Effect of Carbon Content on Primary Recrystallization Texture in Fe-Al-N Alloys

By Tadashi ICHIYAMA,** Ikushi YOSHIDA,** Mizuo EJIMA** and Osamu MATSUMURA**

Synopsis

Effects of carbon content on primary recrystallization texture, AlN precipitation, grain size and drawability are investigated on Fe-Al-N alloys of varying composition, with Al from less than 0.005% up to 0.06%, with N from less than 0.002% up to 0.02%, and with C from 0.001% up to 0.04%.

With increasing carbon content, the amount of grains with (111) lattice plane parallel to the sheet plane decreases, the main component of primary recrystallization texture changes from (111) (110) to (554) (225), grain size decreases, grain shape changes from the "pancake" to the equiaxial type, and the drawability decreases markedly.

These effects of carbon content on various properties of Fe-Al-N alloys are rather inconspicuous for up to 0.01%, but become extremely marked when it exceeds 0.04%. They are explained by the effect of carbon content on AlN precipitation during precipitation treatment prior to cold rolling and during heating for the final annealing temperature.

I. Introduction

The investigation of the recrystallization behaviour of Fe-Al-N alloy and the effect of aluminium and nitrogen contents on it revealed that there are two sorts of mechanisms operating to develop strong (111) recrystallization texture.

The first mechanism is the one which operates in Fe-Al-N alloy steel sheets with aluminium and nitrogen contents comparable to the commercial aluminium-killed steel. AlN which precipitates during the annealing process causes an orientation dependent suppression of recovery. The nucleation probability therefore becomes higher in (111) unrecrystallized regions where recovery is predominantly suppressed. The (111) recrystallization nuclei created in those regions grow rapidly, devouring up the unrecrystallized regions where the recovery has less progressed. Consequently, a (111) texture with a strong (111)<110> component finally develops.

The second mechanism, on the other hand, operates in the steel sheets with aluminium and nitrogen contents both lower than the first case. The effect of suppression of recovery by the AlN precipitation during annealing is insufficient for the first mechanism to operate. Although the nucleation is orientation dependent, aluminium atoms or AlN precipitates hinder the growth of nuclei. As a result of the hindrance of the growth of nuclei, (554)<225> nuclei, which have a preferred orientation relationship with the cold rolled matrix of (112)<110> and (111)<110> orientations, grow predominantly. A (111) recrystallization texture with a strong (554)<225> orientation is formed by this mechanism.

In either case, it is evident that a delicate precipitation behaviour of AlN during the recovery and the recrystallization of the matrix, both when and how much to precipitate, is very essential for the recrystallization mechanism of Fe-Al-N alloys.

Ichiyama et al. pointed out that the precipitation behaviour of AlN varied depending on the carbon content of the steel sheet. It may be predicted, therefore, that in Fe-Al-N alloys to which carbon is added to various levels, the quantity of AlN precipitated during the hot rolling and during the final annealing after cold rolling, and consequently the primary recrystallization texture, vary depending on the carbon levels. Abe and Takagi showed, on the other hand, that the cementite particles in low carbon rimmed steel exerted a serious effect on the primary recrystallization texture just as AlN precipitates did in aluminium-killed steel. It seems a direct effect of carbon on the recrystallization texture of steel sheets. Another example of direct effect of carbon is due to Takechi et al. who showed that the primary recrystallization texture of extremely low carbon steel sheet was different from that of ordinary carbon steel sheet and found that a strong (554)<225> texture developed in it. They pointed out that a difference in the orientation components of cold rolled textures depending on the carbon content was the origin of this difference in recrystallization texture.

As is stated above, it is very probable that the carbon content exerts effects, either directly or indirectly, on the formation of the primary recrystallization texture of Fe-Al-N alloy. A detailed study was made therefore for the effect of carbon content on Fe-Al-N alloy specimens with the carbon content at various levels.

II. Experimental Procedures

The 7 kg ingots were prepared by vacuum remelting electrolytic iron to include all combinations of aluminium and nitrogen contents, each varying in three levels; for Al less than 0.005, 0.02 and 0.06%, and for N less than 0.002, 0.005 and 0.02%. The C content was varied from less than 0.003 up to 0.04%. The ingots were swaged to 20 mm, surfaced to 15 mm, then hot rolled to 2.8 mm thickness. The conditions of hot rolling were as follows: the slabs were solution-treated at 1300 to 1350°C for 1 hr in Ar atmosphere, then hot rolled by two passes, the finishing temperature being 1060°C. In order to get various states of precipitation of AlN the hot-rolled plates were either
quenched directly into brine water, or slowly cooled down to 600, 700, or 800°C, held for 30 min at each temperature, and then quenched. The time required for cooling down to 600, 700, or 800°C was 43, 23, or 10 sec, respectively. Specimens processed as above shall be designated as water-quenched, 600°C-processed, 700°C-processed, or 800°C-processed specimens, respectively. They were then cold rolled to 0.8 mm thickness, the reduction being about 70%.

Table 1 shows the chemical compositions as determined with cold rolled sheets, which can be classified, according to the carbon content, into three groups, namely, group A with C content less than 0.003%, group B with C~0.01%, and group C with C~0.03%. In addition to typical specimens included in Table 1, several supplementary specimens whose C contents varied rather continuously were also prepared.

Cold rolled sheets were heated to 720°C in the atmosphere of N₂ + 2% H₂ with a rate of 50°C/hr, held for 10 hr, then cooled in the furnace. Figure 1 shows a schematic diagram of the procedures after solution heat treatment. Physical and metallurgical properties of the specimens processed as described above were surveyed by metallography, X-ray reflection intensity measurement, uniaxial tensile test, conical cup test, and internal friction measurement.

1. X-ray Reflection Intensity Measurement

Intensities of MoKα X-rays reflected from crystal planes of low indices, 2θ being less than 100°, were measured. Surface layers 30 to 40 μ thickness were removed by grinding with emery paper and with chemical etching. Measurements were made for both sides of three specimens, and the averaged values of six measurements altogether were adopted. Reflection intensity was expressed as the relative intensity against the standard random specimen.

2. Pole Figures

A specimen of about 50 μ thickness taken from the central layer of the annealed specimen was used. The (200) pole figures were made by transmission method with MoKα X-rays.

3. Uniaxial Tensile Test

Uniaxial tensile test was made on a small test piece with a parallel part of 10 mm × 50 mm and the total length of 105 mm. The s-values were determined at
Reflection intensities of the specimen with the peak depends on aluminium and nitrogen contents. The III. 1. Primary Recrystallization Textures of some specimens with a apparatus of inverted torsion pendulum at the frequency of about 1.5 Hz. Resolved carbon and nitrogen contents were separately determined from the analysis of the shape of the Snoek peak by the least squares method.

III. Experimental Results

1. Primary Recrystallization Textures of Fe–Al–N Alloys without Carbon Addition (C<0.003\%)

Figure 2 shows how the precipitation treatment of the hot rolled plates influences the recrystallization textures. It is seen that the manner of influence depends on aluminium and nitrogen contents. The \(\{222\}\) reflection intensities of the specimens with the lowest aluminium level (<0.005\%) are almost constant (5 to 7 times the random intensity) and insensitive to the precipitation treatment, while those of the specimens with aluminium levels 0.02\% and 0.06\% and with nitrogen levels less than 0.002\% and 0.005\% (Specimens A1, A2, A4 and A5) are quite sensitive to the precipitation treatment conditions, i.e., the lower the precipitation temperature, the higher the \{111\} reflection intensity, and attain values even larger than 10 for water-quenched specimens. Sensitivity to the precipitation treatment is also influenced by the nitrogen content which is recognized clearly by comparing specimens with nitrogen less than 0.002\% (A1 and A2) with those with nitrogen level of 0.005\% (A4 and A5). In the former group \(\{222\}\) reflection intensity shows no appreciable difference between water-quenched and 600°C-processed specimens, while in the latter group \(\{222\}\) reflection intensity of 600°C-processed specimens is much lowered compared to water-quenched one.

When nitrogen content is further increased to 0.02\% (A7 and A8), it is seen that the situation becomes less beneficial to the development of \{111\} recrystallization texture.

Figure 3 shows (200) pole figures of some typical specimens. Water-quenched A5, whose aluminium and nitrogen contents are comparable to that of the commercial aluminium-kill steel, possesses a strong \{111\} component parallel to the sheet plane, the primary component being \{111\} \{110\}. Comparing Fig. 3(c), (b) and (a) it will be readily understood that the primary component changes from \{111\} \{110\} to \{554\} \{225\} with decreasing aluminium and nitrogen contents. Such a gradual transition of the orientation component with the chemical composition was discovered and discussed minutely already.\(^{21}\)

It is worth mentioning that the same kind of orientation transition occurs with increasing precipitation temperature in the specimen A3. A comparison of Fig. 3(c), (d) and (e) shows that as the precipitation temperature is increased the primary component changes from \{111\} \{110\} to \{554\} \{225\}, the situation being quite similar to when aluminium and nitrogen contents are decreased while the precipitation treatment is kept unchanged.

2. Effect of Carbon Content on the Primary Recrystallization Texture

Figure 4 shows the values of \(\{222\}\) reflection intensity in the specimens with carbon level 0.01\% (from B0 to B8) and 0.03\% (from C1 to C8), as well as those with no carbon addition (from A0 to A8). It is obvious that for specimens with aluminium levels 0.02\% and 0.06\%, \(\{222\}\) reflection intensity is lowered markedly by increase in carbon content, and this effect becomes more pronounced as the precipitation temperature decreases. The relationship between \(\{222\}\) reflection intensity and the precipitation temperature that was clear for specimens with no carbon addition is no longer as well-defined for those with carbon addition as for those with no carbon addition. Especially for specimens with the carbon level of 0.03\%, the
{222} reflection intensity is not so high, and is nearly independent of the precipitation temperature.

For more minute examination of the effect of carbon content on the texture, {222} reflection intensity was measured for a number of water-quenched specimens with the carbon content varying in a wider range 0.001% to 0.04%, while other compositions remaining similar to A5, B5, and C5. The result is shown in Fig. 5. When carbon content is less than 0.01%, the detrimental effect of carbon on {222} texture is rather slight, but as the carbon content surpasses 0.01%, {222} reflection intensity lowers rather suddenly.

There seems a threshold value of 0.01% for the detrimental effect of carbon on the primary recrystallization texture of Fe–Al–N alloys.

Figure 6 shows (200) pole figures of water-quenched specimens with carbon content 0.006, 0.009, 0.012 or 0.030%, respectively with other compositions similar to specimen A5.

A gradual decrease in {111} component with the increasing carbon content is recognized from a comparison of Fig. 6 and Fig. 3 (c). The primary component changes from {111} \( \langle 110 \rangle \) to {554} \( \langle 225 \rangle \) with increasing carbon content, just as when the aluminium

(a) A1, hot rolled and water quenched
(b) A2, hot rolled and water quenched
(c) A5, hot rolled and water quenched
(d) A5, hot rolled and precipitation treated at 600°C for 30 min
(e) A5, hot rolled and precipitation treated at 800°C for 30 min

\( \times \langle 111 \rangle \langle 110 \rangle \circ \langle 554 \rangle \langle 225 \rangle \)

Fig. 3. (200) pole figures of the finally annealed sheets from materials without C addition

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and nitrogen contents are decreased or when the precipitation temperature is increased for the specimen of the same chemical composition.

3. Effect of Carbon Content on the Precipitation of AlN

The amount of AlN precipitates in the cold-rolled sheets was analyzed by the Beegly method. For all specimens with aluminium less than 0.005\% and for those with aluminium at 0.02\% and 0.06\% levels and with nitrogen less than 0.002\%, however, the AlN content was below the detection limit of this method, regardless of the conditions of the precipitation treatment or the carbon addition. As the nitrogen content was increased to 0.005\% or 0.02\%, AlN precipitation was observed, the degree of which depending strongly on the condition of the precipitation treatments and the carbon content. The results are summarized in Fig. 7. Although in most water-quenched specimens no AlN precipitation was observed, it became detectable and increased further with increasing precipitation treatment temperature. By the precipitation treatment at 800°C for 30 min, large AlN precipitates were observed, which accounted for 70–80\%, of the quantity corresponding to the total acid-soluble aluminium or nitrogen content in the specimens. Comparing specimens of equal nitrogen content (Fig. 7 (a) and (b)) with each other, more AlN precipitates were observed for higher aluminium levels as was already pointed out by Leslie et al.,\(^4\) and Aoki et al.,\(^7\) An examination of curves \((a) 700\,^\circ\text{C}, (b) 600\,^\circ\text{C} and 700\,^\circ\text{C}, (c) 600\,^\circ\text{C} and 700\,^\circ\text{C}\) reveals that the precipitation below 700°C is increased with carbon content. In other words, AlN precipitation during cooling after the solution treatment is accelerated by increasing carbon content.

In the present experimental procedures there are two occasions for AlN precipitation; the first in the course from the solution to the precipitation treatment and the second during the annealing after cold rolling. It is generally believed that the behaviour of AlN precipitation during the second process has a decisive effect on the development of the recrystallization texture of aluminium-killed steel sheets. It was recently observed by Hanai et al.,\(^8\) that fine particles of AlN of cubic structure precipitated during heating which were argued to have a critical influence on the texture development, while Abe and Suzuki\(^9\) inferred that clusters of aluminium and nitrogen atoms or embryos of AlN precipitates which were in the pre-precipitation state played an important role on the texture development from a minute examination of the effect of two-stage annealing of aluminium-killed steel sheets on the recrystallization texture. In order to examine the effect to carbon content on the development of the primary recrystallization texture in Fe–Al–N alloys it is thought desirable to make clear its effect on the formation of such fine AlN precipitates or clusters.

Figure 8 shows how the nitrogen in solution, as determined by the internal friction measurement, changes during the aging at 500°C in the specimens whose chemical compositions are similar to those in Fig. 7 (b) \((A5, B5 \text{ and } C5)\). Preceding to the aging the specimens had been water-quenched after reheating at 1350°C for 15 min. The decrease in nitrogen in solution in the course of aging obviously corresponds to the precipitation of fine AlN or the formation of clusters of aluminium and nitrogen. The nitrogen in solution begins to decrease earlier and the rate after the beginning of decrease, too, is higher in the specimen with lower carbon content than in that with higher carbon content. For example, nitrogen in solution is zero after 10\(^3\) min of aging in a specimen with 0.002\%C, whereas about 10\% of initial nitrogen re-

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**Fig. 5.** Effect of C content on (222) relative intensity in materials containing about 0.06\%Al and about 0.005\%N

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**Fig. 4.** (222) relative intensities of the finally annealed sheets showing difference between materials with and without C addition.
mains in solution in a specimen with 0.03% C even after $3 \times 10^3$ min of aging. It is therefore concluded that the AIN precipitation during the aging process at 500°C is retarded by carbon. Hanai et al.\textsuperscript{5,6} pointed out that the precipitation of AIN in the cold rolled sheet, which was highly strained, was much faster than in the hot rolled sheet. The role of AIN precipitation in the commercial aluminium-killed sheet during the annealing process, therefore, might considerably differ from that in the present quenching experiment. But, the qualitative nature of the effect of carbon content on the precipitation of AIN may be the same in both cases. It is concluded that in the course of heating of cold-rolled sheet the precipitation of AIN is retarded by increasing the carbon content, contrary to the case of cooling of the hot-rolled sheet from the solution treatment temperature.

4. Effect of Carbon Content on the Grain Shape

The manner how the grain shape is influenced by the chemical composition or the precipitation treatment was studied metallographically for the longitudinal cross-section of the annealed specimens.

Photograph 1 shows some typical examples of specimens with no carbon addition. Specimens with aluminium content less than 0.005% possessed equiaxial grains regardless the precipitation treatment while those with aluminium content of 0.02% and 0.06% possessed typical pancake-structure when given a precipitation treatment at low temperatures. The grain shape approaches the equiaxial one as the precipitation treatment temperature goes higher while the size itself remains almost unchanged, which is clearly seen in the sequence b → c → d → e of Photo. 1. It is notable that at the highest precipitation temperature, 800°C, specimen A5 (0.06Al and 0.005N) showed an almost perfectly equiaxial structure (Photo. 1 (c)). This effect of precipitation treatment temperature on the grain shape corresponds well to that on (222) reflection intensities mentioned in Sect. 1, Chap. III. The cause of this effect is perhaps the lowering of nitrogen content in solution in the cold-rolled sheet due to higher precipitation temperature. Increasing nitrogen content seems to decrease the grain size provided that both aluminium content and the precipitation treatment are kept unchanged (Photo. 1 (a), (b) and (f)). This effect is very prominent in the case of nitrogen level of 0.02% (Photo. 1 (f)).

Effect of carbon content is shown in Photo. 2. Table 2 shows average grain size measured along the rolling direction and along the sheet normal and the axial ratio. From Photo. 2 and Table 2 it is readily seen that with increasing carbon content the grain size decreases while the grain shape approaches equiaxial one notwithstanding that the specimens were water-quenched. The change in microstructure due
5. Effect of Carbon Content on the Drawability

Table 3 shows the drawability as well as some related mechanical properties of Fe-Al-N alloys. It is easily recognized that the condition of precipitation treatment and the nitrogen content are two main factors which influence the drawability of the specimens without carbon addition. The lower the precipitation treatment temperature, the better the drawability manifested in r-value and CCV, similarly to the relationship between the recrystallization texture and to increasing carbon content is greater up to 0.01% but the effect seems to saturate at higher carbon level.

Table 3 shows the drawability as well as some related mechanical properties of Fe-Al-N alloys. It is easily recognized that the condition of precipitation treatment and the nitrogen content are two main factors which influence the drawability of the specimens without carbon addition. The lower the precipitation treatment temperature, the better the drawability manifested in r-value and CCV, similarly to the relationship between the recrystallization texture and

![Fig. 7. Effect of C content on AlN precipitation during precipitation treatment](image)

![Photo. 1. Microstructures of the finally annealed sheets from materials without C addition (×100)](image)
the precipitation treatment temperature. Specimens with [200] intensity larger than 10 possess an excellent deep drawability manifested in \( \hat{\epsilon} \) larger than 2.0 and in CCV smaller than 36.5. The increasing nitrogen content has a dual effect on the drawability. Firstly it improves the drawability by formation of AlN effective to \{111\} texture development, while, secondly, it decreases the drawability because it results in smaller grain size, higher yield strength, lower elongation, and lower \( n \)-value. Specimen A8 with nitrogen level of 0.02% is the typical example of these effects.

Comparing water-quenched specimens A5, B5, and C5 in Tables 1 and 3 it is evident that increase in carbon content has a remarkably detrimental effect on the drawability. For a more minute examination of this effect a series of specimens with carbon content varying from 0.001 up to 0.04%, while other compositions maintained similar to specimen A5 were prepared, and the relation between the carbon content and CCV was investigated on water-quenched specimens.

The result is summarized in Fig. 9. With increasing carbon content the drawability manifested in CCV is lowered, but the rate of lowering becomes rather

Table 2. Effect of C content on grain size and axial ratio

<table>
<thead>
<tr>
<th>Grain size (Rolling direction, ( \rho ))</th>
<th>C (%)</th>
<th>0.002</th>
<th>0.006</th>
<th>0.009</th>
<th>0.030</th>
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<tbody>
<tr>
<td>Grain size (Normal direction, ( \rho ))</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Axial ratio</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Photo. 2. Microstructures of the finally annealed sheets from materials with C addition (\( \times 100 \))
(a) 0.006%, 0.06%Al and 0.005%,N, hot rolled and quenched
(b) 0.009%,C, 0.06%Al and 0.005%,N, hot rolled and quenched
(c) 0.030%,C, 0.06%Al and 0.005%,N, hot rolled and quenched

Table 3. Drawability and mechanical properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Precipitation treatment</th>
<th>Yield point (kg/mm²)</th>
<th>Yield elongation (%)</th>
<th>Tensile strength (kg/mm²)</th>
<th>Total elongation (%)</th>
<th>( n ) value</th>
<th>( \hat{\epsilon} ) value</th>
<th>Conical cup value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>WQ</td>
<td>10.7</td>
<td>0.0</td>
<td>25.1</td>
<td>57.3</td>
<td>0.303</td>
<td>2.31</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>600°C x 30 min</td>
<td>10.5</td>
<td>0.2</td>
<td>24.9</td>
<td>57.0</td>
<td>0.306</td>
<td>2.73</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>800°C x 30 min</td>
<td>10.9</td>
<td>0.0</td>
<td>24.8</td>
<td>49.0</td>
<td>0.290</td>
<td>1.82</td>
<td>0.06</td>
</tr>
<tr>
<td>A2</td>
<td>WQ</td>
<td>10.0</td>
<td>0.2</td>
<td>24.4</td>
<td>61.7</td>
<td>0.320</td>
<td>2.53</td>
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<td></td>
<td>600°C x 30 min</td>
<td>10.6</td>
<td>0.0</td>
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<td>56.8</td>
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<td>A5</td>
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<td>0.1</td>
<td>26.4</td>
<td>57.3</td>
<td>0.355</td>
<td>2.88</td>
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<tr>
<td></td>
<td>600°C x 30 min</td>
<td>14.5</td>
<td>0.3</td>
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<td>0.275</td>
<td>1.59</td>
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<td>A8</td>
<td>WQ</td>
<td>19.8</td>
<td>0.0</td>
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<td>41.8</td>
<td>0.201</td>
<td>1.68</td>
<td>0.55</td>
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<td></td>
<td>600°C x 30 min</td>
<td>21.1</td>
<td>2.6</td>
<td>30.7</td>
<td>46.7</td>
<td>0.212</td>
<td>1.91</td>
<td>0.39</td>
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<td></td>
<td>800°C x 30 min</td>
<td>15.8</td>
<td>0.2</td>
<td>28.8</td>
<td>51.8</td>
<td>0.262</td>
<td>1.80</td>
<td>0.43</td>
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<td>B1</td>
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<td>27.0</td>
<td>13.2</td>
<td>29.7</td>
<td>49.3</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>B2</td>
<td>WQ</td>
<td>26.6</td>
<td>14.0</td>
<td>29.8</td>
<td>54.5</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>B5</td>
<td>WQ</td>
<td>28.0</td>
<td>18.0</td>
<td>29.8</td>
<td>52.0</td>
<td>---</td>
<td>1.53</td>
<td>0.48</td>
</tr>
<tr>
<td>B8</td>
<td>WQ</td>
<td>28.8</td>
<td>14.7</td>
<td>31.0</td>
<td>40.8</td>
<td>---</td>
<td>2.48</td>
<td>0.93</td>
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<tr>
<td>C5</td>
<td>WQ</td>
<td>29.9</td>
<td>18.0</td>
<td>31.8</td>
<td>47.0</td>
<td>---</td>
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</table>
The effects of carbon content on the primary recrystallization texture, microstructure and the drawability are summarized as follows.

(1) With increasing carbon content {111} component parallel to the sheet plane decreases.

(2) Main component {111} <110> of the specimens without carbon addition changes to {554} <225> on carbon addition and, at the same time, the {111} intensity goes down.

(3) With increasing carbon content the grain size decreases, and the pancake-structure of the specimens without carbon addition changes to the equiaxial one.

(4) With increasing carbon content both yield and tensile strengths increase while the elongation decreases, and consequently the drawability is lowered.

(5) Effects of carbon content on texture, grain size and mechanical properties as mentioned in (1) to (4) are prominent for carbon contents more than 0.01%.

Those effects mentioned above can be considered to derive, partially at least, from a widely accepted direct effect of carbon content on the mechanical as well as the structural properties of mild steel sheet in general. Many investigations have been made, from both academic and practical points of view, concerning how the carbon content influences the recrystallization texture of cold rolled sheet, and it is generally understood that by lowering the carbon content the texture favourable for deep-drawing is obtained. The mechanism of such a detrimental effect of carbon content on the development of {111} texture is, however, not yet entirely clear.

Abe et al.\textsuperscript{11,12} observed that the super-saturated carbon in solution which existed prior to cold rolling accentuated the {110} <001> component of the recrystallization texture, whereas fine particles of planar cementite precipitated on {110} planes, through changing the local orientation distribution in the deformation band of the cold-rolled sheets, suppressed the generation of the recrystallization nuclei of {110} <001> orientation and encouraged the predominant growth of those of {554} <225> + {111} <110> orientations.\textsuperscript{13}

In the case of Fe–Al–N alloys, there works presumably a factor influencing the recrystallization texture due also to carbon content but other than that mentioned above. The results obtained by the present experiment seem to suggest that the effect of carbon content on the precipitation behaviour of AlN plays an essential role in the development of the recrystallization texture of aluminium-killed steel.

As was stated in Sect. 3, Chap. III the precipitation of AlN during the process from solution treatment to precipitation treatment is accelerated by increasing carbon content. In the specimens with higher carbon contents, therefore, more precipitation of AlN occurs, leaving less nitrogen in solution in the cold rolled sheet, the free nitrogen which later during the annealing is to precipitate as AlN to effectively control the recrystallization texture, than in the specimens with lower carbon contents. Furthermore, the retardation effect of carbon addition on the precipitation of fine AlN during annealing process, inferred from internal friction measurement, can be considered to cooperate with it. Hence, the suppression of recovery due to precipitation of fine AlN during heating process is achieved only insufficiently in the specimens with a high carbon content, which leads to the recrystallization behaviour typical to Fe–Al–N alloys with a too low N content, or the rimmed steel-like one so to speak, and the texture with a principal orientation component of {554} <225> develops, {111} component parallel to the sheet plane being weak. It is considered that the very same mechanism works to produce equiaxial grains.

Next, some consideration shall be given how the increasing carbon content enhances the precipitation rate of AlN during the precipitation process following solution treatment.

Ichiyama et al.\textsuperscript{3} studied the precipitation behaviour of AlN in Fe–Al–N alloys with varying carbon content and found that the peak temperature of precipitation, \textit{i.e.} the temperature at which the precipitation was most favoured, decreased with increasing carbon content. They also observed that the precipitation rate at the peak temperature increased with increasing carbon content for specimens with aluminium content of about 0.1%.

In the present work hot-rolled specimens were air-
cooled down to the pre-determined precipitation temperature. Specimens were, therefore, cooled more slowly as the temperature goes down. Hence, the higher the carbon content, the lower the cooling rate at the precipitation peak temperature, and it is more favorable for the initiation of partial precipitation of AIN, which provides nuclei for precipitation during the following isothermal holding and accelerates the precipitation.

Another possibility that can be pointed out is that fine cementite particles, which precipitate preceding cooled down to the predetermined precipitation temperature, show that during the precipitation treatment followed by quenching the {111} component diminishes with increasing carbon content.

(2) By choosing suitable values for aluminium and nitrogen levels it is possible to establish a very high intensity of {111} component with the {111} <110> as the main component of the texture, provided that no carbon is added to the specimens. On carbon addition, however, the {111} intensity goes down and the main component changes to {554} <225>, even if both aluminium and nitrogen levels are kept unchanged.

(3) Pancake structure typical of the aluminium-killed steel, which is produced when no carbon is added, changes, with increasing carbon content, to equiaxial grains while the size of them is reduced at the same time.

(4) Deep drawability is lowered greatly with increasing carbon content, which is resulted from changes in the primary recrystallization texture and the grain size. These two effects are working cooperatively to reduce the drawability.

(5) Precipitation of AIN is accelerated by the presence of carbon atoms during the cooling process from the high temperature, such as after precipitation treatment, while, on the contrary, it is decelerated during heating from the room temperature in the annealing process.

(6) Effects of carbon content described above are rather small in the range less than 0.01%, but become very conspicuous for the carbon content more than 0.01%

Acknowledgements

The authors would like to express their hearty thanks to Drs. S. Watanabe and T. Ikeno for the permission of publication of this work. Thanks are also due to Mr. Y. Nakagawa for helpful discussions and to Messrs. H. Ohsone and Y. Nakajima for experimental assistances.

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