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E.M. Lauridsen T. Leffers W. Pantleon, T.J. Sabin and J.A. Wert
Risø National Laboratory, Roskilde, Denmark 2000

MODELLING ANISOTHERMAL RECRYSTALLISATION IN AUSTENITIC STAINLESS STEELS

G. J. Hopkin,* and H. K. D. H. Bhadeshia*

* Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, CB2 3QZ. UNITED KINGDOM.

ABSTRACT

The kinetics of recrystallisation have in the past been represented using the classical "Avrami theory". Some authors have used the theory empirically whereas others have incorporated proper nucleation and growth functions into the Avrami equation. In developing such models, it has commonly been assumed that there is in an initial number density of nuclei which begin growth at the instant the material reaches the isothermal heat treatment temperature. The exponent n in the Avrami equation is then obtained by fitting to experimental data. We present here an Avrami representation of recrystallisation kinetics which avoids this procedure and takes account of the nature of the nucleation sites. This allows a meaningful interpretation of the Avrami exponent; the theory is then adapted to anisothermal kinetics using the Scheil rule.

1. OVERALL TRANSFORMATION KINETICS

The theory for overall transformation kinetics was originally developed by Kolmogorov (1937), Johnson and Mehl (1939) and Avrami (1939); its main feature is the treatment of impingement between different particles via an extended space concept. It was our aim to apply the method to recrystallisation, taking into account some specific details of the nucleation site in order to obtain more physically–meaningful parameters from the analysis. The deformed microstructure is identified as α, the recrystallised microstructure as β; there obviously is no change in composition or crystal structure when α "transforms" to β, simply a change in the defect density. The derivation follows well–established practice: nucleation and growth are allowed to occur throughout the sample, in the first instance ignoring impingement so that the calculated volumes are erroneous, *i.e.,* they are the extended volumes. Assuming isotropic growth at a rate Υ and a constant nucleation rate per unit volume $\dot{N}$, the extended volume fraction of β is given by

$$\zeta_\varepsilon = \dot{N}\pi\Upsilon^3 t^4/3 \qquad (1)$$

A change in extended volume fraction can be related to a change in the real volume fraction by multiplying the former by the probability of finding untransformed α:

$$\delta\zeta = (1-\zeta)\delta\zeta_\varepsilon \tag{2}$$

On substituting equations (1) into (2) and integrating over time, we get:

$$\zeta = 1 - \exp\left(-\dot{N}\pi\Upsilon^3 t^4/3\right) \tag{3}$$

2. GRAIN BOUNDARY NUCLEATION

The derivation presented above assumes that nucleation occurs at random throughout the sample. The role of grain boundaries is, however, paramount in the recrystallisation problem; for example, a classic model of the nucleation of a recrystallised grain involves the formation of a grain boundary bulge. The deformed grain surface can therefore be regarded as the nucleation site. It would be more appropriate to avoid the assumption of random nucleation and implement grain boundary nucleation into the Avrami scheme, as first considered by Cahn (1967).

Nucleation on a grain boundary also involves impingement effects since there can be more than one nucleation site on any given grain face. Cahn considered phantom nucleation on the boundary plane and then applied the same sort of theory to deal with the resulting extended area, as Avarmi did for extended volume. The extended area can be converted into a real area of grain boundary consumed by β using a relationship of the form of equation 2. The extended volume can be obtained by integrating all the areas that a plane parallel to the boundary intersects, from a distance $-\infty$ to $+\infty$ normal to the boundary. The extended volume is then converted into a real volume using equation 2.

If $\dot{N}_B$ is the grain boundary nucleation rate per unit area, and O_B grain boundary area per unit volume, the fraction recrystallised is given by (Cahn, 1967):

$$\zeta = 1 - \exp\left[-(b^B)^{-\frac{1}{3}} f^B(a^B)\right] \tag{4}$$

where

$$a^B = (\dot{N}_B\Upsilon^2)^{\frac{1}{3}} t \tag{5}$$

$$f_B(a_B) = a_B \int_0^1 \left[1 - \exp\left\{(-\pi/3)\left(a^B\right)^3\left(1 - 3\Xi^2 + 2\Xi^3\right)\right\}\right].\mathrm{d}\Xi \tag{6}$$

$$b^B = \frac{\dot{N}_B}{8\left(O_\nu^B\right)^3\Upsilon} \tag{7}$$

$$\Xi = \varrho/\Upsilon t \tag{8}$$

where ϱ is a coordinate normal to the boundary plane. There are two limiting solutions,

firstly when a^B is very small *i.e.* the early stages of recrystallisation when nucleation can be considered to occur at random, giving equation 3. The other limiting solution occurs when a^B is large so that all sites are saturated and nucleation stops early in the transformation, in which case:

$$\zeta = 1 - \exp(-2O_B \Upsilon t) \tag{9}$$

We note that when the Avrami equation is applied empirically, by fitting recrystallisation data to an equation of the form

$$\zeta = 1 - \exp\left(-At^n\right) \tag{10}$$

it is frequently the case the $n = 1$. On the other hand, the Cahn approach actually predicts $n = 1$ given site saturation and has the additional advantage that nucleation and growth are included explicitly. In the present work, which deals with an austenitic stainless steel (302), it is experimentally justified to assume site saturation at an early stage of recrystallisation. Fig. 1 shows that the number of recrystallised grains per unit area, as observed on micrographs, is insensitive to the fraction recrystallised, as would be expected from site saturation.

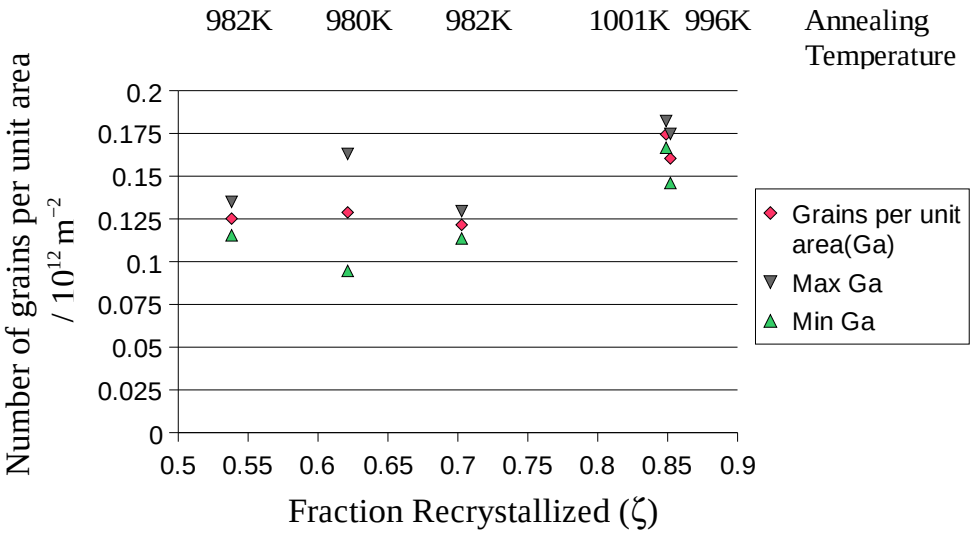

Fig. 1: The variation of number of grains per unit area with fraction recrystallised for samples annealed at different temperatures in a 302 stainless steel.

3. ANISOTHERMAL RECRYSTALLISATION

3.1 Scheil rule. Many industrial annealing processes are anisothermal; stainless steel strip in particular is annealed continuously rather than in batches. To deal with anisothermal annealing, we assume a Scheil rule in which the annealing cycle is treated as a series of isothermal steps, each of magnitude δt. Suppose the first step in this corresponds to a temperature T_1 which in an interval δt_1 gives fraction ζ_1 of recrystallisation. In the next step T_2, transformation begins from zero until it achieves a value ζ_1 and it is then allowed to

continue for a further time period δt_2 to give a total fraction ζ_2. This stepwise calculation is continued until recrystallisation is completed.

For the Scheil rule to be applicable, the reaction must be isokinetic. In other words, all the parameters should have the same temperature dependence. This should be approximately true in recrystallisation since both nucleation and growth essentially are controlled by the motion of the grain boundary. It should be precisely true once site saturation occurs.

4. EXPERIMENTAL METHOD AND RESULTS

Samples of 0.8 mm gauge 302 stainless steel supplied by Avesta Sheffield Ltd. were cut into 1 cm squares, welded onto a type K thermocouple and inserted into a chamber furnace through a chimney in the roof of the furnace to avoid fluctuations in bulk furnace temperatures. The temperature was measured and recorded throughout the heat treatment, for each sample. Samples were mounted, polished and electro-polished, then observed on the plane parallel to the rolling direction using channelling contrast of backscattered electrons on a CamScan S2 scanning electron microscope. The accelerating voltage used was 15 kV at a working distance of approximately 9 mm, the sample was kept normal to the electron beam and the backscatter detector was mounted directly above the sample. An example micrograph is give in Fig. 2 Samples were analysed using a Seescan image analyser from which recrystallised

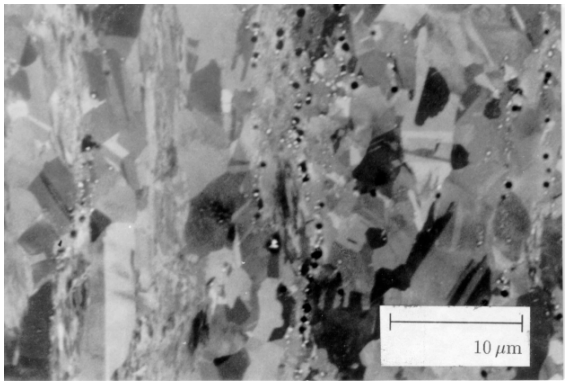

Fig. 2: Micrograph showing a partially recrystallised sample of 302 stainless steel annealed for 600 s at 982 K

grain sizes and fractions recrystallised were measured. The results are listed in Table 1. These data were used to train a model based on anisothermal Cahn kinetics.

Included in Fig. 3 is a comparison of model output and experimental data. Standard calculations for growth and nucleation rates were used, based upon atoms jumping across a boundary and grain boundary bulging respectively. All calculations are anisothermal for samples of thickness 0.8mm entering a furnace at 982 K.

5. CONCLUSIONS

It is found that using an Avarmi type equation but with Cahn's grain boundary nucleation, gives physically meaningful time exponents. The value of the Avrami exponent is predicted to be unity once site saturation occurs. This is consistent with empirical data in

Table 1: Table of experimental results from a type 302 stainless steel

Furnace Temperature T_f / K	Annealing time t / s	Fraction recrystallised ζ	Grain size / μm
980	660	0.62 ± 0.18	0.98 ± 1.32
982	1200	0.70 ± 0.24	1.08 ± 0.16
982	600	0.54 ± 0.24	1.41 ± 0.36
996	615	0.85 ± 0.14	1.31 ± 0.06
1001	660	0.85 ± 0.14	1.21 ± 0.10
1073	30	0.12 ± 0.12	1.92 ± 0.82
1083	45	0.84 ± 0.14	1.41 ± 0.62

the published literature. The model was then adapted for recrystallization during continuous heating using the Scheil rule, and was observed to given reasonable agreement with experimental data after fitting to isothermal data.

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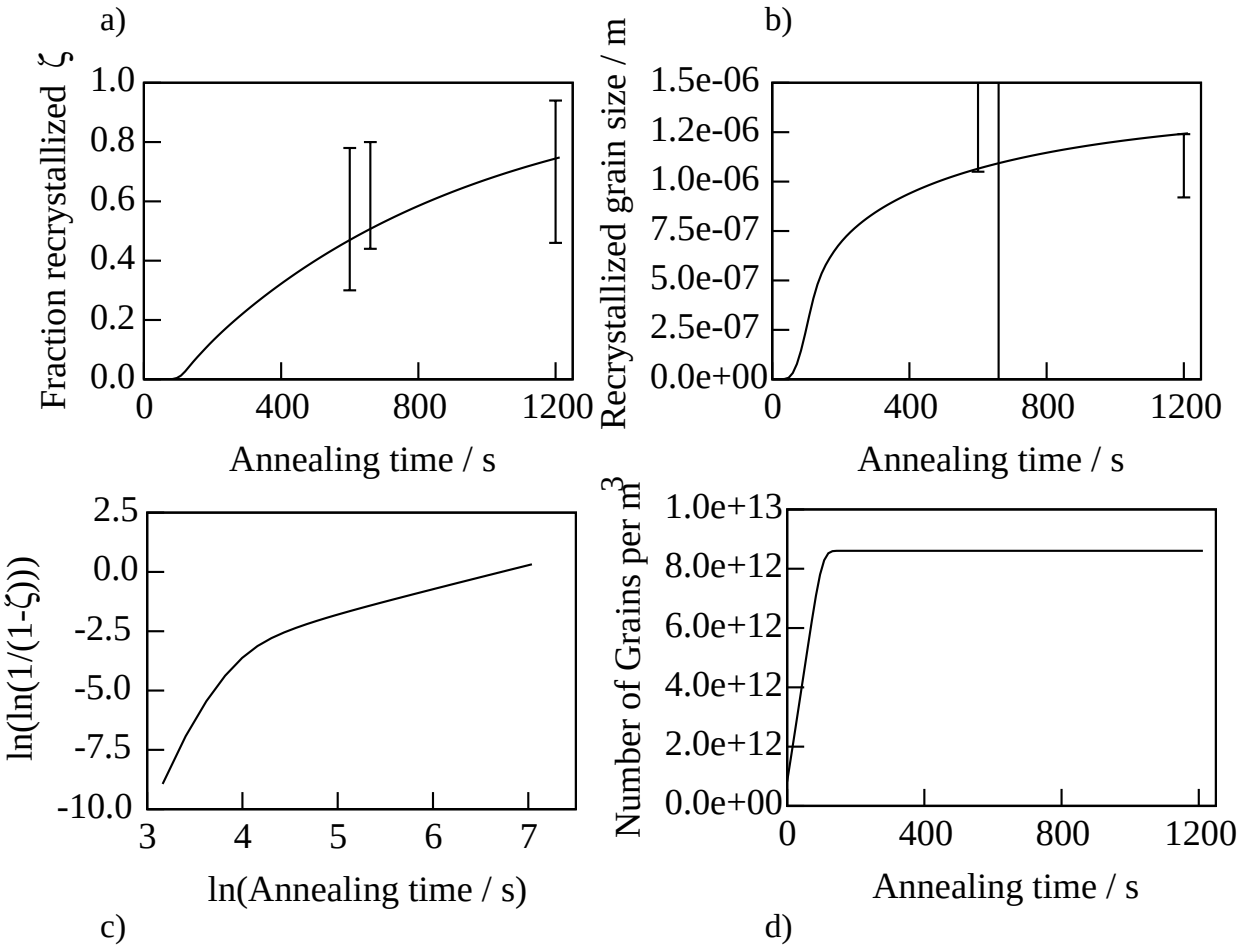

Fig. 3: Example outputs generated using the overall transformation kinetics model, for a 0.8 mm gauge sample in an anisothermal anneal with a furnace temperature of 982 K: **a)** Variation in the fraction recrystallised with time. **b)** Variation of recrystallised grain size with time. **c)** 'Avrami plot' of $\ln(\ln(1/(1-\zeta)))$ against ln(time) the slope of which yields the value of the Avrami exponent n; note that the slope in this case changes from an initial value of 4 to a final value of 1 before the observable onset of recrystallisation. **d)** The variation of the number of recrystallised grains with time - levelling off indicating site saturation has occurred.