Effect of Grain Size on the Yield Stress of Cold Worked Iron

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Effect of ferrite grain size on dislocation strengthening was investigated in low carbon steels (0.006%C–0.15%C) with various grain sizes from 1 to 100 μm. In specimens with slight deformation, dislocation density increases in proportion to the inverse of ferrite grain size. In the dislocation density range below 2×10^{14}/m^2, dislocation density increases linearly against deformation strain but it tends to level off due to the dynamic recovery of dislocations when dislocation density has exceeded it. On the other hand, tensile tests revealed that yield stress follows the Hall-Petch relation for as-annealed specimens but follows the Bailey-Hirsch relation for cold rolled specimens. This means that flow stress depends on only the dislocation density regardless of grain size. As a result, it was concluded that the introduction of dislocations has been promoted with decreasing ferrite grain size and this results in the increase of flow stress in the uniform deformation region.

KEY WORDS: low carbon steel; ferrite grain size; Hall-Petch relation; Bailey-Hirsch relation; dislocation density; strengthening mechanism.

1. Introduction

The strengthening of metals by cold working is known as “work hardening” and it is experimentally found that the work hardening behavior relates to dislocation density in metals. In general, the increment of strength Δσ is given by the equation; Δσ=αGb√d, so called the Bailey-Hirsch relation,1) where α, G, b and d are a constant, shear modulus, Burgers vector of dislocation and dislocation density, respectively. Regarding cold worked iron, the relation between dislocation density and tensile strength was investigated and the values from 0.77 to 1.4 were reported for the parameter α.2–5) The difference in α-values is due to the narrow range of dislocation density (10^{13}–10^{15}/m^2) where the Bailey-Hirsch relation was discussed and also due to the measurement error of dislocation density. The authors have evaluated dislocation density of cold rolled ferritic steel in wider range and proposed α=0.9 summing the results reported until now.6)

On the other hand, the yield stress of as-annealed metals is proportional to the reciprocal of square root of grain size, so called Hall-Petch relation. The authors have found in iron that the equation; σ_y=[GPa]=0.1+0.6 d[μm]^{-1/2} stands up to the grain size more than 0.2 μm.9) and it was confirmed that this equation can be applied to low carbon steels with various carbon content up to 0.2%.10) Here, the question is how the grain size affects to the yield stress of cold worked ferritic steels. In general, it has been believed that the strengthening mechanisms such as solid solution strengthening, grain refinement strengthening and dislocation strengthening cannot be added each other.11) In practice, Morrison investigated the tensile deformation behavior for low carbon ferritic steel with the grain size from 0.2 to 400 μm and indicated that not only yield stress but also the flow stress after yielding is heightened with decreasing grain size.12) However, Evans et al. pointed out for low carbon ferritic steel that the dislocation density is higher in 20 μm grained specimen than 170 μm grained specimen even at the same percentage of tensile deformation.4) This result suggests that the flow stress is simply heightened due to higher dislocation density in the specimen with small grain size. Same result has been reported in high purity nickel with various grain sizes.13) In contrast, the authors found in ultra fine grained iron (0.25 μm) that work hardening does not appear in specimens cold rolled up to 40% in thickness reduction.14) These results indicate that grain refinement strengthening and dislocation strengthening cannot be added simply in the cold worked polycrystalline metals.

In order to clarify the relation between grain refinement strengthening and dislocation strengthening, yield stress of cold worked metals should be investigated for specimens with a wide range of grain size. In this study, low carbon steels (0.006 – 0.15%C) with the grain size from 1 μm to 100 μm was cold rolled and then the cold rolled specimens were provided to investigate the effect of dislocation density.
on yield stress.

2. Experimental Procedure

In this study, three kinds of low carbon steels were used to obtain wide range of ferrite grain size. One is fully ferritic steel (Fe-0.006%C). It is desirable to use only this steel but it was difficult for this steel to obtain fine grained structure below 10 μm. Therefore, the other steels (Fe-0.03%C and Fe-0.15%C) were also used to obtain the grain size smaller than 10 μm. Chemical compositions, volume fraction of pearlite \( V_P \) and cementite \( V_c \) are shown in Table 1. In 0.006%C steel, grain size was controlled in the range from 11 μm to 95 μm through the recrystallization of cold rolled ferrite; 90% cold rolling and then annealing at 973 or 1 153 K for 70 s to 1.8 ks. In 0.03%C steel, grain size was controlled in the range from 3.5 to 42 μm through the 10 to 35% hot rolling at 1 153 K and the recrystallization of cold rolled martensite; water quenching from 1 173 K, 80% cold rolling and then annealing at 873 or 923 K for 1.8 ks. In 0.15%C steel, grain size was controlled in the range from 1.3 μm to 9 μm through the super short interval multi-pass rolling process (SSMR)\(^{10}\) and the normalizing of commercial S15CK. Specimens with various ferrite grain sizes were subjected to cold rolling up to 35% in thickness reduction and then subjected to tensile testing and X-ray diffraction to measure dislocation density.

Tensile testing was performed with Instron-type testing machine at the initial strain rate of 5.6 × 10\(^{-4}\)/s. For as-annealed specimens, the test pieces JIS-5 (1 mm\(^2\), 25 mm\(^3\), 50 mm\(^3\)) were used to obtain stress-strain curves. In addition, small sized test pieces (1 mm\(^2\), 3 mm\(^3\), 6 mm\(^3\)) were used to measure yield stress for cold rolled specimens. Yield stress was evaluated by the lower yield stress for specimens with discontinuous yielding and 0.2% proof stress for specimens with continuous yielding.

Microstructures were observed with optical microscope, scanning electron microscope (SEM) and transmission electron microscope (TEM). X-ray diffractometry was conducted using Cu-K\(\alpha\) on the specimens with electrical polishing. The authors confirmed that the surface layer damaged by sand paper grinding has been completely removed by the electrical polishing. The diffraction peaks were treated with the computer program PDXL2 to remove the background noise and the effect of K\(\alpha\)g. Effect of instrumental function was corrected using well annealed 0.006%C steel on the basis of Gaussian function fitting. From the diffraction angle \( \theta \) [rad] and the full width at half maximum \( \beta_0 \) [rad], the micro-strain \( \varepsilon \) of cold rolled specimens was estimated by the following equation,

\[
\beta_0 \cos \theta = 0.9 \frac{0.02 \sin \theta}{D} \tag{1}
\]

where \( \lambda \) and \( D \) denote the wave length of X-ray (0.154 nm) and the crystallite size, respectively.

In order to avoid the effect of elastic anisotropy, the value of \( \varepsilon \) was determined using the three plots corresponding \{110\}, \{211\} and \{220\}.\(^{10}\) It is known that dislocation density \( \rho \) is proportional to the square of \( \varepsilon \).\(^{10}\) In this study, the value of \( \rho \) was estimated by the following equation\(^{15}\) which was established against the dislocation density measured by TEM.

\[
\rho \left[ m^{-2} \right] \equiv 1.5 \times 10^6 \varepsilon^2 \tag{2}
\]

X-ray diffractometry was performed in 3–5 specimens and the mean value of \( \varepsilon \) was applied for the estimation of dislocation density.

3. Experimental Results

Typical microstructures are shown in Fig. 1. 0.006%C steel has fully ferritic structure regardless of heat treatment conditions, as shown in (a). In the other steels, (ferrite + pearlite) structure (b) or ferritic structure containing small cementite particles (c) were obtained depending on heat treatment conditions. The kinds of microstructure, nominal grain size evaluated by the quadrature method, yield stress and dislocation density in cold rolled specimens are listed in Tables 2 and 3. Regarding the microstructure, ferrite, pearlite and cementite are presented by the symbol \( F \), \( P \) and \( \theta \), respectively. It was confirmed that ferrite grain size

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**Table 1.** Chemical composition of steels used in this study (mass%) and the theoretical volume fraction of pearlite \( V_P \) and cementite \( V_c \).

| Steel          | C  | Si  | Mn  | P  | S  | \( V_P \) | \( V_c \) |
|----------------|----|-----|-----|----|----|----------|----------|
| 0.006%C-Steel | 0.0056 | <0.003 | <0.002 | <0.0003 | – | –        | –        |
| 0.03%C-Steel  | 0.028 | <0.01 | <0.001 | 0.001 | 4% | 0.4%    | –        |
| 0.15%C-Steel  | 0.15 | 0.01 | 0.74 | 0.02 | 0.002 | 19% | 2.2%    |
| S15CK         | 0.16 | 0.24 | 0.45 | 0.02 | 0.014 | 19% | –       |

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**Fig. 1.** Typical microstructure of specimens with ferrite single phase (a), ferrite-pearlite structure (b) and ferrite-cementite structure (c).
is controlled in a wide range from 1.3 to 95 μm and there is no significant texture in every specimen. In addition, TEM observation proved that the dislocation density of annealed specimens is very low ($< 5 \times 10^{12} / \text{m}^2$).

Tensile deformation behavior in as-annealed specimens are displayed in Fig. 2. With decreasing grain size, not only yield stress but also the flow stress after yielding are heightened. Yielding elongation is found in every specimen and it increases with decreasing ferrite grain size. However, it seems that yielding elongation does not exceed 5%. This means that 5% pre-deformation is enough to suppress yielding elongation and realize uniform deformation in any specimens. The relation between ferrite grain size and yield stress is shown in Fig. 3. The lines in this figure present the Hall-Petch relations which have been established in 0.15%C steel and 0.006%C steel. It is found that the Hall-Petch plots in this study are just on the corresponding lines. This means that yielding behavior is governed by the mechanism of grain refinement strengthening. When the amount of solute carbon is less than 60 ppm, the Hall-Petch coefficient (the slope of plots) changes depending on the carbon content. In this study, it was reconfirmed that the Hall-Petch coefficient is identical at 0.6 GPa · μm$^{-1/2}$ regardless of carbon content, although the friction stress is slightly different depending on the chemical composition of steels.

Table 2. Microstructure, ferrite grain size ($d$), dislocation density ($\rho$) and yield stress ($\sigma_y$) of specimens used in this study.

| Micro Structure | as annealed | 5% cold-rolled | 10% cold-rolled | 20% cold rolled |
|----------------|-------------|----------------|----------------|----------------|
|                | $d$ (μm) | $\sigma_y$ (GPa) | $\rho$ ($10^{14} \text{m}^{-2}$) | $\sigma_y$ (GPa) | $\rho$ ($10^{14} \text{m}^{-2}$) | $\sigma_y$ (GPa) | $\rho$ ($10^{14} \text{m}^{-2}$) |
| $F$            | 11        | 0.216          | 1.8            | 0.291          | 3.0            | –              | 5.0            | 0.428          |
| $F$            | 19        | 0.174          | 1.4            | 0.254          | 2.3            | –              | 2.9            | 0.389          |
| $F$            | 57        | –              | 0.80           | –              | –              | –              | –              | –              |
| $F$            | 95        | 0.101          | 0.37           | 0.199          | 0.60           | –              | 0.75           | 0.235          |
| $F+P$          | 3.5       | –              | 5.2            | –              | –              | –              | –              | –              |
| $F+\theta$     | 5.3       | –              | 3.9            | –              | –              | –              | –              | –              |
| $F+\theta$     | 5.9       | –              | 3.5            | –              | –              | –              | –              | –              |
| $F+P$          | 42        | –              | 0.64           | –              | –              | –              | –              | –              |
| $F+\theta$     | 1.3       | 0.585          | 8.0            | 0.572          | 10.0           | –              | 12.1           | –              |
| $F+P$          | 3.4       | 0.438          | 4.3            | 0.463          | 6.2            | –              | 7.2            | –              |
| $F+P$          | 5.2       | 0.357          | 3.1            | 0.416          | 4.3            | –              | 6.3            | –              |

* $F$: ferrite, $\theta$: cementite, $P$: pearlite

Table 3. Microstructure, ferrite grain size ($d$), dislocation density ($\rho$) and yield stress ($\sigma_y$) of S15CK.

| Micro Structure | as heat treatment | 10% cold-rolled | 17% cold-rolled | 35% cold-rolled |
|----------------|------------------|----------------|----------------|----------------|
|                | $d$ (μm) | $\sigma_y$ (GPa) | $\rho$ ($10^{14} \text{m}^{-2}$) | $\sigma_y$ (GPa) | $\rho$ ($10^{14} \text{m}^{-2}$) | $\sigma_y$ (GPa) | $\rho$ ($10^{14} \text{m}^{-2}$) |
| S15CK          | $F+P$            | 9.0            | 4.1            | 0.482          | 8.1            | 0.586          | 12.0           | 0.683          |

* $F$: ferrite, $\theta$: cementite, $P$: pearlite

Fig. 2. Nominal stress-strain curves of specimens with various ferrite grain sizes.

Fig. 3. Hall-Petch relationship in steels used in this study.
stress with cold rolling. In every specimen, yield stress increases with increasing the amount of cold rolling but it is kept at higher level in specimens with smaller grain size overall. This result makes us imagine that dislocation strengthening is added to the strength produced by grain refinement strengthening. However, Evans reported that dislocation density is higher in a specimen with small grain size.4) This suggests that grain size affects the behavior of dislocation introduction, hence the strengthening mechanism should be discussed in connection with the change of dislocation density. The changes of dislocation density with cold rolling are shown in Fig. 5. It should be noted that the dislocation introduction is promoted with decreasing ferrite grain size even at the same percentage of deformation. In the case of large grain sized specimens (i.e. 95 μm), dislocation density increases in proportion to equivalent strain, while it shows nonlinear change against equivalent strain in specimens with the grain size larger than 19 μm. It seems that nonlinear change appears when dislocation density has exceeded a certain value (≈2×10^{14}/m^2). Same tendency has been reported by Keh3) and Evans.4) Such a nonlinear change in dislocation density is probably due to the recovery of dislocations, namely the disappearance of dislocations caused by dislocation reaction. The detail of recovery will be treated again in the session of discussion.

In order to investigate the effect of grain size on the behavior of dislocation introduction, small amount of cold rolling (5%) was charged to specimens with various ferrite grain sizes. The relation between dislocation density and ferrite grain size is shown in Fig. 6. In the grain size region above 20 μm, the effect of grain size is not so significant but dislocation density increases abruptly in the grain size region below 20 μm. In the case of 0.15%C steel, small amount of pearlite or cementite particles is contained with ferrite and they may affect somewhat the behavior of dislocation introduction. In addition, the amount of solute carbon may affect the behavior of dislocation introduction.5) In this study, it was difficult to separate each contribution but it is sure that dislocation introduction is promoted by grain refinement.

The relations between square root of dislocation density and yield stress were summarized in Fig. 7 for all specimens with cold rolling from 5% to 35%. It is found that all data are almost on a straight line (Bailey-Hirsh relation) regardless of grain size and the amount of cold rolling. Relation between the increment of strength ∆σ[GPa] and dislocation density ρ[m^{-2}] is expressed by the following equation, which was already reported by the authors.6)

![Fig. 4. Relation between equivalent strain and yield stress in cold rolled specimens with various ferrite grain sizes.](image1)

![Fig. 5. Relation between equivalent strain and dislocation density in cold rolled specimens with various ferrite grain sizes.](image2)

![Fig. 6. Effect of ferrite grain size on the dislocation density of 5% cold-rolled specimens.](image3)

![Fig. 7. Relation between dislocation density and yield stress in cold-rolled specimens with various ferrite grain sizes.](image4)
4. Discussion

4.1. Effect of Grain Size on the Behavior of Dislocation

In this session, the reason “why dislocation introduction is promoted with decreasing grain size” is discussed first. The total amount of dislocations \( \rho_s \), which has been introduced by plastic deformation, is given by the sum of geometrically necessary (GN) dislocations and statistically stored (SS) dislocations. Ashby pointed out that GN dislocations have to be introduced to accommodate the misfit strain around grain boundary because deformation mode is different in each crystal grain.\(^{18,19}\) According to the Ashby model, the density of GN dislocations \( \rho_G \) is given by the following equation,

\[
\rho_G = \frac{4\gamma}{b \lambda_c} \frac{1}{\lambda_c} \quad (4)
\]

where \( \gamma \), \( b \) and \( \lambda_c \) denote shear strain, Burgers vector of dislocation and the geometrically slip distance, respectively.\(^{19}\) In polycrystalline metals, \( \lambda_c \) corresponds to the grain size \( d \) and, for bcc metals, \( \gamma \) is replaced with tensile strain \( \varepsilon \) as \( \gamma = 2e \). Therefore, the above equation is rewritten as follows:

\[
\rho_G = \frac{8e}{bd} \quad (5)
\]

This equation suggests that, even at same strain, the density of GN dislocations increases in proportion to the reciprocal of grain size. In Ashby model, the density of SS dislocations \( \rho_S \) is treated to be small enough in comparison with \( \rho_G \).\(^{18} \)

On the other hand, Conrad proposed another idea that the density of SS dislocations \( \rho_S \) should be increased with decreasing grain size because the moving distance of dislocations is limited by the grain size.\(^{20}\) In general, the following equation is known in the relation between the total length of moving dislocations \( \rho \) and tensile strain \( \varepsilon \),

\[
\varepsilon = \frac{\rho b X}{m} \quad (6)
\]

where \( X \) and \( m \) denote the average of dislocation movement and Taylor factor (\( m = 2 \) for bcc metals). Conrad put \( X = \varphi d \) (\( 0 < \varphi < 1 \)) under the assumption that the X-value is proportional to the grain size \( d \) and introduced the following equation for the density of SS dislocations \( \rho_S \) which should be introduced by plastic deformation.

\[
\rho_S = \frac{me}{bd} \quad (7)
\]

This equation suggests that the density of SS dislocations increases in proportion to the reciprocal of grain size, if all of introduced dislocations have been stored. Conrad proposed \( \varphi = 0.15 \) for steels with the grain size (32–435 \( \mu \)m).\(^{20}\) Putting \( m = 2 \), \( b = 0.25 \) nm and \( \varphi = 0.15 \), Eq. (7) is rewritten as follows:

\[
\rho_S \left[ \frac{1}{m^3} \right] = \frac{5.33 \times 10^{10} e}{d} \quad (8)
\]

The Eqs. (5) and (7) were established on the basis of different model but they indicate that dislocation density increases in proportion to the reciprocal of grain size. Both models may be applicable actually to explain the increase of dislocation density.\(^{13}\) hence the total amount of dislocations \( \rho_t \) may be expressed by the following equation:

\[
\rho_t \left[ \frac{1}{m^3} \right] = \rho_G + \rho_S = 8.53 \times 10^{10} \frac{e}{d} \quad (9)
\]

In order to check the reasonability of this equation, the result of Fig. 6 was re-plotted in the log-scales, as shown in Fig. 9. The \( \rho_t \)-value calculated by Eq. (9) is shown by a broken line in the figure. Regarding the experimentally obtained dislocation density \( \rho \), the following equation stands up overall.
The experimental data agree well with the calculated values in the range of large grain size (50–100 μm) but the difference between \( \rho \) and \( \rho_i \) becomes larger in the range of small grain size below 20 μm. This result suggests that the recovery of dislocations has occurred in the range of high dislocation density.

### 4.2. Effect of Dynamic Recovery on the Dislocation Density

In the case of ferritic steels, dislocation cell structure develops during cold working with the increase of dislocation density. For example, TEM images of cold rolled specimens (11 μm and 95 μm) are shown in Fig. 10. The distribution of dislocations is not homogeneous even in 5% cold rolled specimens. In 10% cold rolled specimens, clear dislocation cell structure was observed in both specimens. It is found in 20% cold rolled specimens that smaller dislocation cells are formed and the size of dislocation cells is fairly small in the 11 μm specimen. It is already known that there is good correlation between the dislocation cell size and dislocation density in cold worked ferritic steel.\(^{21}\) Since the dislocation density is much lower in the core of dislocation cells than the portion of dislocation cell wall, the total dislocation density is mainly dependent on the volume fraction of dislocation cell wall and the dislocation density at the portion of dislocation cell wall.\(^{21}\) With increasing the amount of cold working, smaller dislocation cells are formed and this leads to the increases of total dislocation density.

On the other hand, the dynamic recovery of dislocations should occur during deformation. The possibility of dynamic recovery becomes larger with an increase of dislocation density. In general, the density of retained dislocations \( \rho^* \) is given by the following equation,

\[
\rho^* = \rho_i - \rho_r \quad \text{(11)}
\]

where \( \rho_i \) and \( \rho_r \) correspond to the amount of introduced dislocations and recovered dislocations.

It is difficult to estimate theoretically the value of \( \rho_r \) but it is roughly estimated from the experimentally obtained data. The relation between \( \rho_i \) and \( \rho \) is shown in Fig. 11. In the range of low dislocation density \((\rho_i < 2 \times 10^{14}/\text{m}^2)\), good agreement is found between \( \rho_i \) and \( \rho \). This result suggests that the dislocations introduced during deformation are almost stored in this dislocation range. As a result, dislocation density increases linearly against strain, as shown in Fig. 5. However, the difference between \( \rho_i \) and measured dislocation density \( \rho \), which corresponds to \( \rho_r \), becomes larger with an increase of \( \rho_r \). This result indicates that the
dynamic recovery of dislocations becomes active when dislocation density has exceeded the critical value $2 \times 10^{14} \text{m}^{-2}$. It should be noted that all data follow an identical line regardless of ferrite grain size. This means that grain size affects the behavior of dislocation introduction but does not give any effect on the dynamic recovery of dislocations. Since dynamic recovery of dislocations occurs dominantly through the cross slip of screw dislocations at nano-scale area, it stands to reason that grain size does not affect the behavior of dynamic recovery of dislocations. As a result, the amount of recovered dislocations depends on only the value of $\rho$, regardless of grain size.

5. Conclusion

Effect of ferrite grain size on dislocation strengthening was investigated in low carbon steels (0.006%C–0.15%C) with various grain sizes from 1 to 100 $\mu$m. The results obtained are as follows.

(1) In as-annealed specimens, the Hall-Petch relation stands up in the relation between yield stress and grain size.

(2) Dislocation introduction by deformation is promoted with decreasing grain size even at the same percentage of deformation. It was suggested that the amount of dislocations, which are introduced at the initial deformation stage, is proportional to the reciprocal of grain size.

(3) In the range of dislocation density up to $2 \times 10^{14} \text{m}^{-2}$, dislocation density increases linearly against strain but the changes of dislocation density become nonlinear in the range of dislocation density above $2 \times 10^{14} \text{m}^{-2}$ because dynamic recovery of dislocations is activated with increasing dislocation density. With decreasing grain size, dislocation introduction is promoted but there is no effect of grain size on the behavior of dynamic recovery of dislocations.

(4) In specimens with cold working more than yielding elongation, Bailey-Hirsch relation stands up in the relation between yield stress and dislocation density regardless of grain size. This means that dislocation introduction has been promoted in specimens with smaller grain size, as a result, the amount of dislocation strengthening increases.

(5) Regarding the relation between grain refinement strengthening and dislocation strengthening, there is no additional relation but competitive relation in terms of the strengthening mechanism.

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REFERENCES

1) J. E. Bailey and P. B. Hirsch: Philos. Mag., 5 (1960), 485.
2) A. S. Keh and S. Weissmann: Electron Microscopy and Strength of Crystals, Interscience Publishers, New York, (1963), 231.
3) D. J. Dingley and D. McLean: Acta Metall., 15 (1967), 885.
4) J. T. Evans and R. Rawlings: Mater. Sci. Eng., 4 (1969), 297.
5) Y. Lan, H. J. Klaar and W. Dahl: Metall. Trans. A, 23A (1992), 545.
6) D. Akama, T. Tsuchiyama and S. Takaki: J. Soc. Mater. Sci. Jpn., 66 (2017), 522.
7) Y. Kimura and S. Takaki: Proc. 1998 Powder Metallurgy (PM) World Cong., EPMA, Shrewsbury, (1998), 573.
8) S. Takaki and Y. Kimura: J. Jpn. Soc. Powder Powder Metall., 46 (1999), 1235.
9) Y. Kimura and S. Takaki: J. Jpn. Soc. Technol. Plast., 41 (2000), 13.
10) M. Etou, S. Fukushima, T. Sakai, Y. Haraguchi, K. Miyata, M. Wakisita, T. Tomida, N. Imai, M. Yoshida and Y. Okada: ISIJ Int., 48 (2008), 1142.
11) R. W. Hertzberg: Deformation and Fracture Mechanics of Engineering Materials, John Wiley & Sons, New York, (1976), 1.
12) W. B. Morrison: Trans. ASM, 59 (1966), 824.
13) T. Narutani and J. Takamura: Acta Metall. Mater., 39 (1991), 2037.
14) S. Takaki, K. Kawasaki, Y. Futamura and T. Tsuchiyama: Mater. Sci. Forum, 503–504 (2006), 317.
15) G. K. Williamson and W. H. Hall: Acta Metall., 1 (1953), 22.
16) G. K. Williamson and R. E. Smallman: Philos. Mag., 8 (1956), 34.
17) K. Takeda, N. Nakada, T. Tsuchiyama and S. Takaki: ISIJ Int., 48 (2008), 1122.
18) M. F. Ashby: Philos. Mag., 21 (1970), 399.
19) M. F. Ashby: Strengthening Methods in Crystals, ed. by A. Kelly and R. B. Nicholson, Elsevier, Amsterdam, (1971), 137.
20) H. Conrad, S. Feuerstein and L. Rice: Mater. Sci. Eng., 2 (1967), 157.
21) Y. Lan, H. J. Klaar and W. Dahl: Metall. Trans. A, 23A (1992), 537.