with respect to T_{CCT}

We get

$$\tau_{TTT}(T_{CCT}) = 1/(d/dT_{CCT}[(A_{e3} - T_{CCT})/\tau_{CCT}(T_{CCT})]) ---5$$

Where τ_{TTT} is the time required for the given percentage transformation, X, when carried out isothermally at T_{CCT}.

While rate of cooling is not constant but cooling rate can be expressed analytically or empirically as

$dT/dt = f_1(x)f_2(T) = f_1(T_{CCT})f_2(T)$ ---6 (Exp: Jominy cooling curve can be expressed in this form)

where x is the distance from the surface of a continuouly cooled sample.

Substituting equation 6 in equation 3, cross multiplying and differentiating

We get

$\tau_{TTT}(T_{CCT}) = 1/(f_2(T_{CCT}) \, df_1/dT_{CCT})$-----7

Equation 5 or 7 can be used for the conversion of CCT diagram to TTT diagram depending on constant cooling rate or case of cooling rate that can be expressed in analytical or empirical form.

Jominy cooling curves can be expressed in equation 6 form and the using equation 7, CCT diagram can be converted to TTT diagram.