On the Formation of Austenite Grains from Prior Martensitic Structure

By Seiichi WATANABE** and Tatsuro KUNITAKE**

Synopsis

Electron microscopic studies have been made of austenite partially transformed from prior martensitic structure in the temperature range between \( A_c_1 \) and \( A_c_3 \). It has been found that each acicular austenite grain which has been formed from ferrite laths with the same orientation has the same crystallographic orientation and the austenite has the Kurdjumov-Sachs orientation relationship with the ferrite. The both lath boundary and cementite play an important role in the formation of acicular austenite grains, with the same orientation. When austenite is formed adjacent to precipitated cementite on the boundary, the austenite must have Pitsch orientation relationship with cementite and the Kurdjumov-Sachs orientation relationship with ferrite.

Consequently, the variant of formation of austenite is limited to only one, so that acicular austenite grains are identically oriented with each other. When the specimen is heated over \( A_c_2 \) after acicular austenite structure has sufficiently been developed, coarse austenite grain structure is formed from the prior coarse \( \gamma \) grain structure.

It is observed that a coarse austenite grain does not consist of a single crystal grain but consists of several divided regions, each of which is corresponding to recovered ferrite regions which have been formed by the recovery of lath martensite during heating.

I. Introduction

Many researches have been made on the acicular austenite grains which are formed from lath ferrites (\( \alpha \)) such as low carbon martensite or bainite when they are slowly heated over \( A_c_1 \) temperature. Those results are summarized as follows:

1) At the beginning of austenitization, the shape of \( \gamma \) grain principally depends upon prior microstructures. When they are martensite or bainite, the \( \gamma \) grains formed are acicular and appear to be bounded by ferrite lath boundary.\(^{1-3}\)

2) Slowly heated to be austenitized from lath ferrite such as martensite and bainite, a coarse \( \gamma \) grain often forms which looks like succeeding to the prior grain even at low austenitizing temperature.\(^{4}\)

3) It is observed by optical microscopy that the acicular \( \gamma \) grains formed at the beginning of austenitization look like having almost identical crystallographic orientation each other.

In order to stabilize the acicular \( \gamma \) grains over comparatively higher temperature range between \( A_c_1 \) and \( A_c_3 \), it is necessary that carbides prevent the lath boundary from migration.\(^{1,3-5}\)

(4) D'Yachenko, et al.\(^6\) studied the austenitizing process by high temperature X-ray technique and found that there appeared a striking texture maxima over \( A_c_1 \) temperature in the case of slow heating and the orientation relationship between \( \gamma \) and \( \alpha \) satisfied the Kurdjumov-Sachs relation. Heated above 880 \( ^{°}C \), this texture maxima disappeared. In the case of fast heating rate there appeared no texture maxima.

(5) Recently two kinds of mechanisms were proposed about this phenomena.\(^7-10\)

(i) Because the transformed acicular \( \gamma \) grains satisfy K-S orientation relationship with \( \alpha \) and have an identical crystallographic orientation relationship even at different locations, their transformation must of necessity be diffusionless.\(^{8}\)

(ii) As the acicular \( \gamma \) grains appear to be confined in the \( \alpha \) lath, the growth to the neighboring lath is made by the mechanism of resonance nucleation transformation over the existing acicular \( \gamma \) boundary.\(^7,9\)

The present authors have observed the \( \alpha \rightarrow \gamma \) transformation by electron microscopy and discussed the reason for identically oriented formation of acicular \( \gamma \) grain and studied the condition for the coalescence of the acicular \( \gamma \) grains to succeed the prior \( \gamma \) grain.

II. Experimental Procedure

1. Materials

The steels were air-melted in an induction furnace having a capacity of 100 kg. The chemical compositions of the steels are listed in Table 1. The ingots were forged to a plate of 13 mm in thickness in the temperature range of 900\(^°\) to 1 200\(^°\)C. Specimens 10\( \times \)10\( \times \)3 mm were machined from plates to be subjected to heat treatments. \( A_c_1 \) and \( A_c_3 \) temperatures of these steels were measured by dilatometer. Steel A: \( A_c_1=720^°\)C, \( A_c_3=859^°\)C, Steel B: \( A_c_1=600^°\)C.

Table 1. Chemical composition of specimens (wt%)

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>N</th>
<th>sol Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.13</td>
<td>0.25</td>
<td>0.76</td>
<td>0.004</td>
<td>0.008</td>
<td>0.19</td>
<td>0.98</td>
<td>0.55</td>
<td>0.51</td>
<td>0.007</td>
<td>0.056</td>
</tr>
<tr>
<td>B</td>
<td>0.40</td>
<td>0.12</td>
<td>—</td>
<td>0.004</td>
<td>0.007</td>
<td>—</td>
<td>9.16</td>
<td>—</td>
<td>—</td>
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</tr>
</tbody>
</table>

100 kg air melt


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*** The term 'acicular' is used here as it appears in the two dimensional section under the microscope.
2. Heat Treatment

Specimens were transformed completely to martensite by quenching from 1300°C in order to obtain the prior lath structure. Subsequent heat treatments were as follows: (Fig. 1)

Heat treatment (a): Heated at temperature between AC1 and AC3 for appropriate periods, specimens were quenched to observe the traces of austenitized structure.

Heat treatment (b): After heated at temperature between AC1 and AC3, specimens were heated over Ac3 so that completely austenitized and quenched to observe the γ grain structure. Heating rate of these heat treatments was 200°C/min.

Metallographic studies were made by optical microscope and Hitachi electron microscope of accelerating voltage 200 kV using a technique of direct observation of thin foils.

III. Experimental Results

1. Formation and Growth of Austenite from Martensite Structure

Photograph 1 shows microstructure of steel A water-quenched from 1300°C. Almost entire region in a γ grain transformed to martensite on the only one habit plane and formed a bundle of martensite laths. Each bundle consists of aggregates of two parts which are darkly or lightly etched respectively and have different crystallographic orientation relation.11,12) Prior austenite grain boundaries are observed as sharp lines.

Microstructures subjected to heat treatment (a) are shown in Photo. 2. Photograph 2(a), which is heated at 730°C shows that cementsite line in rows and fine precipitates-like γ form along martensite lath boundaries. In Photo. 2(b), heated at 775°C, precipitates-like γ grows up to elongated grains and impinging elongated γ grains coalesced to one globular grain. There appeared no boundaries in a coalesced globular grain. In Photo. 2(c), heated at 830°C, no traces of ferrite lath appear and equiaxed γ grains exist. These results are summarized in Table 2. Table 2 indicates that in the low temperature range of AC1 to AC3, fine elongated γ grains formed but in the higher temperature range equiaxed grains formed. In the lower temperature range from AC1 to AC3, ferrite laths didn't recrystallize but recover and grow up to coarse ferrite. Photograph 3 shows recovered...
and grown up ferrites. These grown-up coarse ferrites are considered to be respectively corresponding to darkly or lightly etched parts of martensites in Photo. 1, which have same habit plane but different crystallographic orientation relation and consist a bundle of martensites. It is supposed that there remain the effects of martensite laths, because inside of these recovered ferrites elongated $\gamma$ formation is observed along the martensite laths.

As shown in Photo. 4, $\gamma$ grains also formed on the prior grain boundaries. They are equiaxed and similar to the grains, as shown in Photo. 2(c), formed when heated at 830°C. Within the grains, elongated $\gamma$ appeared along martensite lath, but on the boundaries the equiaxed globular grains formed.

Photograph 5 shows the electron microstructure of steel A which was quenched from 750°C. It is supposed that Fe$_3$C partly dissolved into solution and acicular $\gamma$ were enriched with C because twinned martensites which are characteristic of high C martensite are observed by following quenching. From this photograph, acicular $\gamma$ grains which have been supposed to be confined in ferrite lath are recognized to be corresponding to the martensite lath. Undissolved cementites remain on the lath boundaries and it is supposed that acicular $\gamma$ nucleates on these Fe$_3$C, in contact with lath boundaries. In the lower temperature range in which acicular $\gamma$ transforms, cementites always exist on lath boundaries.

As steel B contains 9% of Ni, acicular $\gamma$ which is formed by applying heat treatment (a) is stable at

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Microstructure</th>
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| 730°C       | 1. Precipitates-like austenite along $\alpha'$ lath boundary  
              2. Cementites along $\alpha'$ lath boundary  
              3. Recovered ferrite                               |
| 775°C       | 1. Elongated austenites along $\alpha'$ lath (acicular)  
              2. Grown up globular austenite  
              No boundary is observed in globular austenites.    |
| 830°C       | 1. Equiaxed austenites  
              2. No cementite is observed.  
              3. Any traces of $\alpha'$ lath are not observed.  |

$\text{Ac}_1 = 720°C$  $\text{Ac}_3 = 859°C$

![Photo. 4. $\gamma$ formation at prior $\gamma$ grain boundaries](image1)

![Photo. 5. $\gamma$ formation in $\alpha'$ lath in steel A](image2)
room temperature.

Photographs 6(a) and (b) show the electron microstructure of steel B. Though each acicular γ independently formed, it shows that the orientation relationship of these acicular γ is identical because every acicular γ formed is bright in the dark field image. Orientation relationship between acicular γ and ferrite satisfies the Kurdjumov–Sachs relation \(^{13}\) \(\{110\}_\gamma/\{111\}_\gamma\) and \(\langle111\rangle_\gamma/\langle110\rangle_\gamma\) as shown in Photo. 6(b).

Photograph 7 shows the orientation relationship between ferrite and cementite and it meets the Bagaryatskii orientation relationship \(^{14}\) \((100)_\gamma/(011)_\gamma\).
(010)ₜ//(111)ₜ and (001)ₜ//(211)ₜ. It is well known that the orientation relationship between cementites and ferrite in the tempered martensite satisfies the Bagaryatskii relation.

The microstructure obtained from heating at comparatively higher temperature of \( A_{C1} \) to \( A_{C3} \) is shown in Photo. 8. Photograph 8 shows that the recrystallization of ferrite lath begins and lath structure changes to equiaxed shape. In the higher temperature range of \( A_{C1} \) to \( A_{C3} \), no cementites are observed and formed \( \gamma \) is no longer confined in ferrite lath.

![Photo. 8](image)

2. On the Coarse \( \gamma \) Grain Formation

Steel A was subjected to heat treatment (b); first being held at intermediate temperature for appropriate time, then heated over \( A_{C3} \) to be completely austenitized and followed by quenching.

Figure 2 shows the relation between the intermediate temperature and \( \gamma \) grain size. When 750°C is selected for the intermediate temperature, formed \( \gamma \) grains become very coarse as if they succeed to the prior \( \gamma \) grains, in this case, the grains at 1300°C. Either the intermediate temperature is higher or lower than 750°C, finer \( \gamma \) grains form.

The microstructure, of which intermediate temperatures are 650°C, 750°C and 850°C, is shown in Photo. 9. The \( \gamma \) grains intermediate held at 750°C are coarser than others and look like succeeding to the prior \( \gamma \) grains formed at 1300°C. But following characteristics are different from ordinary ones.

1. Fine equiaxed \( \gamma \) grains appear along prior \( \gamma \) grain boundaries and the boundaries of resulted

![Fig. 2](image)

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coarse γ grains consist of aggregates of fine equiaxed grains. (see Photo. 4)

(2) In the matrix there are isolated fine grains which have different orientation relation from surrounding matrix. It is observed upper right in Photo. 10. (also, see Photo. 9)

(3) As shown in Photo. 10, there are darkly or lightly etched parts, of which boundaries are complicated finely-stepped lines. The unit of the step is believed to be corresponding to the width of acicular lath. It is supposed that the region having the same orientation of acicular γ is a recovered coarse α and these recovered α remember the prior common habit plane and on the following quenching, they transform to the martensite on that habit plane.

As one γ grain transforms on one habit plane, it looks like succeeding to the orientation of prior γ grain. However, if a prior grain is divided into two parts which transformed to martensite on different two habit planes, two corresponding γ grains could form from it. On the other word, one bundle of martensite corresponds to one final γ grain. Since in this experiment 1 300°C is selected for the quenching temperature of the pre-treatment, initial γ grains are large and finally formed acicular γ grains coalesced to coarse grains. But even though the prior microstructure is fine, formed γ grains are likely to grow until their size becomes to the initial γ grain size.

IV. Discussion

1. The Orientation Relation of Acicular γ Grains

Since there are 24 transformation variations which satisfy the K-S orientation relationship, if all variants are allowed, 24 kinds of differently oriented γ grains are obtained even though the prior structure consists of a single crystal. So there must be a proper condition on which no other variants transform.

In Fig. 3, it is assumed that there exists definite orientation relationships among α, γ and cementite. This assumption does not contradict to the electron microscopic observations. In Fig. 3 such directions that must be parallel with each other according to Kurdjumov-Sachs, Bagaryatskii and Pitsch relation-

ship are shown a, b and c respectively drawn as continuous lines, alternate long and short dash lines and broken lines.

It can be considered that when γ transforms from martensite structure, it is advantageous for austenite to transform in contact with the habit plane or ferrite lath boundary taking the interfacial energy into account. As shown in Photo. 1, the prior martensite forms on one habit plane. This habit plane is, for example, shown as (011), in Fig. 3. Generally the habit plane of low carbon martensite is {011}, and growth direction is <111>. In Fig. 3 the habit plane is situated in contact with one edge of the pentahedron of ferrite. It corresponds to axis a in Fig. 3 being vertical to the habit plane that γ transforms in contact with a habit plane satisfying the K-S orientation relationship. In such a case the number of K-S variants is limited and 4 different oriented variations are possible in transformation; after γ is settled so that axes a in γ and α are made parallel with each other, there are still 2 ways of arrangement of γ for axis b to be made parallel with each other.

Taking an antiparallel direction into account, there are 2×2=4 different ways of arrangement by which K-S orientation relationship is satisfied and at the same time γ transforms in contact with a habit plane.

From the point of view of interfacial energy, it can be reasonable to assume that γ advantageously grows in the same direction as the ferrite lath growth direction <111>, in Fig. 3. Because the axis b is fixed in this direction, variants of formation reduced to 2 ways; parallel and antiparallel direction of axis a. The habit plane and growth direction of martensite appear to remain as substructure during heating, as shown in Photo. 3. Cementite precipitated in tempered martensite has Bagaryatskii orientation relationship with α and there are 12 distinguishable variations in Bagaryatskii relation. But if cementites precipitate on lath boundary satisfying Bagaryatskii relation,
Bagaryatskii variants reduced 2 ways. In addition, Pitsch orientation relationship between α and cementite (θ) is satisfied (100)α//[(111)]c, (010)α//[(110)]c, and (001)α//[(112)]c, then the γ formation is limited to only one way.

γ transformed on that way should be in contact with both martensite lath boundary and cementite. It is observed that in Photo. 5 these 3 phases are in contact with each other at lath boundary and in Photos. 6(b) and 7(b) K–S and Bagaryatskii relationship are satisfied respectively between α and γ, α and cementite.

Matsuda, et al. suggested that acicular γ transforms diffusionlessly from martensite structure when heated slowly over Ac1, but if diffusionless transformation occurs, there must be comparatively large non-equilibrium overheating state. If no cementites play as nucleation sites, acicular γ is to transform at higher temperature over Ac1. It suggests a transformation with diffusion that acicular γ develops mainly just above Ac1 temperature when it is slowly heated. According to Judd, et al. plate-like γ partly diffusionlessly transforms from cementites when cementites are separated from grain boundaries or sub-boundaries by strain annealing, but on the interfaces form no such plate-like γ. This result also suggests that acicular γ transforms with diffusion.

According to authors’ mechanism, growth of width of acicular γ is made by the coalescence of commonly oriented γ grains or spreading in the recovering ferrite lath.

Kinoshita, et al. introduced the idea of resonant nucleation. According to this idea, γ newly nucleates on the interfaces of acicular γ and grows in the neighboring ferrite lath.

It is necessary for ferrite lath boundaries to be stable over Ac1 temperature for the formation of acicular γ from cementites. But heated at comparatively higher temperature range between Ac1 and Ac3, cementites dissolve into solution and ferrite laths begin to recrystallize. Therefore γ no longer transforms on the limited habit plane so that they have no identical orientation relationship. In this case they nucleate on the cementites similarly as occurring at the lower temperatures.

2. The Mechanism of Coarse γ Grain Formation

When comparatively lower temperature between Ac1 and Ac3 is selected for intermediate temperature so that identically oriented acicular γ formed and then heated over Ac3, it is advantageous for identically oriented acicular γ to grow continuously rather than newly to nucleate. Because it is necessary for newly nucleated γ to get over the activation energy of nucleation, identically oriented acicular γ grows to coalesce and succeeds the prior γ grain structure. Because at the prior γ grain boundaries, γ transforms in contact with prior grain boundaries rather than ferrite lath boundaries, γ at the boundaries does not transform having the identical crystallographic orientation relation. Thus the prior γ grain boundaries consist of aggregates of fine equiaxed γ grains.

In the matrix, γ grains which nucleated for example on the inclusions do not transform on the same K–S variant as surrounding parts. Such γ grains grow to form isolated grains.

In Fig. 4 preceding to the austenitization, martensite laths begin to recover and grow. It is considered that the crystallographic orientation relation of acicular γ is exactly agreed with each other only within the recovered α and different from each other within the different recovered α. Photograph 3 shows the coarse recovered α. There remain substructure or traces of habit plane of martensite within recovered α because acicular γ forms in the recovered α when it is heated over Ac1.

V. Summary

1. When martensite is heated at comparatively lower temperature range from Ac1 to Ac3, identically oriented acicular γ forms along martensite lath boundaries. Acicular γ has Kurdjumov–Sachs orientation relationship with surrounding α.

2. The reason for the formation of identically
oriented \( \gamma \) is considered to be as follows:

(i) There exist definite orientation relationships among cementite-\( \alpha \), \( \alpha - \gamma \) and \( \gamma \)-cementite respectively which are called as Bagaryatskii, Kurdjumov-Sachs and Pitsch orientation relationship.

(ii) As \( \gamma \) forms in contact with cementite at the martensite lath boundary where the interfacial energy is decreased, the variants of K-S relation are reduced to 4 and those of Bagaryatskii relation are reduced to 2. And if it is assumed that the direction of \( \gamma \) is restricted by the growth direction \([111]_\alpha \), the variants of K-S relation are reduced to 2.

(iii) If Pitsch relationship and above mentioned two K-S variants and two Bagaryatskii variants are satisfied at the same time, \( \gamma \) transforms on the one limited orientation relation. As mentioned above, the following conditions are necessary for acicular \( \gamma \) to have identical crystallographic relation;

i) There remain cementites over \( \text{Ac}_1 \) temperature.

ii) Martensitic ferrite laths are stable over \( \text{Ac}_1 \) temperature.

(3) When heated over comparatively higher temperatures between \( \text{Ac}_1 \) and \( \text{Ac}_3 \), cementites dissolve into solution, and the recrystallization of ferrite lath occurs so that identically oriented acicular \( \gamma \) no longer forms.

(4) In case prior \( \gamma \) grains are coarse, coarse \( \gamma \) grains are formed, which look like succeeding the prior coarse ones, when heated at temperatures above \( \text{Ac}_3 \) after the sufficient development of acicular \( \gamma \) at relatively lower temperatures between \( \text{Ac}_1 \) and \( \text{Ac}_3 \). This is probably due to the reason that it is advantageous for identically oriented acicular \( \gamma \) to grow continuously rather than newly to nucleate, taking the activation energy into account.

(5) The coarse \( \gamma \) grains formed in this way are different from ordinary ones in the following characteristics.

i) The prior \( \gamma \) grain boundaries consist of aggregates of finer equiaxed \( \gamma \) grains.

ii) In the matrix, there exist isolated parts which have independent orientation relation with surroundings.

(iii) Grains are divided into several parts corresponding to recovered \( \alpha \) regions but one grain transforms on the common habit plane so that it does not look like being divided into several parts.

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REFERENCES

1) M. Baeyer: Trans. ASM, 30 (1942), 438.

2) A. E. Nehrenberg: Trans. AIME, 188 (1950), 162.


16) W. Pitsch: Arch. Eisenhuettenw., 34 (1963), 381.