Improvement in rolling workability of Fe$_3$Al by high-speed rolling

A Muraoka$^1$, H Utsunomiya$^1$, R Matsumoto$^1$ and T Sakai$^2$

$^1$Division of Materials and Manufacturing Science, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
$^2$Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

E-mail: akira.muraoka@mat.eng.osaka-u.ac.jp

Abstract. High-speed rolling is expected to improve the deformability of difficult-to-work alloys. In this work, high-speed rolling was applied to Fe$_3$Al, and the rolling workability was investigated. Fe-28%Al was prepared by plasma arc melting and multi-pass hot-rolled to a sheet 2 mm in thickness, followed by heat-treatment. Both the hot-rolling and heat-treatment were carried out at 1173 K. These specimens were rolled in a one-pass operation with a thickness reduction of 30 % at 1000 m/min in the temperature range from 573 to 973 K. Rolling at 5 m/min was also conducted for comparison. Sound sheets without defects or cracks were obtained even at 673 K in the high-speed rolling, while sound sheets were obtained only above 1173 K in the low-speed rolling. EBSD analysis showed that fine grains were formed either after the high-speed rolling at 873 K or after the low-speed rolling at 1073 K. Vickers hardness is not sensitive to the rolling speed below 773 K and decreased above 773 K and 1173 K in the high-speed rolling and low-speed rolling, respectively. The rolling workability of Fe$_3$Al was significantly improved by the high-speed rolling.

1. Introduction

Some intermetallic compounds have been expected for structural materials, e.g., Ni$_3$Al, Ti$_3$Al, TiAl and Fe$_3$Al. In particular, Fe$_3$Al is an intermetallic compound which shows transformation from the D0$_{21}$ to B2 structures around 823 K. It has many advantages such as low cost, low density, high specific strength and good resistance to oxidation or sulfidation. Thus, it is an environmentally and economically friendly material. However, binary Fe$_3$Al shows very poor ductility as other intermetallics [1], which is a major barrier to its practical applications. So far, many works have been done in order to improve the ductility. The addition of Cr has been widely studied, since first proposed by McKamey et al. [1]. Other alloying elements are also effective for improvement in the ductility [2-4]. Nevertheless, the workability is not improved by such additional elements. For example, Fe-27.8%Al-5.0%Cr-0.1%Zr was rolled in a multi-pass operation with approximately 10 % reduction per pass at room temperature; edge cracking was noticed after about 40 % reduction [5]. In these cases, the rolling speed was no more than approximately 30 m/min. Because both alloying elements and rolling at low speeds are industrially inefficient, other efficient processing methods are required.

Recently, the authors [6, 7] reported that rolling faster than 200 m/min (3.33 m/s) enabled Mg alloys to roll in a one-pass operation with a heavy reduction of 50 %. This is because the time of contact between the sheet and the cold rolls is very short, which does not only prevent heat transfer to rolls during rolling, but also increase heat produced during rolling. Therefore, the temperature during
rolling is higher than the initial rolling, and the grains remain fine due to the low heating temperature of the sheet before rolling and high Zener-Hollomon parameter deformation.

In this study, this high-speed rolling method is applied to Fe$_3$Al in expectation of improved rolling workability compared with conventional rolling with a low speed. Binary Fe-28%Al, where Al is richer than the stoichiometry, was used in order to evaluate only the influence of speed.

2. Experimental procedure

Fe-28%Al (at.%) ingot was prepared by plasma arc melting under argon atmosphere using pure iron and aluminum. The details can be found in [8]. The ingot was hot-rolled to a thickness of 2 mm in several pass operations at 1173 K, followed by homogenization at 1173 K for 1 h and furnace cooling. This hot-rolling process was carried out at 5 m/min with about 15% reduction per pass. The sheet was cut into specimens with 25 mm length and 20 mm width. Two dummy steel sheets, whose lengths were 100 mm and widths and thicknesses were the same as the specimen, were welded to both the front and back of the specimen in the rolling direction by tungsten inert gas welding.

These sheets were rolled in a one-pass operation with a thickness reduction of about 30% at 1000 m/min (16.7 m/s, high-speed) in the temperature range from 573 to 973 K at 100 K intervals. Hereafter, this preheating temperature is referred to as the ‘rolling temperature’. Rolling at 5 m/min (8.33 x 10^{-2} m/s, low-speed) was also performed for comparison with that from 573 K to 1273 K. The rolls were coated with machine oil for lubrication, and the sheets were quenched into water immediately after the rolling. The high-speed rolling was operated on a rolling mill with rolls 530 mm in diameter which has water sprays after the rolls as shown in Figure 1, and the rolling mill with rolls 310 mm in diameter was used for the low-speed rolling.

The microstructure of the rolled sheets was examined by electron backscatter diffraction (EBSD) on the longitudinal section in the SEM. The specimens were mechanically polished and electropolished using a mixture of 7% H$_2$SO$_4$ and 93% CH$_3$OH at 25 V and 273 K. The electron beam automatically scanned in 2 µm steps in the area of 2 x 1 mm$^2$. In the EBSD analysis, the crystal structure was assumed to be bcc. For the Vickers hardness test, ten points were measured around the mid plane of the rolled specimens using a load of 200 g at room temperature. The hardness of annealed specimens in the temperature range from 573 to 973 K was also measured.

![Figure 1. Schematic view of the high-speed rolling mill.](image-url)
3. Results

3.1. Rolling workability

Figure 2 shows the appearance of rolled sheets, where \( r \) is the reduction in thickness of the specimen by rolling. In low-speed rolling below 1073 K, cracks and defects developed in the Fe\(_3\)Al specimen area of the sheets. Particularly, scissors cracks, where cracks initiate at edges and propagate in the rolling direction, developed at both 773 K and 873 K. Sound sheets without cracks and defects were obtained above 1173 K.

In contrast, sound sheets were obtained above 673 K in the high-speed rolling. Even at 573 K, the specimen had a minor crack on its surface, though the reduction in thickness of the high-speed rolled sheets is larger than that of the low-speed rolled ones. This indicates that high-speed rolling enables Fe\(_3\)Al to be rolled at a lower temperature, which was roughly 500 K lower.

![Figure 2](image)

Figure 2. Appearance of low-speed/high-speed rolled sheets as a function of rolling temperature.

![Figure 3](image)

Figure 3. Inverse pole figure maps of low-speed/high-speed rolled sheets as a function of rolling temperature.
3.2. Microstructure and texture
Inverse pole figure maps of ND (top) and RD (bottom) orientations measured by EBSD analysis are shown in Figure 3. After the heat-treatment at 1173 K, equiaxed grains which have little preferred orientation were observed. In either the low-speed rolled sheets below 973 K or the high-speed rolled sheets below 773 K, grains elongated parallel to the rolling direction. In either the low-speed rolling at 1073 K or the high-speed rolling at 873 K, some fine grains believed to be recrystallized grains were formed. Grain size increased with rolling temperature due to grain growth during preheating in the furnace. The texture components of the rolled specimens were similar to those of typical bcc rolling textures, i.e., α-fiber, <110>//RD and γ-fiber, <111>//ND.

3.3. Micro-hardness
Figure 4 shows Vickers hardness of the specimen before and after rolling. The hardness of the rolled specimens was not sensitive to the rolling speed below 773 K, and decreased above 773 K in the high-speed rolling and above 1173 K in the low-speed rolling. It means that high-speed rolling causes the softening temperature to decrease by 400 K. In the figure, hardness of the sheets which were heated in the same furnace, but not rolled is also shown. The hardness is much lower than that after rolling. It is also lower than that of the initial sheet shown by a dashed line. It means that work hardening in the hot rolling is significant. The difference between the hardness before and after the rolling decreases with heating temperature, particularly above 773 K in the high-speed rolling. In other words, dynamic restoration is apparent above 773 K.

4. Discussion
Fe-28%Al sheets were rolled in a one-pass operation with a thickness reduction of 30 % at 1000 m/min in the temperature range from 573 to 973 K. In the high-speed rolling, sound sheets were obtained even at a temperature 500 K lower than the lowest rollable temperature in the low-speed rolling. The hardness decreased above 1173 K in the low-speed rolling and 773 K in the high-speed rolling. The temperature of hardness drop was 400 K lower. Some fine grains were observed at 1073 K in the low-speed rolling and 873 K in the high-speed rolling.

These results can be explained consistently if occurrence of dynamic recrystallization in hot rolling is assumed. If dynamic recrystallization occurred at lower temperatures in high-speed rolling, it is a possible cause for the improvement in rolling workability. In the low-speed rolling, a gradual decrease occurred below 1173 K, resulted in a slight drop of the hardness. On the other hand, in the high-speed rolling, the hardness shows an abrupt drop above 773 K. Thus, the rolling workability of Fe₃Al may be improved by high strain rate deformation and dynamic recrystallization associated with it. When the...
sheet is in contact with the rolls, cracks may develop in low-speed rolling due to the temperature drop. It is supposed that the temperature during the high-speed rolling was higher than that during the low-speed rolling.

The dynamic recrystallization at lower temperatures in high-speed rolling is mostly attributed to higher temperatures during rolling. The temperature change in hot rolling is due to (i) heat generated by plastic work (ii) and friction, as well as (iii) heat loss to the rolls. The plastic work is mostly converted to heat. Flow stress increases with strain rate, so that (i) heat by plastic work increases with speed. A higher relative velocity between the rolls and the specimen produces higher frictional heat. Meanwhile, the high-speed rotating rolls prevent heat transfer to the rolls from sheets due to the short contact time.

If we assume that the thickness temperature distribution is constant, the temperature change of the specimen during rolling can be estimated using equation (1),

\[ \Delta T = \Delta T_p + \Delta T_f - \Delta T_R \]

where \( \Delta T \) is the total change in temperature during rolling, \( \Delta T_p \) is the temperature rise due to plastic work, \( \Delta T_f \) is the temperature rise due to friction and \( \Delta T_R \) is the temperature drop due to contact with cold rolls. \( \Delta T_p \) is calculated using the values of the processing heat, which is estimated by the mean flow stress (shown in Table 1), the equivalent strain, the density of the sheet (7057 kg/m\(^3\)), and the specific heat of the sheet (shown in Table 1). Similarly, \( \Delta T_f \) is calculated using the value of the frictional heat, which is estimated by the assumed friction coefficient of 0.2, the flow stress, the speed of the rolls, the relative velocity and contact time between the rolls and sheet, as well as the thickness reduction, the density and the specific heat of the sheet. \( \Delta T_R \) is calculated using the value of the conductive heat from the material to the rolls, which is estimated by temperatures of the sheet and the rolls, the contact time of the sheet and the rolls, the thermal conductivity of the sheet (shown in Table 1) and the rolls of 73.3 J/(msK), the density of the sheet and the rolls of 7870 kg/m\(^3\), and the specific heat of the sheet and the rolls of 444 J/(kgK), and the thickness reduction. The details of this method can be found in [9, 10]. The temperature difference during the high-speed rolling and the low-speed rolling is estimated to be 80-250 K as shown in Table 1. Here, the flow stress is substituted by the yield stress of Fe-25%Al, and the values are extrapolated from [11]. The values of the specific heat and the thermal conductivity are extrapolated from [12, 13].

**Table 1. Temperature difference during the high-speed rolling and the low-speed rolling.**

| Rolling temperature [K] | Mean flow stress [MPa] | Specific heat of the sheet [J/(kgK)] | Thermal conductivity of the sheet [J/(msK)] | Temperature during low-speed rolling [K] | Temperature during high-speed rolling [K] | Temperature difference [K] |
|-------------------------|------------------------|--------------------------------------|--------------------------------------------|----------------------------------------|------------------------------------------|---------------------------|
| 573                     | 110                    | 807                                  | 16.8                                       | 493                                    | 578                                      | 85.3                      |
| 673                     | 170                    | 814                                  | 16.9                                       | 561                                    | 682                                      | 121                       |
| 773                     | 340                    | 820                                  | 17.0                                       | 633                                    | 814                                      | 181                       |
| 873                     | 270                    | 827                                  | 17.0                                       | 694                                    | 893                                      | 199                       |
| 973                     | 90                     | 833                                  | 17.1                                       | 730                                    | 968                                      | 248                       |

Chen et al. [14] tested the mechanical properties of Fe-28%Al under a strain rate ranging from \(10^{-4}\) to \(1300\) s\(^{-1}\) at room temperature, and concluded that the yield stress is sensitive to the strain rate. In this work, the values of strain rate were about \(5.9 \times 10^{-2}\) s\(^{-1}\) in the high-speed rolling and \(2.6\) s\(^{-1}\) in the low-speed rolling. According to Chen’s data, the flow stress in high-speed rolling could be about 1.3 times as high as that in low-speed rolling. If we suppose that the work during rolling was completely converted to heat, the processing heat is at least 1.3 times higher in the high-speed rolling. Given that the rolling was carried out at an elevated temperature while Chen’s work was done at room
temperature, the influence may be more significant; however, it may be less than the experimental value of 500 K, which is the difference of the temperatures where the hardness decreased.

As shown in Table 1, the temperature during the low-speed rolling is 80-250 K lower than the rolling temperature, while the temperature during the high-speed rolling is as high as the rolling temperature. However, the sheet was successfully rolled at 673 K in the high-speed rolling, and the temperature during rolling is estimated to 682 K. If the factor which influences the workability was only temperature, the sheet could be successfully rolled in the low-speed rolling at 873 K, because the temperature estimated is 694 K.

Therefore, it is impossible to explain the improvement in rolling workability (< 500 K) by only the influence of temperature (< 250 K). Other factors, such as the grain size of the specimen, could affect rolling workability. In the case rollability is improved, the grain size is kept finer because the specimen can be held at a lower temperature before rolling. Materials having a finer grain microstructure are generally easier to deform. Thus, the rolling workability of Fe₃Al is further improved by high-speed rolling. Furthermore, the change in the deformation mode such as slip systems may occur. In order to clarify the improvement in workability, more studies are required.

5. Conclusions
Fe-28%Al sheets were rolled in a one-pass operation with a thickness reduction of 30 % at 1000 m/min in the temperature range from 573 to 973 K. Sound sheets without defects or cracks were obtained even at 673 K in the high-speed rolling, while sound sheets were obtained only above 1173 K with rolling at 5 m/min.

Grains of rolled sheets were elongated parallel to the rolling direction. After either the low-speed rolling above 1073 K or the high-speed rolling above 873 K, equiaxed recrystallization grains were observed.

The hardness is not sensitive to the rolling speed below 773 K, and decreased above 873 K and 1173 K in the high-speed rolling and low-speed rolling, respectively.

These results indicate that the rolling workability of Fe₃Al is significantly improved by high-speed rolling. The improvement in the workability of Fe₃Al by high-speed rolling is mainly due to a smaller temperature drop in hot rolling by a short contact time with rolls. The temperature difference between the high-speed rolling and the low-speed rolling is estimated to be 80-250 K.

Acknowledgement
This work was supported by the “Global COE Program: Center of Excellence for Advanced Structural and Functional Materials Design” from MEXT.

References
[1] McKamey C G, Horton J A and Liu C T 1988 Scr. Metall. 22 1679
[2] Falat L, Schneider A, Sauthoff G and Frommeyer G 2005 Intermetallics 13 1256
[3] Schneider A, Falat L, Sauthoff G and Frommeyer G 2005 Intermetallics 13 1322
[4] Matsumoto N, Kaneno Y and Takasugi T 2007 Tetsu-to-Hagané 93 400
[5] Morris D G, Muñoz-Morris M A and Gutierrez-Urrutia I 2010 Mater. Sci. Eng. A 528 143
[6] Utsunomiya H, Sakai T, Minamiguchi S and Koh H 2006 Magnesium Technology 2006 eds A A Luo, N R Neelamegham and R S Beals (San Antonio: TMS) pp 201-204
[7] Hamada G, Sakai T and Utsunomiya H 2010 Adv. Mater. Res 89-91 227
[8] Yasuda H Y, Kouzai K, Kawamura Y and Umakoshi Y 2010 ISIJ Int. 50 147
[9] Kokado J 1970 Sosei-to-Kakou 11 816
[10] Ataka M 1972 Seisankenkyu 24 225
[11] Nishio Y and Tanahashi T 2004 Mater. Sci. Eng. A 387-389 973
[12] Rudajevová A and Sima V 1997 Mater. Res. Bull. 32 441
[13] Rudajevová A and Buriáněk J 2001 J. Phase Equilibria 22 560
[14] Chen M, Lin D, Xia Y and Liu C T 1997 Mater. Sci. Eng. A 239-240 317