Interaction of prior deformation and heating rate on austenitisation kinetics

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Abstract:

Common steel manufacturing processes often include multiple hot and cold deformation steps, followed by a subsequent heat treatment involving austenitisation of the alloy.

It is well known that the energy and structure of defects that deformation introduces in the alloy is able to change its phase transformation behaviour. Indeed, as most mechanical and structural components require a carefully designed microstructure for optimum mechanical properties, understanding and accounting for changes in the phase transformation behaviour becomes of supreme importance.

The effect of deformation on the kinetics of austenitisation from a mixture of ferrite and pearlite in a hypoeutectic steel has been investigated using dilatometry and electron microscopy.

Two interesting principles emerge from this work. Firstly, slow heating can stabilise the initial microstructure such that austenite formation is retarded. Secondly, the combined effects of heating rate on the initial microstructure and on the kinetics of thermally activated processes, can lead to a minimum in the austenite-start temperature as a function of the heating rate. Otherwise, deformation accelerates transformation by adding to the stored energy in the initial microstructure.

Introduction:

One of the main side effects of deformation in metals is the accumulation of residual stresses which can cause shape distortion when the component is annealed. Virtually all final shaping operations introduce some residual stresses.

There is another consequence of deformation that often is overlooked. The energy and the structures of defects that deformation introduces in steel can change its phase transformation behaviour.

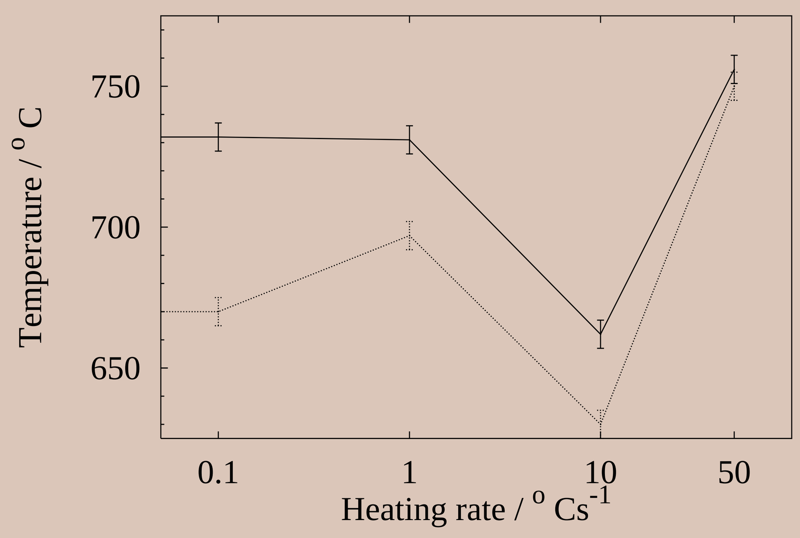

Figure: (1) The A_{c1} temperature as a function of heating rate and deformation [$\varepsilon = \mathbf{0.0}$ (solid line) and $\varepsilon = \mathbf{1.26}$ (dotted line)]. Lines are printed only as a guide.

However, when the changes in transformation kinetics are studied including the effect of the heating rate, an initially surprising effect is observed. Both the start and finish transformation curves present minima at an intermediate heating rate. As will be shown, the actual effects on transformation reaction are quite complex functions of strain and heating rate.

Effect of deformation on austenitisation:

Deformation of the parent phase tends to accelerate the rate of any reconstructive transformation. Nucleation and growth rates of austenite are increased by deformation.

Figure 2 presents the dilatometric curves registered during the transformation to austenite during a slow heating experiment (heating rate of 0.1°C s^{-1}), for three different levels of deformation, $\varepsilon = \mathbf{0.0}$, $\varepsilon = \mathbf{0.45}$ and $\varepsilon = \mathbf{1.26}$. Figure 1 shows the start of austenite transformation for each heating rate considered (0.1, 1.0, 10 and 50°C s^{-1}) for both the undeformed ($\varepsilon = \mathbf{0.0}$) and heavily deformed samples ($\varepsilon = \mathbf{1.26}$).

For each individual heating rate, an increase in the level of deformation leads to a decrease in the transformation temperature.

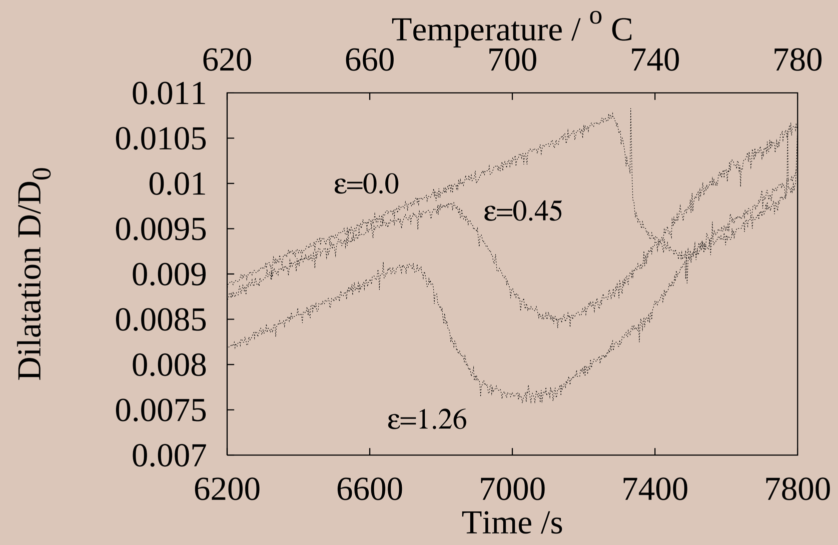

Figure: (2) Comparison between the dilatometric curves registered during the transformation to austenite during a slow heating experiment (heating rate of 0.1°C s^{-1}), for three different levels of deformation, $\varepsilon = \mathbf{0.0}$, $\varepsilon = \mathbf{0.45}$ and $\varepsilon = \mathbf{1.26}$.

Effect of deformation on cementite spheroidisation:

The reduction of transformation temperature is not the only effect of deformation on the austenitisation of a hypoeutectoid steel. Deformation also influences the overall kinetics of austenitisation. The original microstructure consists of ferrite and fine pearlite. In the right circumstances, for example during slow heating, this initial microstructure can undergo changes before the austenite begins to form. Such changes can be accelerated when the sample is deformed before heating. One of the possible changes involves the spheroidisation of the lamellar cementite. It is expected that spheroidisation is more rapid in deformed alloys. The extent of spheroidisation is in turn likely to influence the subsequent formation of austenite. Therefore short heat treatments close to the critical austenite formation temperature or even a slow heating rate can modify the starting microstructure.

Effect of microstructure:

The microstructure of an alloy influences the kinetics of transformation in several ways. Variations in the morphology and number density of cementite must influence the nucleation and growth of austenite. In pearlite colonies, austenite tends to nucleate at the ferrite/cementite interface on the edges of the colonies . In ferrite/spheroidised cementite, nucleation occurs preferentially at the ferrite/cementite interfaces that lay at ferrite/ferrite grain boundaries, which represents a reduction of suitable potential sites when compared with pearlite colony boundaries. The coarseness of the microstructure also defines the mean diffusion path for the atoms involved in reconstructive transformations, and must therefore influence the transformation rate. The morphology of the phases involved partially defines their relative stability, via the ratio of surface energy to volume. Finally, some phases (*i.e.* cementite) may not have their equilibrium chemical compositions, which reduces their stability. Then, during slow heating or short heat treatments, as they are able to evolve towards their equilibrium composition, they become more stable.

This effect has been observed in the present case by comparing the composition of perlitic and spheroidised cementite, as described in *Modelling Induction Hardening*, VDM Verlag Dr. Muller (2008), ISBN-10: 3639062965.

Slow heating rates:

Three more samples were studied to compare the effect of slow heating rates on the evolution of microstructure following deformation. The specimens were heated at 0.1 and 10°C s^{-1} to 680°C followed by a quench to ambient temperature. Figure 3 shows the microstructure of a deformed ($\varepsilon = \mathbf{1.26}$) sample heated at 0.1°C s^{-1}. It is evident that there is extensive spheroidisation. Figure 4 shows the microstructure of another deformed ($\varepsilon = \mathbf{1.26}$) sample heated this time at 10°C s^{-1}, with only mild spheroidisation. Finally, an undeformed sample was heated at the fast heating rate; Figure 5 shows that the original microstructure is essentially retained.

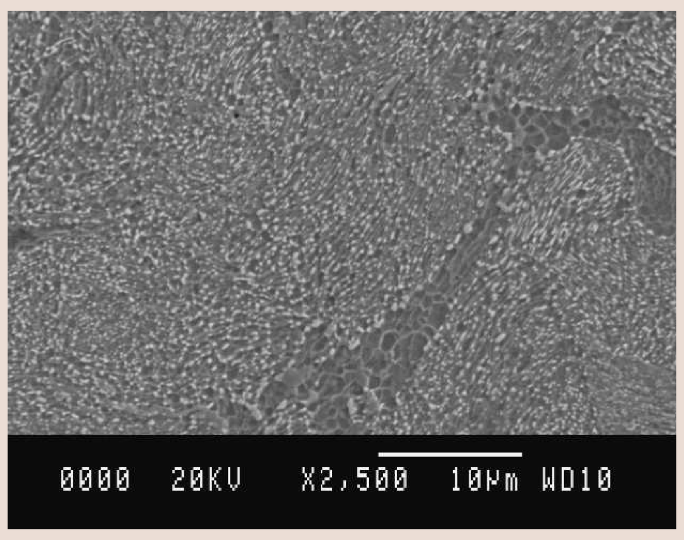

Figure: (3) Microstructure of a deformed ($\varepsilon = \mathbf{1.26}$) sample heated at a slow heating rate (0.1°C s^{-1}) showing the spheroidisation of cementite in pearlite.

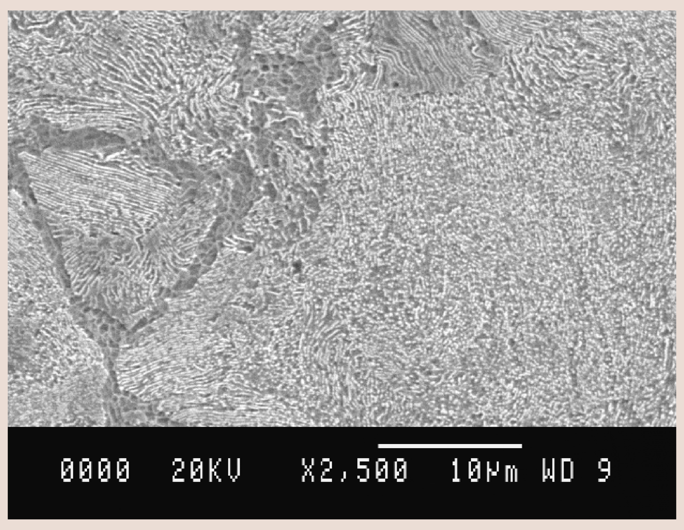

Figure: (4) Microstructure of a deformed ($\varepsilon = \mathbf{1.26}$) sample heated at a fast heating rate (10°C s^{-1}) showing the partial spheroidisation of cementite in pearlite.

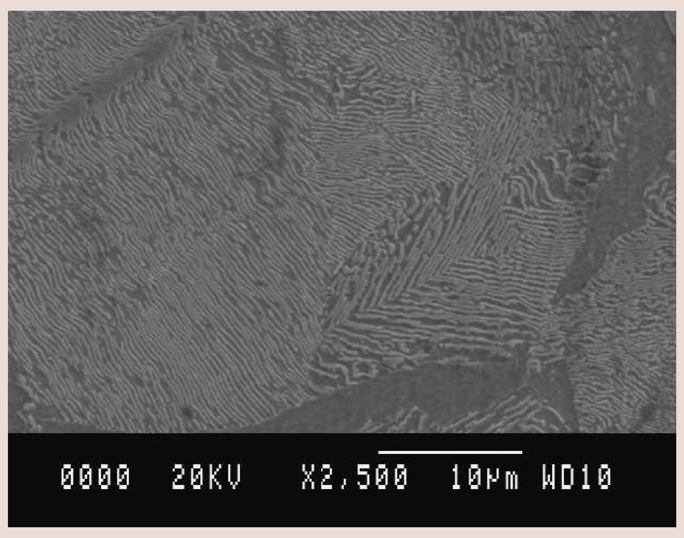

Figure: (5) Microstructure of an undeformed sample heated at a fast heating rate (10°C s^{-1}) showing the absence of spheroidisation of cementite.

These examples show that at slow heating rates, and especially when the initial microstructure has been deformed, subsequent changes occur which may influence the development of austenite.

Combined effect:

As shown earlier, figure 1 represents the transformation-start during heating for undeformed and deformed ($\varepsilon = \mathbf{1.26}$) samples. The two curves have similar shape, but the A_{c1} temperature is in all cases lower for the deformed samples. Deformation has accelerated transformation kinetics. It is not surprising that the difference between the two curves becomes smaller at high heating rates, since the transformation becomes promoted to higher temperatures, making the effect of initial differences in microstructure less important.

There is nevertheless, that peculiar minimum at 10°C s^{-1} in both the curves as a function of heating rate. At the slowest of heating rates, the initial mixed microstructure of ferrite and pearlite becomes stabilised during heating prior to the formation of austenite. As already described, the stabilisation takes the form of the spheroidisation of the cementite lamellae in the pearlite, together with a shift in the chemical composition of the cementite towards equilibrium.

However, these effects are reduced at intermediate heating rates, since the austenite then forms from an initial (not completely spheroidised) microstructure which has a higher free energy due to the greater interfacial area per unit volume and the non-equilibrium composition of cementite, therefore leading to a decrease in A_{c1}.

At faster heating rates, in which spheroidisation does not have time to occur, austenite grows directly from pearlite. At very fast heating rates, the temperature at which austenitisation starts becomes higher, and the effect of deformation in the kinetics of phase transformation becomes less important compared to overheating.

Experimental procedure:

Sample material:

The composition of the material used in this study is shown in the following Table:

	C	Si	Mn	Cr	Ni	Mo
wt.%	0.54	0.2	0.74	0.20	0.17	0.05

Bars of the alloy were deformed by swaging to a final diameter of 8 mm. The initial diameters were chosen to produce a range of final deformation levels. The calculation of strain assumes constant volume during homogeneous plastic deformation. Up to four different levels of deformation have been studied, including undeformed material (0.0, 0.45, 0.89 and 1.26).

Microscopy and chemical analysis

Samples for scanning electron microscopy (SEM) were etched with 2% nital (2% concentrated nitric acid in methanol). A JEOL JSM-820 scanning electron microscope was used for medium to high magnification imaging using secondary electrons at 20 kV. Chemical analysis was done in a JEOL JSM 5800LV equipped with energy dispersive X-ray spectroscope (EDS) at 15 kV.

Dilatometric tests:

Dilatometric tests were done using a Thermecmastor Z simulator, manufactured by Fuji Electronic Industrial Co. Ltd. All the experiments were done in vacuum ($\approx$ 10^{-2} Pa) to prevent oxidation. Heating rates from 0.1°C s^{-1} to 50°C s^{-1} have been used.

Dilatometry is used to monitor the progress of phase transformations. Phases with different crystalline lattices have different thermal expansion coefficients. The expansion coefficient of a given phase is usually constant. Therefore a plot of dilatation against temperature during heating at a constant rate, for instance, gives a straight line. The slope of the line will be different for each phase, and therefore, deviations from the straight line indicate some phase transformation. Figure 6 shows an example of a typical dilatometric curve in which the start and finish of the transformation from ferrite/cementite to austenite have been highlighted. For this purpose, the actual value of dilatation is not relevant, and only its variation should be taken into account.

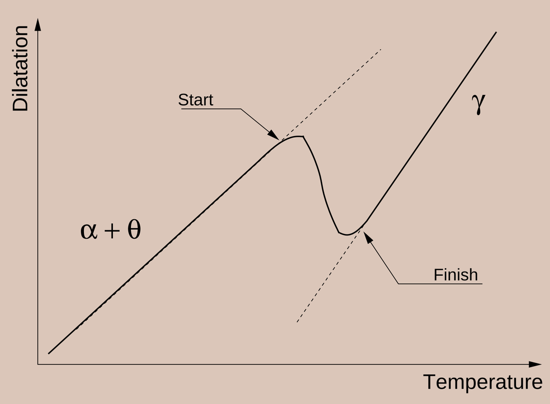

Figure: (6) Schematic dilatometric curve showing the start and finish of transformation from ferrite and cementite ($\alpha + \theta$) to austenite (γ) during constant heating.

Conclusions:

The effect of deformation on the kinetics of austenitisation from a mixture of ferrite and pearlite in a hypoeutectic steel have been characterised. It is found that deformation in general accelerates the transformation rate, and at the same time it reduces the temperature at which spheroidisation of cementite happens and accelerates its kinetics.

Spheroidised cementite is more stable than lamellar pearlite, and thus transformation to austenite from the later proceeds at a faster rate than from the former.

At slow heating rates in deformed materials, spheroidisation occurs and stabilises the microstructure against transformation to austenite. An annealing heat treatment performed at sufficient temperature, given the level of deformation of the alloy, can produce the same spheroidisation effect. At faster heating rates, austenite grows directly from pearlite, as spheroidisation does not have time to occur. At very fast heating rates, the temperature at which austenitisation starts becomes higher, and the effect of deformation in the kinetics of phase transformation becomes less important compared to overheating.

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