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THE STRUCTURE EFFECT ON SELECTIVE GROWTH IN RECRYSTALLIZATION

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Abstract: The effect of the dependence of grain boundary mobility on misorientation angle and that of structure of the matrix on the growth selectivity during primary and secondary recrystallization are discussed. It was found that the longer is the distance travelled by the growing grain boundaries and the wider the range of the misorientation angles between the new grains and the matrix, the less is the difference between the grain boundary mobilities of the growing grains, necessary for the manifestation of growth selectivity. So during secondary recrystallization the latter is more manifest. In primary recrystallization after moderate deformations, the growth selectivity will be the least obvious when the deformed matrix consists of small differently oriented areas at whose borders new grains nucleate simultaneously. The secondary grain boundaries should be characterized by "effective" mobility, which depends on the number of the adjacent grains and their dimensions, as well as on the growing grain misorientation in relation to these grains. In the small grained material without a texture, the effective boundary mobilities of any grains are equal, and so the growth selectivity in such a material is non-existing.

Although a great number of experimental date demonstrate the validity of oriented nucleation and selective growth theory, some authors still believe that during recrystallization the texture develops either by oriented nucleation or by selective growth. Apparently, this can be explained by experimental conditions (purity, structure and texture of the studied samples, mode and degree of cold deformation, the way of nucleation of new grains or the initiation of growth of existing grains, and the recrystallization anneal conditions) under which one of the aspects of the texture formation mechanism is manifest. Our aim is to give a thorough examination of the specific structural features affecting growth selectivity, hence the texture development, during the course of primary and secondary recrystallization.

It is common knowledge that different growth rates of various grains are characteristic of selective growth and may depend both on the driving force and on the grain boundary mobility. As deformed matrix areas of different orientations vary in strain energy (see e.g. Ref. 1), the primary grains consuming the areas may grow at different rates. In secondary recrystallization the driving force can vary, depending on the size, dislocation density or free surface energy of the grains; these affect their growth rate. However, we are not going to analyze the growth selectivity caused by the orientation dependence of the driving force. The only subject of our investigation is selective grain growth due to different grain boundary mobilities. This approach to the subject, being limited as it is, will help us to stress the main trends.

According to P. A. Beck[2], "pure" growth selectivity is clear from the fact that grains with greater boundary mobility will grow faster during the anneal, resulting in an increase in their relative volume, hence the corresponding texture components. The grain boundary mobility depends on the angle and axis of misorientation, as well as on the boundary type.[3]

So far there have been just a few experiments on the boundary-type effect on its mobility.[4,5] The results indicate that tilt boundaries migrate faster than do twist boundaries when misorientation parameters are alike. However, it is not quite clear just what causes the grain shape anisotropy: the dependence of boundary mobility on the type of the boundary[5], or the dislocation arrangement in the deformed metal.[4] In matrix with strong texture, the driving force for secondary recrystallization is by 3 orders of magnitude less than the driving force for primary recrystallization, so the effect of the boundary type on its mobility is supposed to be revealed more strongly in the former. Nevertheless, there is no experimental evidence to support this. Probably it can be explained by the fact that, as a rule, a growing grain has a boundary of one and the same--mixed--type all along.

There is so far very little systematic information about the dependence of grain boundary mobility on the misorientation angle. Our analysis will be based on the results[6,7] obtained for the wide range of misorientation angles in strictly controlled conditions of boundary geometry, impurity content and driving force value. According to these studies,[6,7] the activation energy for tilt boundary motion is practically independent of the misorientation angle, ranging from 35 to 90° <1010> for zinc 99.998 at % purity and from 20 to 45° <100> for aluminum 99.98 at % purity. However, no matter how much the activation energies for migration differ, this can give rise to significant differences in grain boundary mobilities. So we can come to the conclusion that the changes in mobility within the misorientation range, where the boundary motion activation energy is approximately constant, are not so great as those within the whole misorientation range, where the activation energy is strongly dependent on misorientation. At a low impurity content cusps are known to exist in the mobility vs misorientation plot.[3] However, as has been shown[7], the increase of the impurity content up to the value characteristic of commercial material causes considerable decrease in the mobility of "special" boundaries, and high-angle boundaries with extraordinarily great mobility are ceasing to exist.

As far as the dependence of mobility on the axis of misorientation is concerned, experiments on f.c.c. metals, for instance, show that high-angle boundaries with <111> rotation axis have greater mobility than the others.[9] True, it is yet not possible to compare the mobilities of grain boundaries with equal misorientation angles when the axes are not identical. At the same time, on the basis of the results[10,11], we draw the conclusion that the mobility of mixed high-angle boundaries is not very much dependent on the misorientation axis.

According to the aforementioned results, the ratio of the crystallite growing rates during primary recrystallization in commercial purity material is mainly dependent on the range of misorientation angles between the spontaneously nucleated grains and the deformed matrix. Judging by the results[12,13] all these grains have high misorientation angles. Therefore, when in some areas of the deformed matrix the grains with high misorientation angles nucleate and consume the adjacent matrix, the mobility of the boundary does not so much affect the growth of the grains as in the case of the grains having various misorientation angles with the matrix.

We will consider now how the structure of the matrix affects selective grain growth. The experiment[14] demonstrating the existence and the prevailing role of growth selectivity during primary recrystallization seems to be the most convincing. Grinding of the upper surface of the rolled crystal with the subsequent annealing causes the formation of new grains which lack preferred orientation.[14] After these grains have grown and reached the lower surface, the annealing texture was found on this surface. It is worthwhile to note that the new grains were nucleated simultaneously and that the deformed crystal had a single-component texture[14], i.e. during the entire period of the primary recrystallization the difference in the growth rate was continually maintained.

As a rule, however, deformation texture has a number of components even within one grain[15], except for some cases of deformation of single crystals with specific orientation. In the deformed metal having areas of different orientations, the new grains will have different orientation relationship with these areas. In this case, only the recrystallized grains having high mobility boundaries with respect to all the areas of the deformed matrix might have the maximum growth velocity.* But will the new grain have enough time to grow through a number of deformed matrix areas with different orientations before the impingement on other new grains? We don't think it inevitable.

Actually, recrystallized grains do nucleate during the anneal mostly near the grain boundaries or second phase inclusions, at transition bands, near Neumann bands and so on, i.e. in the regions which, except for the interphase boundaries, border the areas of deformed material belonging to different texture components. So the new grains nucleated at the borders of those differently oriented areas can consume only the closest areas as some further area borders may be already occupied by other new grains which will prevent the first ones from growing. The situation will be quite different when the recrystallized grains do not nucleate simultaneously.** Those earlier nucleated may have enough time to consume the deformed matrix regions where the induction period of nucleation is longer. In this case the conditions for the growth selectivity are expected to be more favorable. In case the induction periods of nucleation

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* The compromise annealing texture theory[3] is based on these ideas.

** Differences in induction periods of nucleation can depend not only on the deformed material structure but also on the annealing conditions[16] and on the precipitation occurring along with primary recrystallization.[1]

in the aforementioned regions are approximately equal the compromise texture theory can hardly be applied to the annealing texture development in material with multi-component deformation texture. The growth selectivity during primary recrystallization may be fully manifest only when the deformed grains have no regions similar to Neumann or deformation bands where the deformed grain orientation changes greatly. The greater are the dimensions of the deformed material areas having single component orientation, the greater will be the manifestation of growth selectivity.

Let us estimate what difference should exist between growth rates, V_1 and $V_2 (V_1 > V_2)$ of two grains starting to grow simultaneously, so that their radii ratio, R_1/R_2, might be k. Let the grains have a spherical form, the initial radii being r; and let the grains grow without any mutual hindrance (Figure 1a). Figure 2a gives the dependence of V_1/V_2 on R_1/r for different values of

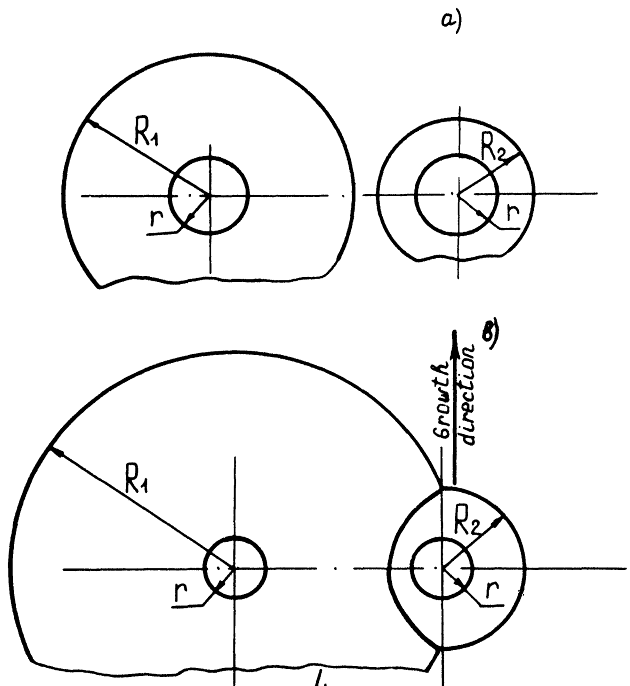
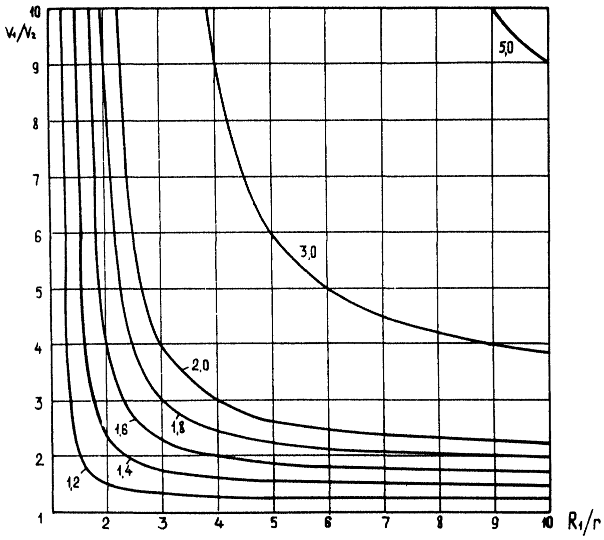
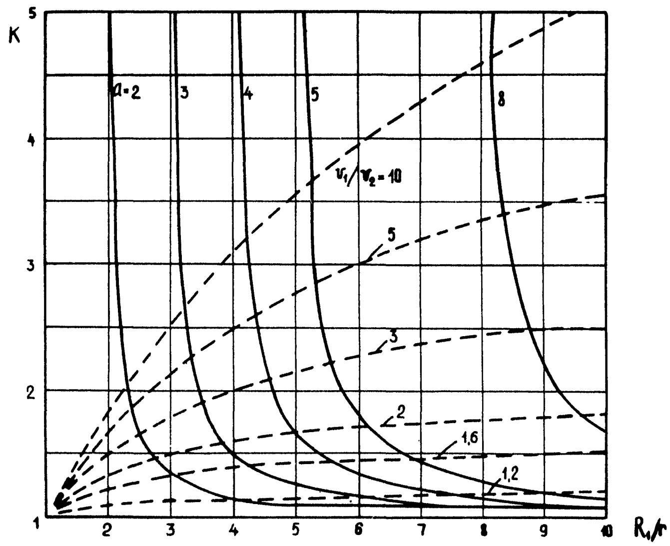


FIGURE 1. The arrangement of two grains growing at rates V_1 and V_2 $(V_1 > V_2)$: (a) without any contact between the grains; (b) with a contact. r = initial radius of grains; R_1 and R_2 = final radii of grains.



2(a)



2(b)

FIGURE 2. (a) The dependence of V_1/V_2 (necessary for getting a certain value of $k = R_1/R_2$) on the size of faster growing grain, R_1/r (see Figure 1a) (b) The dependence of $k = R_1/R_2$ on R_1/r for different values of V_1/V_2 (broken lines) and that of k on R_1/r for different values of $a = L/r$ (see Figure 1b). These relations help to determine the conditions under which the contact of two grains will prevent one of them from growing.

k. It can be seen that the greater is the distance, R_1, swept by the boundary of the grain with a higher growth rate, the smaller will be the difference between V_1 and V_2 for a given value of the two grain radii ratio, k. If the relation $k = R_1/R_2 = 2$ is assumed to indicate growth selectivity manifestation, then the grain with the greater boundary mobility will grow 9 times faster at $R_1/r = 2$ and only about 2.3 times faster at $R_1/r = 10$.

Now, the contact of two grains growing in one direction (Figure 1b) is to be considered. The grain with greater boundary mobility will prevent its neighbor from growing further. Let us assume that initially the grains are at a distance L. Figure 2b shows full line curves for $k = f(R_1/r)$ at different values of $a = L/r$, when the grain growing faster has fully prevented its neighbor from further growing in the direction indicated in Figure 1b. The broken curves show the relation of $k = \phi(R_1/r)$ found from the data of Figure 2a for different values of V_1/V_2. The points of intersection of the two families of curves allow us to determine the conditions under which the contact of the neighboring grains will lead to the termination of one of the neighbors' growth. With k being constant, the smaller is R_1 by the moment this happens, the greater is V_1/V_2 ratio, and the smaller the distance, L, between the two grains.

According to a great number of data on primary recrystallization the primary grain nucleus increases 3 to 20 times while growing. If we take the value of $R_1/r = 10$ typical of the material after moderate deformations, then as Figure 2b shows, to obtain $R_1/R_2 = 2$ the ratio of the boundary mobilities of two neighboring grains nucleated simultaneously should be 10 to 2.5, depending on their initial distance. Since in secondary recrystallization the grain diameter increases by 3 orders of magnitude as compared to the initial one the boundary mobilities ratio should not be so great as in primary recrystallization to achieve a noticeable growth selectivity. Since the grains do not start growing simultaneously, the values of V_1/V_2 which make growth selectivity noticeable will change. However the main trend remains unchanged: the longer the competition distance of the growing grains the more obvious the growth selectivity.

Thus the selective growth during primary recrystallization depends not only on grain boundary mobilities, but also on the dimensions and arrangement of the deformed matrix areas belonging to different texture components, and on the relative length of the regions where the recrystallized grains nucleate as well as on their induction periods.

What are the structure features that affect the growth selectivity during secondary recrystallization?

It is difficult to analyze the selective growth during secondary recrystallization since the secondary grain is surrounded by crystallites with different orientations and therefore its misorientation with each adjacent crystallite is not the same. So the secondary grain boundary has various angles and axes of misorientations at different parts of the boundary and therefore a certain "effective" mobility may be assumed to characterize it. In the matrix without texture any grain misorientation relative to its neighbors is on the average the same. When the matrix has texture, any grain misorientation relative to its neighbors depends on how much its orientation differs from that of the latter. As is clear, the effective boundary mobility in the first case will be equal for all the grains and so in the matrix without texture the growth selectivity is impossible. In the second case, the effective mobility of growing grain boundary will be greater if the grain orientation differs from that of its neighbors a great deal, and if it has few neighbors with an orientation similar to that of its own. Our estimate[17] shows that in the weakly textured matrix, differently oriented grains have boundaries with various effective mobilities.

In a secondary recrystallization matrix with texture the grains having different orientations can be arranged irregularly (we will call this type of matrix "homogeneous") or in groups ("non-homogeneous" matrix). The latter arrangement occurs when a secondary recrystallization matrix is formed after deformation and annealing of the coarse grained material. In the homogeneous matrix the effective boundary mobility of the secondary will be more or less constant; in the non-homogeneous one it should change with boundary migration. However, in the matrix with multicomponent texture, the crystallites, whose effective boundary mobility is large enough in all the components of matrix texture, will grow no matter whether the matrix is homogeneous or not. This is due to considerable increase in secondary grain dimension which results in the grain getting into contact with all matrix texture components. At the same time the secondary grain can be expected to grow faster in a homogeneous matrix rather than in a non-homogeneous one. The fact is that an obstacle such as a crystallite with unfavorable misorientation will be overcome by secondary grain boundary more easily* than an obstacle in the form of a group of crystallites having low misorientations or twin relations with the secondary grain.

* Such crystallites become included grains.[18]

Besides the texture of secondary recrystallization matrix and the arrangement of differently oriented grains, the effective boundary mobility should also depend on the secondary grain dimensions. If the secondary grain size is relatively small, then the number of adjacent matrix grains will be rather small too, and there will be a rather high probability of difference between the orientation of these grains and the preferred matrix orientation. Therefore, the effective mobility of small secondary grain boundary will differ from the same grain boundary mobility when this grain gets larger.

It is also interesting to note that the effective mobility of secondary grain boundaries should be related to the dimensions of matrix grains with different orientations. If the grains of some component of the matrix texture happen to be larger than other component grains, the probability of contact between the large matrix grains and the secondary grain decreases, hence the influence of the abovementioned texture component on the effective mobility of the secondary grain boundary reduces.

CONCLUSIONS

1. The longer the distance swept by the moving boundaries the more manifest is the growth selectivity due to different grain boundary mobilities. So in secondary recrystallization when the grain linear dimension increases by about 3 orders of magnitude, the growth selectivity is more manifest than in primary recrystallization when the nucleus diameter does not grow more than by one order of magnitude.

2. The larger the deformed matrix areas with a single component orientation and the wider the range of the misorientation angles between the new grains and the matrix, the more manifest is the growth selectivity at primary recrystallization. The growth selectivity in a material with single component texture achieves its maximum, which depends on the number of new grains.

3. The primary recrystallization in the deformed material with multicomponent texture and with the structure of small differently oriented areas results in the nucleation of grains with high misorientation angles relative to the adjacent matrix and with high mobility boundaries. If the induction periods of grain nucleation are approximately equal, then the conditions for growth selectivity are the least favorable. With unequal nucleation induction periods, the growth selectivity is more manifest which leads to the compromise texture formation.

4. The growth selectivity in secondary recrystallization is related to the texture of the small grained matrix being consumed. In a matrix without a texture

the growth selectivity is non-existing.

5. The growth selectivity in secondary recrystallization is determined by the effective boundary mobility of the growing grain which depends on the misorientation between the growing grain and all the components of the matrix texture, and on the arrangement and dimensions of the differently oriented matrix grains, as well as on the growing grain dimensions.

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