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Effect of slight deformations on grain growth in iron

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The influence of slight deformations on grain growth after primary recrystallization has been investigated in pure iron specimens. A stage of abnormal growth is always observed in the range of deformations studied (about 2 to 10% in tension), whilst the absence of deformation leads to normal growth. Some kinetic considerations are made, on the basis of current theories.

1. Introduction

In a previous paper [1], some conditions affecting grain growth after primary recrystallization were given, and a first attempt to study the kinetics of the process was undertaken. In particular, concerning the effect of slight deformations on grain growth, a critical value for secondary recrystallization in pure iron was found (about 2%), depending on initial grain size and annealing temperature. Above this limit, the essential feature of abnormal grain growth was observed only within a narrow strain range (about 5%); for higher deformations, the growth was so rapid that the entire process was found to be almost completed even at the lowest annealing times.

The aim of the present work was to give more detailed information on the kinetic features of growth after elongations of less than 10%, by using suitable temperature ranges and annealing times at which the different stages of growth can be observed for all the deformations studied.

2. Materials and methods

High-purity iron ($\geqslant$99.998%), from Koch-Light Ltd, was used for the present research. Two series of specimens were previously prepared, by cold working and subsequent annealing at different temperatures to complete primary recrystallization. The specimens of batch (a) were obtained in the form of square rods, 50 mm long, $5 \times 5\,mm^2$ cross-section, with a mean grain size of about 50 μm. For batch (b), square rod specimens of the same length were prepared, $3 \times 3\,mm^2$ in cross-section, with a mean grain size of about 200 μm.

In both series, after slight plastic deformation in tension of about 2, 5 and 10%*, secondary growth was investigated using isothermal anneals at 690° C, for increasing times. The temperature was chosen on the basis of preliminary results obtained from isochronal treatments of specimens prepared in the same manner.

The anneals were performed in a quartz tube (with a protective H_2 atmosphere) maintained at the chosen temperature; the specimens were introduced into the hot zone using a technique which allows the temperature to be reached within a few seconds.

After each anneal, micrographs were taken of the sample surface, and the mean linear grain size was obtained by the intercept method.

3. Results and discussion

Fig. 1 (log scale) shows the evolution of the main grain diameter† as a function of annealing time for the different amounts of cold working and for the two different series of specimens.

Two typical trends are observed for deformed and undeformed samples, respectively. The grain growth of all the strained samples, as is well known, occurs in three stages: the first where a small or null average growth is observed; an inter-

*One specimen was undeformed.

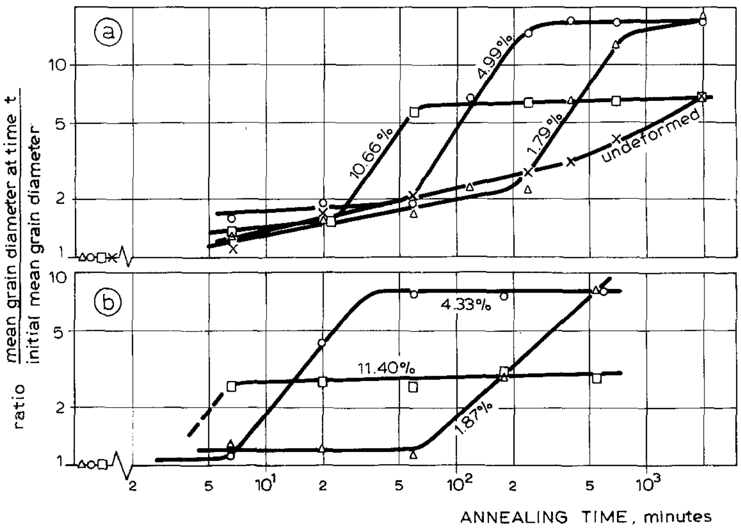

Figure 1 Isothermal grain growth at 690° C for two different series of tension strained specimens. Amounts of deformation are indicated.

mediate stage of rapid growth, where the typical feature of the abnormal growth of few grains clearly appears (see Fig. 2a, b and c); and a final stage with negligible increase in grain size.

On the other hand, the mean grain size of the undeformed sample shows a regular continuous variation throughout the annealing time, thus confirming the basic characteristics of "normal" growth (see Fig. 2d).

In deformed specimens, the initial stage of almost complete inhibition of growth may be attributed to the restraining effect exerted on boundary motion by the partially polygonized structure introduced by slight deformations. The higher the amount of deformation, the shorter the period of inhibited motion preceding the stage of rapid growth. This confirms the results previously obtained [1] and may be similarly interpreted as being due to effects of primary recrystallization, the importance of which grows when the amount of deformation increases. Primary recrystallization effects, in this range of slight deformations, do not involve a true nucleation and growth process, but only supply an additional driving force originating from the energy stored after plastic deformation; this shows up in the lattice essentially with a locally inhomogeneous distribution of the defects introduced by deformation. After this "incubation period", the evolution of growth becomes controlled essentially by the reduction of total surface energy of the grains.

The occurrence of local processes controlled by the driving force of primary recrystallization may also account for another feature of the results, i.e. the final sizes reached by samples strained to different extents: larger sizes are, in fact, attained by less deformed specimens, as is generally recognized. The introduction of higher amounts of plastic strain enhances the probability of occurrence of regions with a higher defect concentration, where incubation of the nuclei for secondary recrystallization is favoured; higher strains lead, therefore, to higher numbers of nuclei, and to a lower final grain size.

The present results, partially inconsistent with previous work [1], do not indicate a critical deformation, below which grain growth does not occur. In our case, one can observe the initiation of abnormal grain growth whatever the amount of deformation introduced for all samples. The existence of such a critical value of deformation was probably inferred from results obtained at temperatures not high enough to produce grain growth after reasonably long annealing times.

The differences between the two batches of specimens should not be attributed primarily to their different mean grain sizes. The different pretreatments used in the preparation of the samples are probably responsible for their different behaviour as regards the length of their incubation periods. This does not seem, however, to have affected the dependence of secondary growth features on the amount of deformation, as discussed above.

†Relative conventional units (initial mean grain diameter = 1).

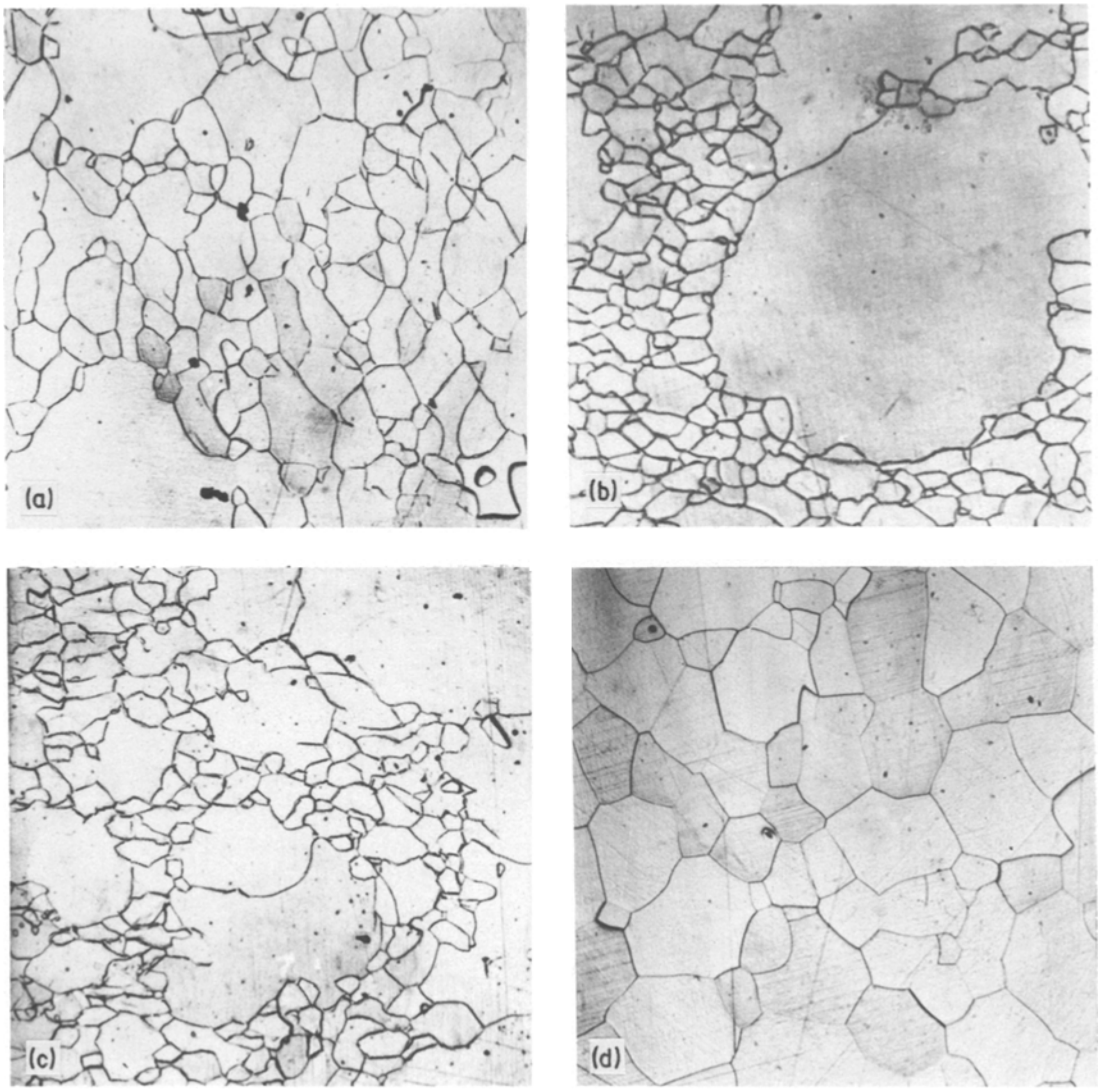

Figure 2 Micrographs of samples, showing different stages of grain growth during isothermal annealing at 690° C. (a) Elongation: 1.79%; anneal: 240 min; (b) elongation: 4.99%; anneal: 60 min; (c) elongation: 10.66%, anneal: 20 min; (d) undeformed; anneal: 240 min. × 50.

A more quantitative examination of the present results may be attempted. The slopes of the kinetic curves (log scale) may be grouped in three ranges, which are sharply distinguished: (a) slopes within the range 0 to 0.10, characterizing initial and final stages for the specimens undergoing abnormal grain growth: (b) a nearly constant slope of about 0.25 for the only sample showing normal grain growth; (c) slopes ranging from 0.9 to about 1.4 for the stage of rapid abnormal growth situated between the initial and final stages mentioned at point (a).

This numerical pattern may be examined from the standpoint of current kinetic theories for secondary growth [2–4].

In a simplified form, assuming that the driving force, p, of the process depends on grain size, D, according to:

$$p = \alpha/D, \tag{1}$$

where α is a coefficient dependent on interface energy and on form factors, and further assuming that the velocity of the boundary, expressed as $\mathrm{d}D/\mathrm{d}t$, is proportional to the driving force (through the mobility coefficient, m)

$$\mathrm{d}D/\mathrm{d}t = mp, \tag{2}$$

one can obtain

$$\mathrm{d}D/\mathrm{d}t = \alpha m/D. \tag{3}$$

By integration of Equation 3 we obtain:

$$D^2 - D_0^2 = \alpha m t. \tag{4}$$

If D_0 is negligible with respect to D, Equation 4 becomes:

$$D = kt^{0.5}, \tag{5}$$

where $k = \sqrt{(\alpha m)}$.

It is known that in the real processes of normal growth, the exponent is commonly found to be less than 0.5; the expression

$$D = kt^n \tag{6}$$

is thus generally used. The value $n = 0.25$ obtained for the specimen undergoing normal growth is quite satisfactory.

More attention will be now given to the value of the exponent n (i.e. the slope in logarithmic diagram) for the stage of rapid abnormal growth. This stage gives slopes which can only be approximately determined but which fluctuate around the value of 1. This value, i.e. the exponent n in Equation 6, if confirmed by successive tests, should involve a linear dependence of D on annealing time. The velocity of growth, dD/dt, would thus be found to be constant and not dependent on time and, therefore, neither on growing grain size. This would appear inconsistent with Equations 1 and 2, but the actual structural peculiarity of abnormal growth may explain the discrepancy. In fact, this type of process which occurs through growth of a few very large grains at the expense of the remaining small ones is quite different from what happens during normal growth, in which an increase of mean grain size takes place in a continuous statistical competition among all the grains.

In our case, therefore, the driving force, p, should be provided by the large difference in size between the few large grains and the remaining small ones; this difference would not be seriously reduced during most of the growth process, thus allowing the driving force to remain practically constant.

4. Conclusions

(1) Slightly deformed samples, elongated by 2 to 10%, exhibit a stage of abnormal grain growth, regardless of the amount of strain; on the other hand, normal growth is observed in the undeformed sample.

(2) The higher the amount of strain, the lower the incubation period prior to abnormal growth.

(3) Higher final grain sizes are attained by less deformed samples.

(4) The exponent n in the kinetic equation is 0.25 for normal grain growth; values of n around 1 are obtained in the stage of abnormal growth.

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