THE BAINITE FORMATION UNDER STRESS IN Cu-Zn-Al ALLOYS

K. Takezawa, H. Imamura, K. Tanizaki, S. Sato

To cite this version:

HAL Id: jpa-00221972
https://hal.archives-ouvertes.fr/jpa-00221972
Submitted on 1 Jan 1982

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
THE BAINITE FORMATION UNDER STRESS IN Cu-Zn-A1 ALLOYS

K. Takezawa, H. Imamura, K. Tanizaki and S. Sato

Department of Applied Physics, Faculty of Engineering, Hokkaido University, Sapporo, 060, Japan

(Revised text accepted 29 September 1982)

Abstract. - Single crystals of Cu-29.8at%Zn-6.1at%A1 alloy with different orientation were heated at temperatures higher than 420°K under a tensile stress. Two variant crystals of bainite having different habit planes, for example (12112) and (12211) for [10651] tensile direction, from that of stress-induced martensite, (12111), were observed after a certain period of incubation. The variant crystal having a maximum Schmid factor with respect to the shear on the habit plane was preferably formed in the martensite case. The close-packed plane of martensite is to be transformed from (110) plane of matrix crystal by the shear of (212)[111]. On the other hand, it is found that the variant crystal of bainite having (12211) habit plane has a larger Schmid factor with respect to the shear of (212)[111], which would also transform (110) matrix plane to the close-packed plane. The other variant having (12112) habit plane has an orientation such that the fcc structure can be formed by crossing with the first one in pair. The crossed region of these two bainite crystals was observed as a pink-colored area. Electron diffraction patterns indicate that the bainite has a disordered 9R structure. It is supposed that the intrinsic transformation shear producing the close-packed structure operates preferably in the bainite case, whereas the minimization of strain energy in the transformation is dominant in the martensite case. A mechanism of the shape change associated with the stress-induced bainitic transformation is also discussed.

Introduction. - The bainitic transformation takes place at temperature higher than 420°K in the shape memory Cu-Zn alloys [1]. This transformation accompanying the diffusion of Zn atoms often produces a macroscopic shape change so-called "reverse shape memory" [2] and modifies the characteristics of the usual shape memory effect. The crystallographic nature of the bainite and martensite are very similar and it is considered that the transformation strains producing both products are not much different [3-5]. In this study the bainite crystals produced under stress in single crystals of a Cu-Zn-A1 alloy were crystallographically examined comparing with the stress-induced martensites and discuss the mechanism of shape change due to the stress-induced bainitic transformation.

Experimental procedure. - Single crystals of Cu-Zn-A1 alloys containing 29.8at%Zn and 6.1at%A1 were grown in an argon-filled quartz capsule by the modified Bridgman method. Homogenized B single crystals were cut by a spark machine to a form of tensile specimen. The specimen was pulled at 423 to 523 K under a load of 100 to 250 MPa, followed by heating for 10 to 30 min. on keeping the load and temperature unchanged. Then, the specimen was unloaded and etched electrolytically to reveal the formation of bainite crystals. The specimen with the etched surface was again pulled in the same direction at room temperature to observe the relief of stress-induced martensite. A similar morphological examination on the two kinds of transformation was made of polycrystalline specimens by using optical as well as electron microscopy. The electron diffraction patterns taken from thin bainite plates were analysed to identify the crystal structure.
Experimental results.- Fig. 1 indicates the variation in tensile stress during the isothermal treatment at 473°K of a single crystal having [1017] stress axis. Following to the formation of bainite in the specimen, the stress level decreased gradually during the heat treatment to the point indicated by arrows where the stress level was adjusted to keep 100 MPa. The bainite crystals were formed after a period of incubation of about 6 min. in this experiment. The incubation period was found to be almost the same, independent of the amount of load, 100-250 MPa, and the tensile directions in this series of experiments. The etched surface showed that the bainite crystals having two variants of the habit plane, (12211) and (12112), were formed during the heat treatment [3, 6]. It is to be mentioned that the stress-induced martensites produced in the second elongation at room temperature have different habit plane variants from these.

Photo. 1 is an example clearly demonstrating the difference in habit planes of bainite and martensite. The photograph was taken by a microscope on the etched surface after heating the specimen for 15 min. at 493°K under a tensile load of 100 MPa in [511] direction. One observes the small black contrasts which correspond to bainite variant crystals with two orientations given above (Photo. 1(a)). Upon loading at room temperature a dark contrast indicating the relief of the stress-induced martensite appeared and it moved from left to right in the view of micro-
scope. Upon unloading the boundary between dark and white region moved in the reverse direction without any disturbance at the bainite precipitates. The boundary, which is the trace of habit plane of the stress-induced martensite, can be indexed as $(12\bar{1}11)$ and the variant crystal is the most probable one having a maximum Schmid factor with respect to the shear on this habit plane. The above result was confirmed for various specimens with different stress axis. The situation holds when the tensile direction is indexed as $[u\bar{v}w]$, where $u>v\geq w>0$.

In Photo. 1, two bainite crystals with $(12\bar{1}1n)$ and $(12112)$ habit planes were observed separately. However, they grew to form a crossed structure with increasing the heat-treatment time. Fig. 2 shows a variation in stress during the heating at $473^\circ K$ when a single crystal was pulled in $[1\bar{1}0\bar{8}]$ direction. The bainitic transformation started after an incubation of 6 min. and a large drop in stress level appeared after heating the specimen for 9 min. At the time when the stress was suddenly decreased, a locally stretched region appeared in the specimen as shown in a sketch of Fig. 2. The heavily deformed region was colored by pink, indicating the formation of $\alpha$ phase crystals with fcc structure [7]. A morphological examination revealed that the stretched region was composed of the crossed structures with a high density.

![Stress vs. Time Graph](image)

Fig. 2
(a) A marked drop in stress associated with the formation of numerous crossed structures of bainite.
(b) The deformation is concentrated to the region where a large number of crossed structures are formed as indicated by arrow. The drop in (a) corresponds to the formation of this region.

![Electron Micrograph](image)

Photo. 2 Electron micrograph showing the crossing of bainite crystals. The habit planes are bent at the crossed structure and the contrast is modified inside the crossed region.
Photo. 2 is an example of electron micrographs taken for a thinned polycrystal-line specimen which was subjected to an enough heat-treatment for the bainite formation. Two variant bainite crystals as in Photo. 1 grew to form a crossed structure. As previously reported \[8\&10\], the stress-induced $\beta_1$ martensite variants with modified 9R structure, which have a particular crystallographic relation with each other, can only cross to form fct $\alpha_1$ martensite of 3R structure. The observed pair of bainite variants in this work was just the same as the martensite pair previously reported \[9\]. It is to be noticed that the habit plane traces of two bainite variants clearly bend at the crossed region and the contrast inside the crossed region is different from the fine structure in the bainite as seen in a circle of Photo. 2.

Photo. 3 A typical electron diffraction pattern of bainite (a) with a key diagram (b). The angle $\gamma$ is exactly $90^\circ$.

A typical diffraction pattern of the bainite crystal is represented in Photo. 3 which assures that the crystal structure is 9R. Comparing with the diffraction pattern from the modified 9R structure of $\beta_1$ martensite, one can notice that the angle $\gamma$ indicated in Photo. 3(b) is not $88^\circ$ but exactly $90^\circ$. Moreover, contrary to the martensite case, neither spots nor streaks due to the superlattice structure were observed in various diffraction patterns with different orientations. These results support that the bainite crystal with 9R structure is not ordered and the crossed region has also a disordered structure of 3R, i.e., fcc.

Discussion.- It might be very important to discuss the reason why one has different variant crystals of bainite from those of martensite. It would occur if the shape deformations due to the both transformations are different from each other. Accordingly, we first try to calculate the shape change due to the bainitic transformation by the phenomenological theory to check this point.

Since no data are available associated with the compositional change or the change in lattice parameter, during the bainitic transformation in Cu-Zn-Al ternary alloys, we utilize the experimental results in Cu-Zn binary alloys. The authors have measured the change in lattice parameters by X-ray diffraction during the bainitic transformation in Cu-40.5wt$\%$Zn alloys \[6\]. The results have been analysed by using the equilibrium values reported by Beck and Smith \[11\] and it has been concluded that the concentration of Zn atoms in bainite crystal, $c_b$, is nearly a constant, i.e. 35a$\%$, whereas that in $\beta_1$ matrix crystal, $c_o$, is changed from 40 to 68a$\%$ Zn \[6\]. If we use these values and set the dilatation parameter $\delta=1$, the habit plane normal $\mathbf{p}$ and shear direction $\mathbf{d}$ can be obtained as shown in the top three rows in Table 1, the values of $\mathbf{p}$ being different from (12112). If we use $\delta=\sqrt{3}/2$, $\mathbf{p}$ and $\mathbf{d}$
instead of 1, where $V_b$ and $V_m$ are the corresponding volume of bainite and martensite crystals, respectively [12], the value of $p$, is obtained independent of $C_o$ and $C_b$, as shown in the fourth row in Table 1, which is close to (12112) and also close to the value of martensite calculated as shown in the bottom row. The value of shear direction $\delta$ for the bainite is also derived to be almost the same as that for the martensite. Therefore, the shear deformation should be almost the same in both transformations. From the above calculation, we conclude that the variant crystals should be the same as that of martensite. Consequently, the present experimental results support that the factor determining the preferred variants of "stress-induced bainite" is not the overall macroscopic shear deformation of bainite which could relax the applied stress.

We now consider the possibility of having different shear systems to nucleate a small bainite crystal. Referring to the previous study on the pre-martensitic products in $B_1$ matrix in Cu-Zn alloys [13], we propose a model of double shears producing the bainite nucleus as shown in Fig. 3. This model is similar to Burger's model for the bcc-hcp transformation [14] but a second shear of $(1\overline{1}0)<1\overline{1}0>$ is added to get the 9R stacking sequence. For the variant crystal having (12111) habit plane as in Table 1, the first shear in Fig. 3(a) brings (110) matrix plane to the close-packed plane by (1i2)[1xi] shears and $2\overline{1}R$ stacking is attained by the second shear of (1i2)[110] in Fig. 3(b). If (112)[111] shear is operated on (110) plane instead of (1i2)[1xi] shear, the bainite product has the same lattice correspondence as the first one but different habit plane, i.e., (12111). The Schmid factors for (112)[111] shear and (112)[111] shear with respect to [u v w] tensile direction, $S(112)$ and $S(112)$, respectively, have a relation such that $S(112)-S(112)=-(u+v)(u+v)<0$. Consequently, if we assume the shear producing the close-packed plane predominates in the process forming bainite nucleus, the experimental fact that the variant crystals having (12111) appear instead of those having (12111) can be understood without difficulty.

The growth of bainite will be controlled by the diffusion of Zn atoms from the product to the matrix [14] and the experimental results that the incubation period appeared to be independent of the direction and amount of the applied stress can be interpreted by this mechanism. Moreover, as far as the process which produces the "reverse shape memory" is concerned, one could interpret that the bainitic transformation proceeds by the diffusion controlled growth of the stress-induced variant crystals having (12111) habit plane with a similar strain field as that of martensite.

<table>
<thead>
<tr>
<th></th>
<th>$C_o$</th>
<th>$C_b$</th>
<th>$\delta$</th>
<th>$\Phi$</th>
<th>$\Phi$</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bainite</td>
<td>0.40</td>
<td>0.35</td>
<td>1</td>
<td>0.640</td>
<td>0.229</td>
<td>0.733</td>
</tr>
<tr>
<td></td>
<td>0.44</td>
<td>0.35</td>
<td>1</td>
<td>0.619</td>
<td>0.243</td>
<td>0.747</td>
</tr>
<tr>
<td></td>
<td>0.48</td>
<td>0.35</td>
<td>1</td>
<td>0.594</td>
<td>0.258</td>
<td>0.761</td>
</tr>
<tr>
<td></td>
<td>$C_o$</td>
<td>$C_b$</td>
<td>$\sqrt{V_b/V_m}$</td>
<td>0.716</td>
<td>0.185</td>
<td>0.674</td>
</tr>
<tr>
<td>Martensite</td>
<td>0.40</td>
<td></td>
<td>1</td>
<td>0.717</td>
<td>0.156</td>
<td>0.679</td>
</tr>
</tbody>
</table>

Table 1 Calculated habit planes and shear directions of bainite and martensite. $C_o$ and $C_b$ are the concentration in matrix and bainite, respectively. $\Phi$, $\Phi$ and $\delta$ and the habit plane normal, shear direction, and dilatation parameter, respectively.
It has been reported so far that two variants of martensite having (12111) and (12112) habit planes are stress-induced in pair by pulling single crystal specimens in a direction near [100], and also that the variants in pair can easily cross to form an α martensite having fcc structure, which plays a very important role to produce the reversible shape memory. In the present work, in addition to the variant having (12111) habit plane, which is preferably formed by the requirement of close-packed structure, the other one having (12112) habit plane was transformed in pair with the first one.

The second variant crystal has an orientation such that it can easily cross with the first one to form fcc crystal. The β matrix crystal in the present alloy is unstable at higher temperature and finally transform to the equilibrium fcc structure, i.e., α phase. Therefore, it is quite reasonable that two bainite crystals having particular orientations which could easily produce the α crystal by crossing appeared in pair in the present experiment.

References