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# Tensile Properties and Work Hardening Behaviour of Alloy 6016 in Naturally Aged and Pre-aged Conditions

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The tensile properties and work hardening behaviour of naturally aged and pre-aged alloy 6016 were investigated using tensile testing, and the work hardening behaviour of the materials was modelled using the Kocks-Mecking-Estrin approach. Pre-aged samples were given a stablising heat treatment of 20 s at 150, 200 or 250 ºC, and aged naturally for 24 h prior to testing. The results show that natural ageing causes an increase in strength and a decrease in the strain-hardening exponent (n) of the material, but has little effect on the elongation. Increasing the pre-ageing temperature increases the strength very slightly, but decreases both the n-value and the K-value. Naturally aged samples show a higher work hardening rate than as-quenched samples. Increased pre-ageing temperatures slightly decrease the work hardening rate of the alloy. The differences in work hardening rate between naturally aged and pre-aged alloy 6016 are discussed in relation to microstructural characteristics resulting from different heat treatments.

***Keywords:*** *Work hardening; 6xxx alloy; natural ageing; pre-ageing*

## 1. Introduction

Forming of 6xxx series sheet alloys is typically carried out in the naturally-aged or pre-aged conditions. Pre-ageing is carried out before final ageing to stabilise the material and improve the final age hardening response [1]. It is unclear, however, how such a pre-ageing treatment may affect the formability before ageing. Natural ageing and pre-ageing heat treatments are thought to produce some microstructural changes in the materials, such as formation of clusters [2-3] and/or coherent zones [4], which in turn can influence not only the subsequent age hardening response [4], but also the work hardening behaviour [5-6]. Since the formability is related to both the tensile properties and the work hardening behaviour, an investigation of these properties can aid the development of heat treatments for improved formability. This information is potentially useful for developing heat treatments with suitable combinations of both formability and age hardening response.

In the present study, the tensile flow behaviour of alloy 6016 in naturally-aged and pre-aged conditions is examined, and the work hardening behaviour of the alloy is modelled. This study is intended to supply information for further work aimed at establishing relationships between microstructure, work hardening behaviour and formability of 6xxx sheet alloys.

## 2. Experimental Procedures

A 6016-based alloy, of composition 0.95% Si, 0.42% Mg, 0.13% Cu, 0.21% Fe and 0.07% Mn (wt.%) was cold rolled to 0.9 mm thick sheet and then subjected to a solution treatment at 550 ºC for 0.5 h followed by a rapid quench into water. Two sets of heat treatments were employed on as-quenched samples. One set of samples was naturally aged for 3 h (NA3h), 24 h (NA24h) or 168 h (NA168h), while the other set of samples was pre-aged immediately after quenching at 150, 200 or 250 ºC for 20 s, and then naturally aged for 24 h. No subsequent artificial ageing was performed.

Tensile testing was conducted on heat treated specimens at a constant strain rate of $1\times10^{-3}s^{-1}$. True stress ($\sigma$)-true strain ($\varepsilon$) curves of the specimens were computed assuming the conservation of volume in the uniform elongation regime. The strain-hardening exponent, n, and the strength coefficient, K, were determined according to ASTM E646-00, and the true plastic strain ($\varepsilon^p$) was determined from $\varepsilon^p=\varepsilon-\sigma/E$, where $E$ is the Young's modulus. The work-hardening rate was determined by numerically differentiating the plastic portions of the true stress-true plastic strain data using a moving regression analysis. Each data point on the $\sigma$-$\varepsilon^p$ curve, and the six adjacent data points (three on each side), were used to obtain a best-fit linear regression line, and the slope of this line was treated as the work-hardening rate at that point. The resulting derivative was then smoothed to reduce the noise in the data.

## 3. Results

### 3.1 Mechanical Properties

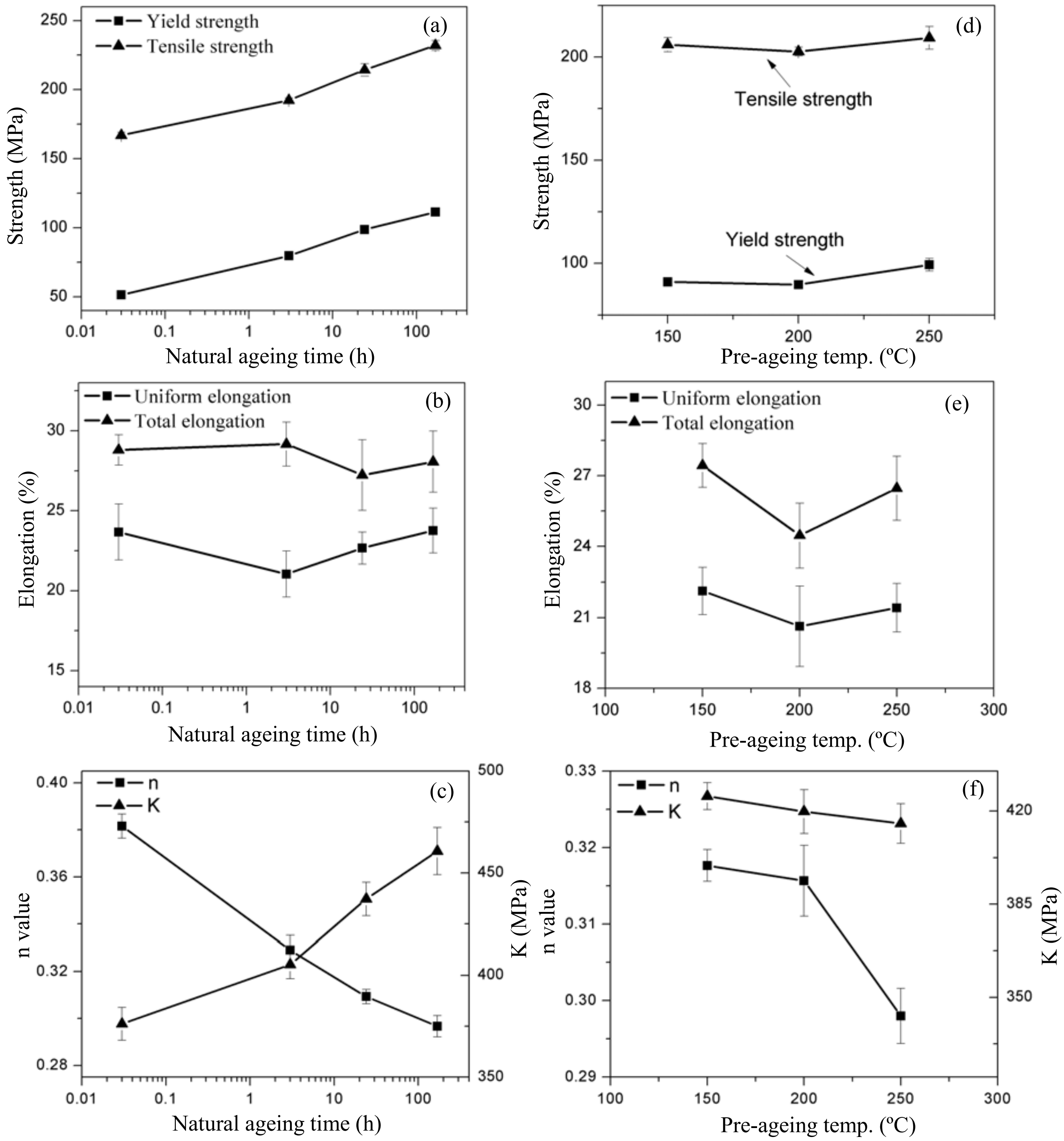


Fig. 1: Effect of natural ageing on (a) strength, (b) elongation and (c) values of n and K, and pre-ageing temp. on (d) strength, (e) elongation and (f) values of n and K

The essential mechanical properties produced after the various ageing treatments are given in Fig. 1. As shown in Fig. 1(a, b), the strength of the material increases significantly with natural ageing but the elongation remains relatively constant. On the other hand, the strain-hardening exponent, n, decreases with increasing natural ageing time. A higher n-value is normally beneficial in forming processes as it increases the amount of uniform plastic strain, which enlarges the process window and facilitates the forming of complex geometries [7]. This result would then suggest that as-quenched samples have a better formability than those naturally aged. However, Campbell [5] found the formability of the 6xxx alloys in the naturally aged condition was superior to that in the as-quenched condition due to an ability to maintain a high work hardening rate to much larger strains/stresses.

Furthermore, the pre-ageing treatments employed in this study influence the properties of alloy 6016 as shown in Fig. 1 (d-f). With increasing pre-ageing temperature, the n-value decreases significantly, while the strength and elongation exhibit only small changes.

### 3.2 Work Hardening Behaviour

The plastic portions of the true stress - true strain curves for alloy 6016 with different heat treatments are shown in Fig. 2. In Fig. 2(a), it can be observed that the as-quenched sample shows substantial evidence of serrated flow. This diminishes as natural ageing proceeds. The most striking feature that can be observed from Fig. 2(a) is a slight increase in the level of work hardening as natural ageing proceeds from the as-quenched condition to the 168 h natural ageing condition. In contrast, Fig. 2(b) shows data for pre-aged samples, where the level of work hardening decreases with increasing pre-ageing temperature.

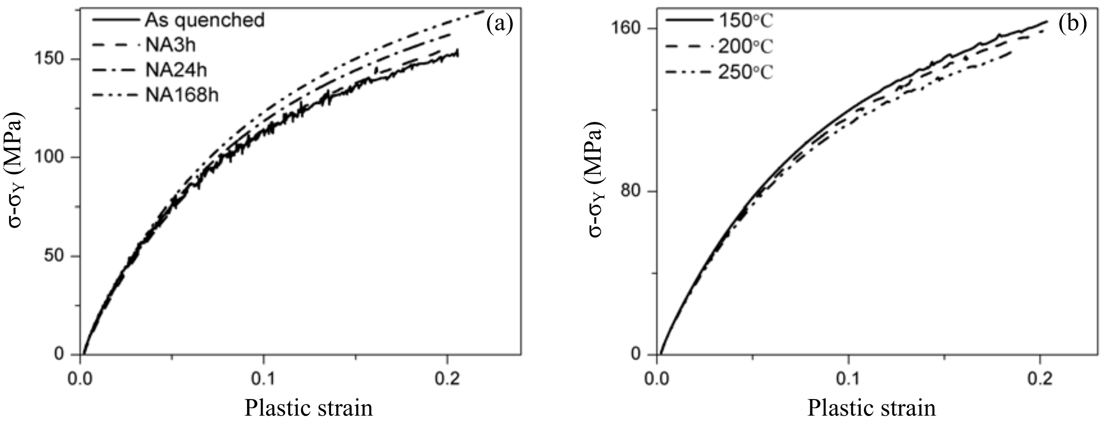


Fig. 2: Plastic stress-strain curves for (a) as-quenched and naturally aged and (b) pre-aged samples

It is conventional to examine work hardening behaviour by plotting the instantaneous work hardening rate ($\theta$) *vs* the increase in plastic flow stress ($\sigma$-$\sigma_Y$). This is known as a Kocks-Mecking plot [6]. As shown in Fig. 3, the evolution of work-hardening rate with stress exhibits a section with a linear decrease of $\theta$ with $\sigma$-$\sigma_Y$ (as found by Kocks and Mecking). The work hardening rate evolution of naturally aged samples and pre-aged samples are quite similar. Work hardening rates increase with increasing natural ageing time and decreasing pre-ageing time. It should be noted that as-quenched samples show different work hardening evolution characteristics than naturally aged samples.

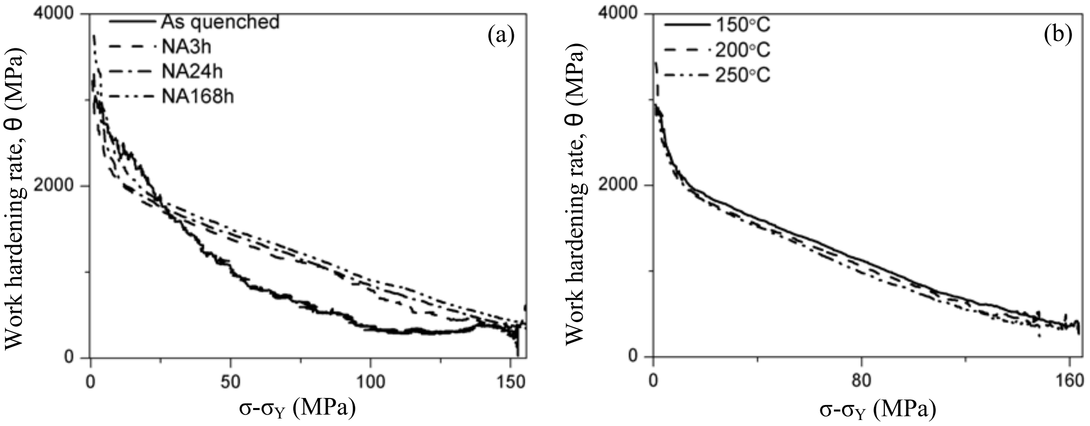


Fig. 3: The instantaneous work-hardening rate vs plastic flow stress for (a) as-quenched and naturally aged and (b) pre-aged 6016 samples

### 3.3 Modelling of Work Hardening Behaviour

The theoretical framework for the development of constitutive laws for alloys containing shearable and nonshearable precipitates has been reviewed by Estrin [8]. The formulation for the evolution of dislocation density with plastic strain can be written as a generalisation of the Kocks-Mecking-Estrin approach [9]:

$$\frac{\partial \rho}{\partial \varepsilon^{p}} = k_1 \rho^{1/2} - f_s k_2 \rho \, . \tag{1}$$

where $\rho$ is the dislocation density, $\varepsilon^p$ is the true plastic strain, and $k_1$, $k_2$ and $f_s$ are model parameters. The first term on the right-hand side of Eq. (1) represents the dislocation storage rate due to trapping of dislocations by other dislocations, and the second term is a dynamic recovery term, where $f_s$ represents a modifying factor due to the effect of dislocation/precipitate interactions on dynamic recovery. The form of Eq. (1) implies that clusters and coherent zones do not contribute to the dislocation storage rate directly, but rather influence the dynamic recovery rate. However, Zolotorevsky *et al* [10] found that $k_1$ can be influenced by the presence of zones in the microstructure. The flow stress contribution from dislocation hardening, $\sigma_{\perp}$, can be written as

$$\sigma_{\perp} = \alpha_{\perp} G b M \sqrt{\rho} \, . \tag{2}$$

where $\alpha_{\perp}$ is a constant of the order of 0.3, $b$ is the magnitude of the Burgers vector, $G$ is the shear modulus, and $M$ is the Taylor factor. Furthermore, Cheng *et al* [9] suggested that the flow stress can be modelled as follows:

$$\sigma = \sigma_{ss} + (\sigma_{\perp}^{h} + \sigma_{ppt}^{h})^{1/h} \, . \tag{3}$$

where h can vary between 1 and 2, and $\sigma_{ss}$ is the flow stress contribution from the solid solution (i.e. the 'friction stress'). When there is a high density of weak obstacles and a low density of strong obstacles (i.e. mainly shearable obstacles, as in this study), then h = 1 is an appropriate choice.

Values for the model parameters $k_1$, $f_s$ and $k_2$ were determined by fitting to experimental data. The sum of the terms $\sigma_{ss}$ and $\sigma_{ppt}$ in Eq. (3) for different conditions was determined from the yield strength for each condition. It was further assumed that these quantities did not vary during straining. As shown in Fig. 4, the model fits the experimental data quite well. With increasing natural ageing time, $k_1$ increases and the $f_s k_2$ term decreases slightly. On the other hand, with increasing pre-ageing temperature, $k_1$ remains relatively constant but the $f_sk_2$ term shows an increase. A higher $k_1$ and a lower $f_s$ $k_2$ suggest a higher work hardening capability [9].

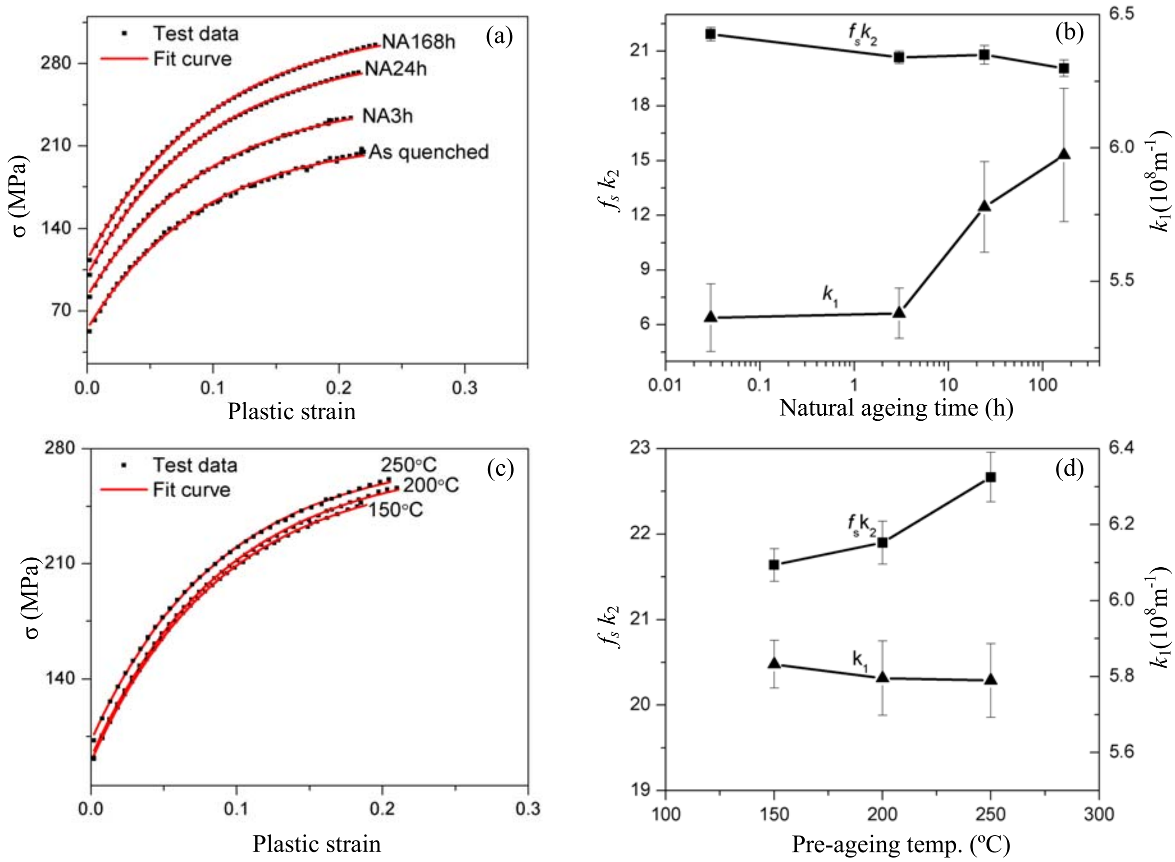


Fig. 4: Stress-strain curves and model parameters for (a, b) naturally aged and (c, d) pre-aged conditions

## 4. Discussion

During natural ageing, the formation of clusters and/or coherent zones causes an increase in strength [11-12], as shown in Fig. 1(a). Furthermore, weak dislocation obstacles (i.e. clusters and/or zones) are thought to be easily sheared by dislocations, which would cause a decrease in the work hardening capability of the alloy compared to alloys with harder obstacles. In this study, the naturally aged samples maintain a higher work hardening rate at larger stresses (see Fig. 3(a)), a higher dislocation storage rate ($k_1$) and a slightly lower dynamic recovery rate ($f_sk_2$) compared to as-quenched specimens (Fig. 4(b)). This means that naturally aged samples have a better work hardening capability than as-quenched samples. Futhermore, increasing the number density and volume fraction of weak obstacles by natural ageing may also increase the work hardening rate of the alloy slightly. There are many factors that may lead to this result. For example, Deschamps *et al* [6] found a higher work hardening rate in the T4 condition as compared to the as-quenched material in a 6111 alloy, and attributed it to the presence of zones and dynamic precipitation. On the other hand, Hutchinson *et al* [13] found, in an Al-Cu-Sn system, that GP zones dissolve into the matrix during straining, thereby increasing the Cu solute content of the matrix, which in turn causes a higher work hardening rate at large strains.

For those samples subjected to short-time (20 s) pre-ageing treatments at high temperatures (as in this study), only small clusters are believed to exist [11]. Increased pre-ageing temperatures may decrease the number of such clusters and thus cause a decrease in the work hardening rate. This is seen in the behaviour of the parameters $k_1$ and $f_sk_2$ in Fig. 4(d). Further work is needed to clarify the current experimental results.

This study suggests that the nature of the obstacles to dislocation motion makes a significant difference to the work-hardening rate. It seems that the presence of clusters and/or zones in naturally aged samples results in a higher work hardening rate compared to that of a supersaturated solid solution, whilst the absence of zones in pre-aged samples perhaps slightly reduces the work hardening rate of the alloy. The nature of the obstacles and the microstructural evolution during straining should be investigated further to provide more information for understanding the work hardening behaviour for the purpose of enhancing the formability of pre-aged 6xxx alloys.

## 5. Summary

The tensile properties and work hardening behaviour of alloy 6016 were investigated in various naturally aged and pre-aged conditions. The results obtained are as follows:

(1) Natural ageing (0-168 h) causes an increase in strength but relatively little change in the elongation. As for the strain hardening parameters, n decreases and K increases with increasing natural ageing time.

(2) Increasing the pre-ageing temperature from 150 to 250 ºC increases the strength marginally but reduces the values of both n and K.

(3) Naturally aged samples containing both clusters and zones show a higher work hardening rate than as-quenched samples.

(4) Increasing the pre-ageing temperature from 150 to 250 ºC decreases the work hardening rate of the alloy.

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## 6. References

[1] Y. Birol: Mater. Sci. Eng. A 391 (2005) 175-180.
[2] L. Zhen and S. B. Kang: Mater. Letters 37 (1998) 349-353.
[3] A. Serizawa, S. Hirosawa and T. Sato: Metall. Mater. Trans. A 39 (2008) 243-251.
[4] F. A. Guo, Y. L. Ji, X. Gao and B. C. Muddle: Aluminum alloys, Ed. by J. Hirsch, B. Skrotzki and G. Gottstein, (WILEY-VCH, Weinheim, 2008) pp. 849-855.
[5] K. Campbell, I. Dover, T. R. Ramachandran, J. D. Embury: Metals Forum 2 (1979) 229-235.
[6] A. Deschamps, S. Esmaeili, W. J. Poole and M. Militzer: J. Phys. IV France 10 (2000) 151-156.
[7] A. R. Loukus, G. Subhash, M. Imaninejad: J. Eng. Mater. Tech. 129 (2007) 233-241.
[8] Y. Estrin: Unified Constitutive Laws of Plastic Deformation, Ed. By A.S. Krausz and K. Krause, (Academic Press New York, 1996) pp. 69-106.
[9] L. M. Cheng, W. J. Poole, J. D. Embury and D. J. Lloyd: Metall. Mater. Trans. A 34 (2003) 2473-2481.
[10] N. Yu. Zolotorevsky, A. N. Solonin, A. Yu. Churyumov, V. S. Zolotorevsky: Mater. Sci. Eng. A 502 (2009) 111-117.
[11] L. F. Cao, P. A Rometsch, H. Zhong and B. C. Muddle: PRICM-7 (2010) in press.
[12] P. A. Rometsch, L. Cao and B. C. Muddle: The 12th International Conference on Alumnium Alloys (2010) in press.
[13] C. R. Hutchinson, J. D. C. Teixeira, L. Bourgeois: Aluminum alloys, Ed. by J. Hirsch, B. Skrotzki and G. Gottstein, (WILEY-VCH, Weinheim, 2008) pp. 1647-1652.