What tools can we use to track and predict the response of steels to welding?

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Abstract

The aim of this paper is to introduce the reader to the basics of phase transformation in materials, specifically steels, and how it applies to welding. Different types of phase transformation in materials are presented with examples. Modified phase diagrams such as continuous cooling transformation diagrams which are used widely to predict the resulting microstructure in a material undergoing thermal cycles are introduced and explained. The mechanical properties, stability and ease of formation of the most common phases in steels are ranked. Dilatometry which is one of the most common methods of building continuous cooling transformation diagrams is also introduced. AISI 4140 was used as an experimental example to show the different phase transformations from austenite and how a finalized continuous cooling transformation diagram is built.

Keywords: AISI 4140, Continuous Cooling Transformation, CCT, Phase Transformation, Dilatometer

During any arc welding process (or similarely any heat treatment), various sections of the base metal undergo different thermal cycles depending on the distance from the arc. As the thermal history of the material is altered, "phase transformations" can occur in the material and the consequent microstructure and mechanical properties of the material can significantly vary. For example, the ultimate tensile strength of a plain carbon steel containing 0.76 wt% carbon can be varied between 700 MPa (100 ksi) and 2000 MPa (300 ksi) depending on the type of heat treatment used [1]. Having a good understanding of what phases form and how much of each phase is present with each thermal cycle is crucial to developing a sound welding procedure. The product of a phase transformation is the formation of at least one new phase with dissimilar physical and chemical properties compared to the parent phase. The product phase of a phase transformation might have a different crystal structure than the parent phase as well. All phase transformations in materials fall under three main categories: diffusion-dependent transformations with constant number and composition of phases (e.g. solidification of pure metals), diffusion-dependent transformations with varying number of present phases and/or variation in composition of the phases (e.g. eutectiod reactions such as formation of pearlite from austenite), and diffusionless transformations which lead to the formation of metastable phases (e.g. formation of bainite and martensite from austenite) [1].

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The best way to demonstrate the progress of any phase transformation is to plot the temperature as a function of the transformation time using a logarithmic time scale. The reason for using a logarithmic time scale lies in the nature of the rate of phase transformations which can be described as an exponential function of temperature (Arrhenius relationship) [1]. Figure 1 shows a schematic of a phase transformation progress curve as a function of time (log scale). This curve is also commonly referred to as the phase fraction curve. This figure also shows the three most important points in any phase fraction curve (i.e. transformation start, mid-point, and finish points).

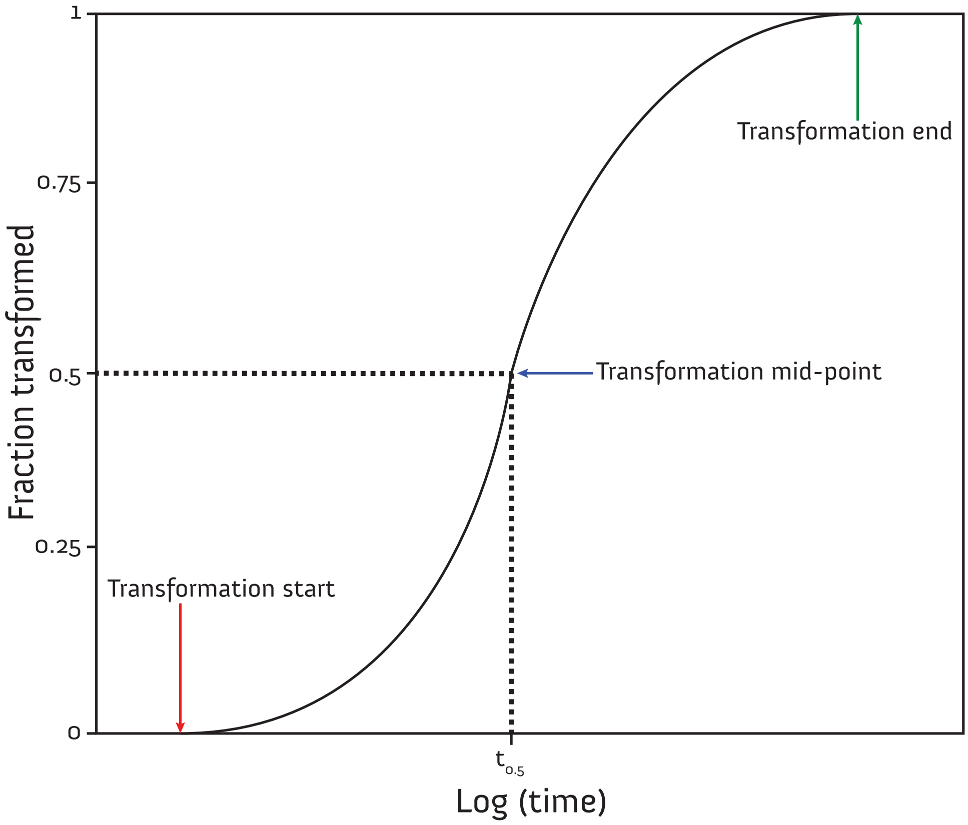

Fig. 1: A schematic of a typical phase fraction curve showing the progression of a phase transformation with time.

Modified phase diagrams are often used to portray the time and temperature dependency of the phase transformations in a specific alloy composition. These diagrams differ from the well known "equilibrium" phase diagrams in the fact that they incorporate the parameter of time. There are two types of modified phase diagrams: time-temperature transformation (TTT) diagrams and continuous cooling transformation (CCT) diagrams. TTT diagrams are used when the material is heated or cooled to a specific temperature and kept at that temperature for a predetermined time duration (emphasis being on holding time at constant temperature). Figure 2 shows a schematic of a TTT diagram for a plain carbon steel. CCT diagrams are commonly constructed for a specific alloy composition that will be undergoing thermal cycles that contain cooling rates (emphasis being on constant cooling rate from high temperature). CCT diagrams are more often used in welding applications to determine the phases that form with each cooling rate. A schematic of a CCT diagram for a low alloy carbon steel is shown in

Figure 3. Every CCT diagram contains a number of key cooling rates which are the borderline of a change or addition of a phase transformtaion. These important cooling rates along with the phases that will form in the regions between each of them are shown in Figure 3. The addition of alloying elements other than carbon (such as Ni, Si, Cr, Mn, Mo) to a steel composition can lead to significant changes in the appearance of the modified phase diagrams. Alloying elements will typically tend to shift the transformation curves (curves in Figure 2 and Figure 3) to longer times (i.e. curves will shift to the right). Some alloying elements will promote the formation of specific phases (e.g. Nb tends to promote the formation of bainite in microalloyed steels [2]) and hence increase the stability temperature range of that specific phase at the expense of decreasing the presense of other phases in a modified phase diagram.

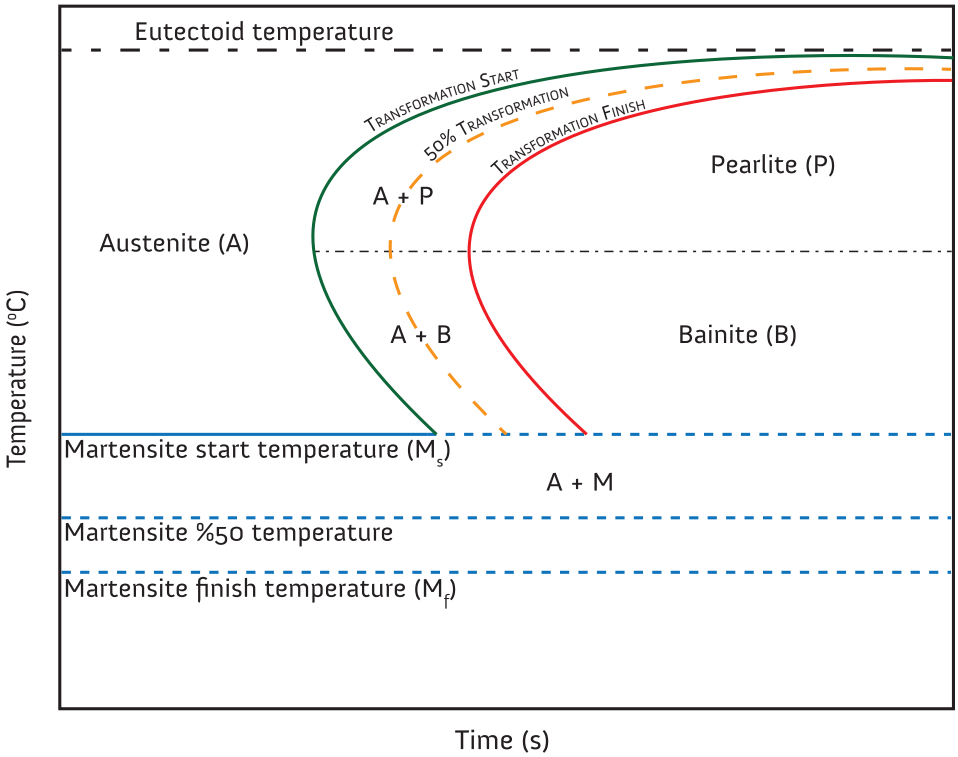

Fig. 2: A schematic of a time-temperature transformation diagram for a plain carbon steel.

Phase transformations in materials are a product of change in composition or temperature or both. During welding phase transformations are most commonly a product of varying temperature. This means during welding for the specific alloy composition, a phase boundary is crossed in the equilibrium phase diagram or equivalently a modified phase diagram upon heating or cooling. An equilibrium phase diagram can be used to predict the phases present in the alloy ONLY if the heating or cooling is carried out at extremely low rates (sometimes as low as 0.01 K/min) which is not practical in welding. A CCT diagram does not suffer from this limitation and can be used with all ranges of cooling or heating rates. Hence, a CCT diagram will predict "metastable" phases in addition to the stable phases in the alloy cooled/heated at non-equilibrium rates. This advantage over equilibrium phase diagrams makes CCT diagrams more practical to the welding industry and the predictions from these diagrams closer to reality.

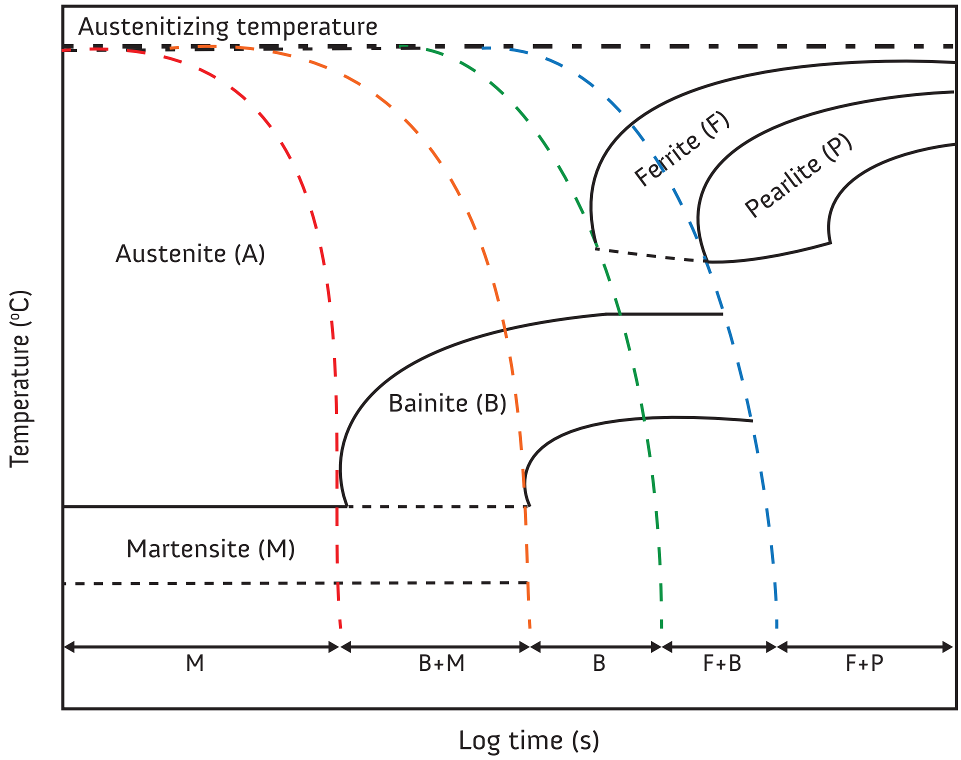

Fig. 3: A schematic of a continuous cooling transformation diagram for a low alloy carbon steel.

From a strength and toughness point of view, some phases (or microconstituents) are more desirable to form in weldments and some are considered detrimental. Figure 4 shows the variation in the mechanical properties, stability and ease of formation between the most common microconstituents found in steels.

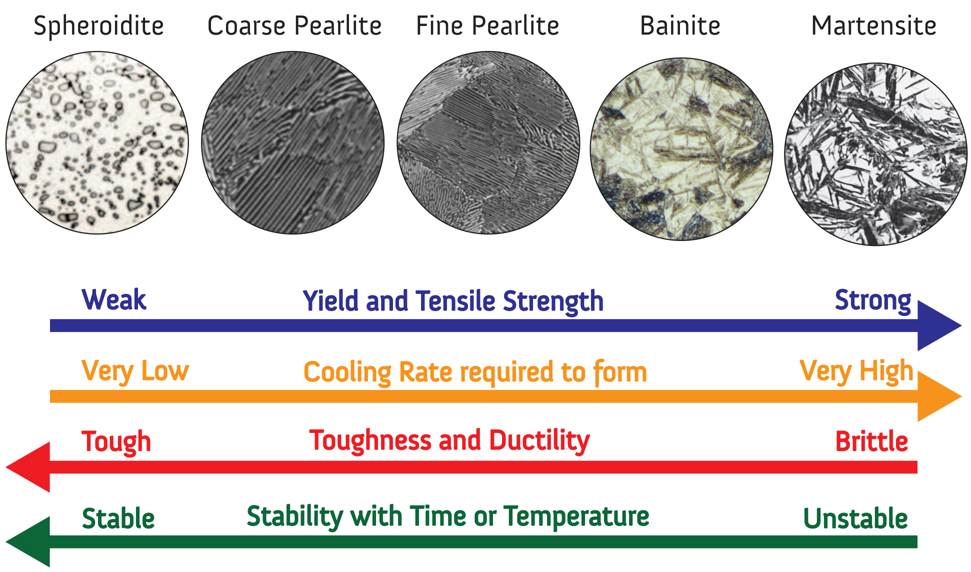

Fig. 4: The variation of strength, toughness, stability and required cooling rate to form between the most common microconstituents found in stees l.

Dilatometry is one of the common methods by which the thermal response of a material may be measured over a wide range of temperatures. In addition, any phase transformations in the material can also be recorded. In dilatometry the test sample is heated in a specially designed furnace (usually induction heating is used) and then controlled cooled. The slower cooling rates are controlled by furnace cooling but higher cooling rates must be controlled by gas quenching. Using a dilatometer, cooling and/or heating data are plotted as temperature versus time. Also, dilation is recorded against temperature. Any slope change indicates a phase transformation. There are many types of dilatometers. Dilatometers may use a pushrod, capacitor, or optical system to sense expansion. Figure 5 portrays the internal components of a pushrod dilatometer which is the most common type of dilatometer used for research purposes. Figure 6 shows an actual dilation curve for an austenite to martensite phase transformation in AISI 4140 steel recorded in a Linseis RITA L78 pushrod dilatometer. A similar curve but for austenite to bainite transformation in AISI 4140 steel is shown in Figure 7. The comparison of these two graphs illustrates how the cooling rate dictates the type and temperature of the transformations in steels.

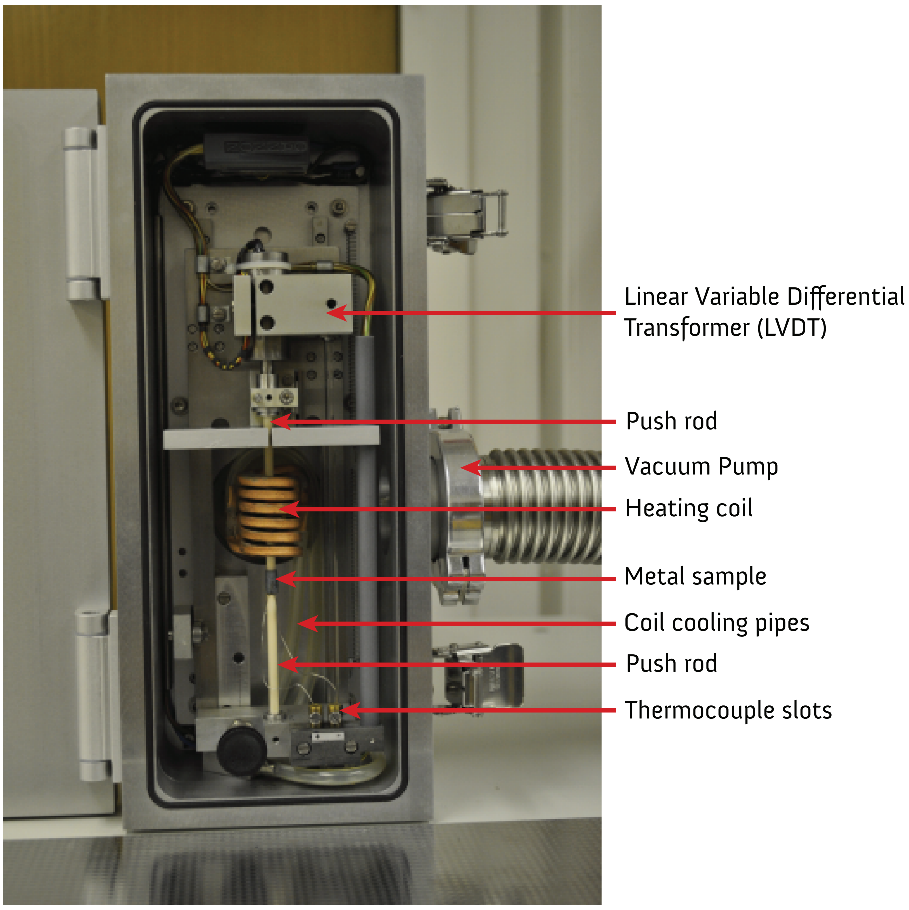

Fig. 5: The internal components of a Linseis RITA L78 pushrod dilatometer capable of heating and cooling rates of up to 2500 K/s.

To construct a CCT diagram using a dilatometer, samples of the test material must be heated with the same heating conditions (i.e. same heating rate, initial microstructure, austenitizing temperature and time) but cooled at different rates. At each cooling rate transformation start and finish temperatures must be determined from the dilation versus temperature curve. For every type of transformation, locus of start points and finish points give the transformation start line and finish line respectively. The

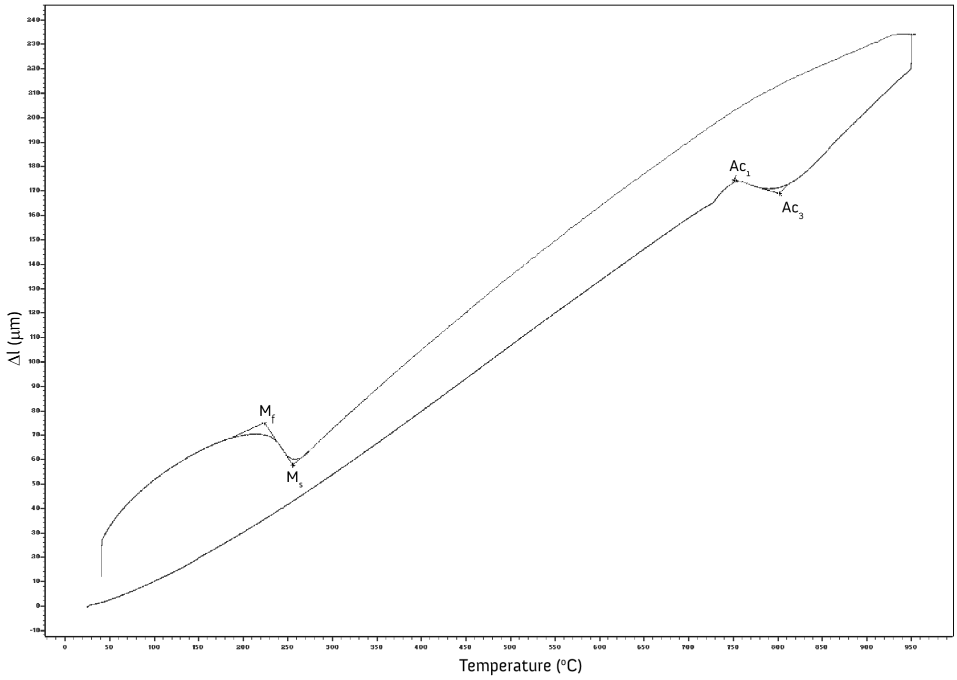

Fig. 6: Dilation curve for an austenite to martensite phase transformation in AISI 4140 steel recorded in a Linseis RITA L78 pushrod dilatometer. Cooling rate=400 K/s. Symbols used in this graph are Ac_1: temperature at which austenite begins to form during heating, Ac_3: temperature at which transformation of ferrite to austenite is completed during heating, M_s: temperature at which transformation of austenite to martensite is initiated and M_f: temperature at which transformation of austenite to martensite is completed.

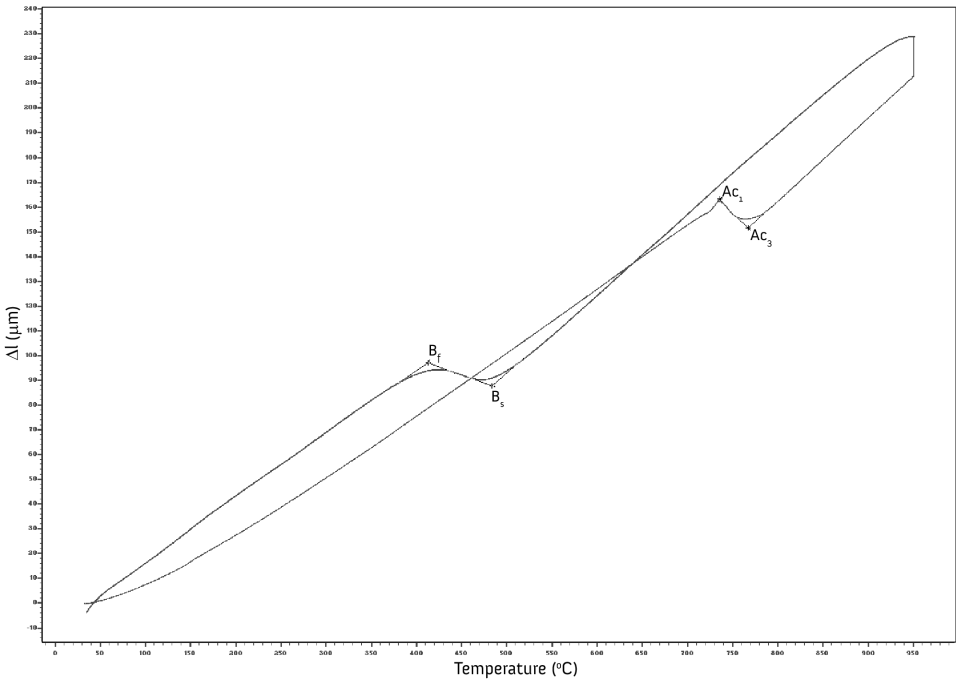

Fig. 7: Dilation curve for an austenite to bainite phase transformation in AISI 4140 steel recorded in a Linseis RITA L78 pushrod dilatometer. Cooling rate=1 K/s. Symbols used in this graph are Ac_1: temperature at which austenite begins to form during heating, Ac_3: temperature at which transformation of ferrite to austenite is completed during heating, B_s: temperature at which transformation of austenite to bainite is initiated and B_f: temperature at which transformation of austenite to bainite is completed.

resulting map is a CCT diagram. Figure 8 demonstrates how the finalized CCT diagram for AISI 4140 appears. This CCT diagram was constructed at the Canadian Center for Welding and Joining (CCWJ) using a Linseis rapid induction thermal analysis (RITA) L78 high speed quenching dilatometer.

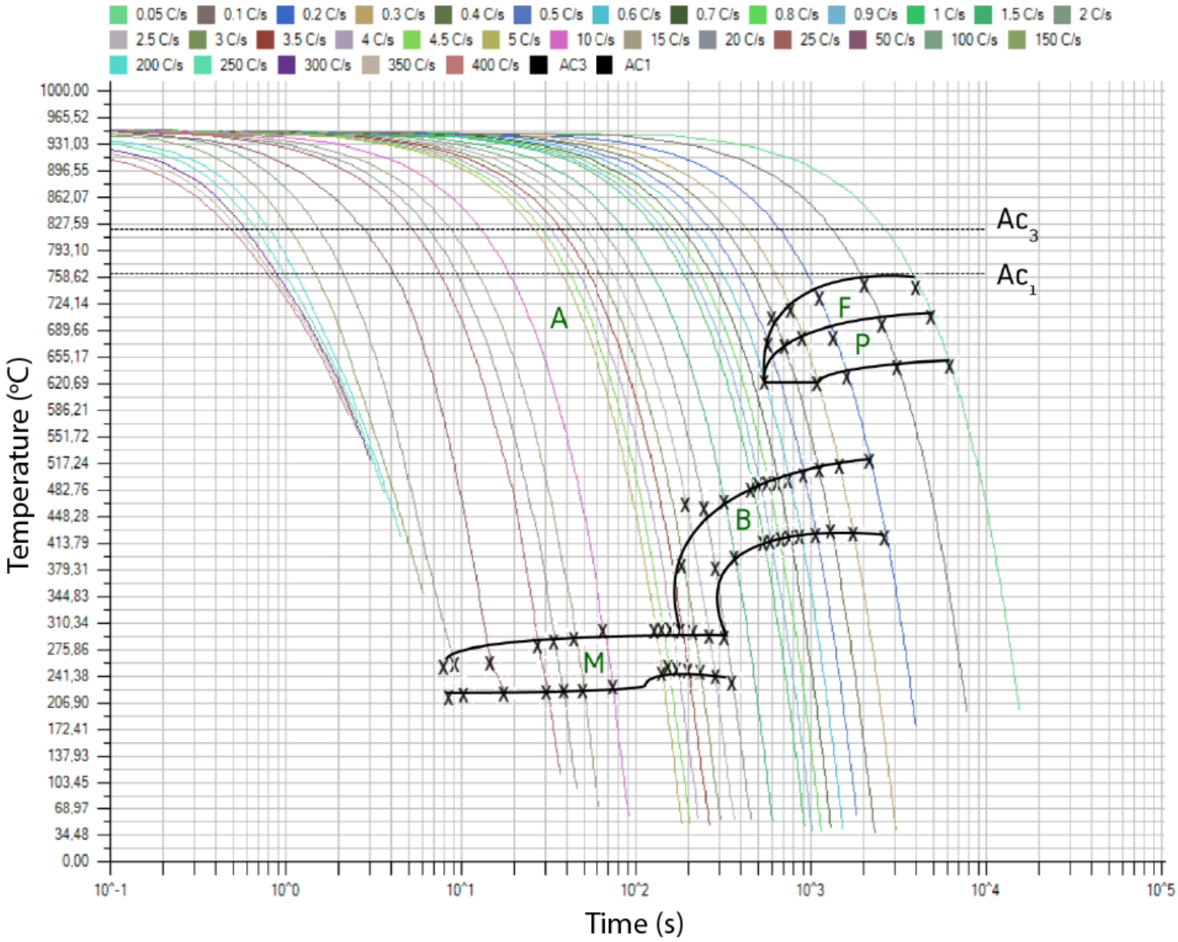

Fig. 8: CCT diagram constructed for AISI 4140 steel using a Linseis RITA L78 pushrod dilatometer. Cooling rates range from 0.05 K/s up to 400 K/s. Symbols used in this graph are A: austenite, B: bainite, F: ferrite, M: martensite, P: pearlite, Ac_1: temperature at which austenite begins to form during heating and Ac_3: temperature at which transformation of ferrite to austenite is completed during heating.

In summary, TTT and CCT diagrams are similar to equilibrium phase diagrams with the addition of the parameter of time. The microstructure of the material can be predicted using TTT and CCT diagrams. A modified phase diagram (i.e. CCT or TTT) is specific to only one composition of an alloy and hence, a new modified phase diagram has to be constructed for every new composition of an alloy. One of the most common instruments used to build a CCT diagram is a dilatometer which measures the change in the length of a material with temperature.

References

[1] W. D. Callister and D. G. Rethwisch: *Fundamentals of Materials Science and Engineering: An Integrated Approach*, Wiley, 2012.

[2] T. Gladman: *The physical metallurgy of microalloyed steels*, 1997.