Influence of Casting Defects on Tensile Properties of ADC12 Aluminum Alloy Die-Castings

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Cold flakes, one of casting defects, were observed through acoustic microscopy in aluminum alloy die-cast plates (ADC12), and specimens having a cold flake of different sizes were prepared and subjected to the tensile testing. The tensile strength linearly decreased with the size of the cold flake, and the decreasing rate of the strength was greater for the specimen with the exposed cold flake than that with the embedded cold flake. The in-process ultrasonic measurement was carried out during tensile testing, and it was found that the oxide layer of the cold flake was detached from the matrix to form a crack before final failure. Then by using the linear fracture mechanics, the critical value K_{IC}^* at failure was evaluated to be 8–10 MPa·m^{1/2} from the tensile strength, which value was slightly lower than the fracture toughness of the matrix of 11–14 MPa·m^{1/2}. [doi:10.2320/matertrans.F-MRA2008814]

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1. Introduction

Aluminum alloy die-casts are often used in products such as automobiles, and suffer repeated loading and thermal cycling in usage. Therefore, all factors to affect the mechanical properties of die-casts should be recognized and reliability of these components must be guaranteed. From this point of view, lots of studies have been carried out on tensile properties and fatigue properties of die-casts containing porosity,^{1–7)} shrinkage cavity,^{8,9)} oxide inclusion,^{10–12)} microstructure^{13–15)} and other casting defects.^{16–25)} Among casting defects, interests have been concentrated in the effect of the cold flake,^{21–25)} one of irregular structures. The cold flake is introduced in die-cast products during production process: when the molten metal is poured in the shot sleeve and pushed in a die by a plunger, the initially solidified layer of the melt is broken into small parts, and these parts distribute in the molten metal to remain as cold flakes. At the time when the molten metal attaches the sleeve wall, the oxide layer is formed on the cold flake, and the oxide layer is often contaminated by lubricants and accompanied by pores²⁶⁾ to reduce wettability with the matrix. Therefore, mechanical properties of die-casts are largely decreased with the amount of the cold flake.²⁷⁾ Although many efforts have been done to eliminate cold flakes, no success has been attained to eliminate them completely from die-cast products.²⁸⁾

Recently, the authors^{29,30)} carried out the ultrasonic measurement and the acoustic microscopy of aluminum alloy die-cast plate (ADC12) containing cold flakes, and it was found that the oxide layer and the body of the cold flake were observed as bright and dark regions in the acoustic image, respectively. The authors³⁰⁾ also carried out the bending test, and showed that a crack propagated through the coarse cold flake directing transversely to the bending stress. The critical stress intensity factor for final failure was also evaluated from the bending strength. In the previous work,³⁰⁾ however, the bending strength was not precisely measured, and the critical stress intensity factor was analyzed without verification of existence of the crack in the specimen prior to

the final failure. Then, the authors³¹⁾ have carried out the in-process ultrasonic measurement, and it was found that the cold flake detached from the matrix to form a crack during tensile testing. From these circumstances, it is vital to verify the effect of the oxide layer on the strength quantitatively, and also to evaluate the criterion for final failure from the standpoint of the fracture mechanics.

In the present work, the tensile testing was carried out with aluminum alloy die-cast plate (ADC12) containing coarse cold flakes to verify the effect of the size and the direction of the cold flake on the tensile strength quantitatively. And the criterion for the final failure was discussed from the standpoint of the fracture mechanics.

2. Experimental Procedure

2.1 Specimen preparation

Aluminum alloy die-cast plates (ADC12, nominal composition of Al-11 mass% Si-2.5 mass% Cu) of 4 mm in thickness, 300 mm in length and 100 mm in width were produced by using wider gates and longer shot time lags to contain greater cold flakes in the die-cast plates. Then, acoustic images with an area of 18 mm × 18 mm were obtained with the scanning acoustic microscope (SAM) by using a probe generating a longitudinal wave of 50 MHz in frequency and with a focal distance of 12 mm in water. Acoustic images were obtained at positions 2 mm below the surface within 72 mm × 234 mm in area as shown in Fig. 1, which was composed of 52 images. In the figure, the oxide layer of the cold flake is observed as a bright segment or granule. Fine spots in the figure are silicon crystals in the matrix. Specimens having a cold flake of different sizes were prepared for tensile testing, as shown in Fig. 2.

2.2 Tensile testing

The tensile testing was carried out with a crosshead speed of 0.5 mm/min (the initial strain rate of about $1.85 \times 10^{-4} \text{ s}^{-1}$) to fracture. Then fracture surfaces were observed through optical microscope and scanning electron micro-

Fig. 1 Acoustic image of die-cast plate for preparation of tensile specimen. Bright segments and large spots show oxide layers of cold flake, and fine spots are silicon crystals in matrix.

Fig. 2 Shape and dimensions of specimen for tensile testing.

Fig. 3 Setup for in-process ultrasonic measurement during tensile testing.

scope (SEM). A nominal tensile strength was obtained as a load at fracture (P_f) divided by an area of the initial cross section (A_0). Then, an effective strength was obtained as a load at fracture (P_f) divided by an effective cross section ($P_f/(A_0 - A_{OL})$, where A_{OL} is the area of the oxide layer of the cold flake). In the calculation of the effective strength, specimens containing a cold flake inclined with an angle of $5\pi/12$ rad (75°) or more from the tensile direction were chosen, and an area of the oxide layer of the cold flake was measured on the fracture surface.

2.3 Ultrasonic measurement

As shown in Fig. 3, the in-process ultrasonic measurement was carried out during tensile testing with a probe generating a longitudinal wave of 20 MHz in frequency encapsulated in a water bag made of a latex membrane about $70\mu\text{m}$ in thickness to examine detachment of the cold flake from the

Fig. 4 Typical stress-strain curves for specimens with and without cold flake.

matrix in the tensile testing. In the measurement, the ultrasonic wave was incident normal to the specimen surface and focused at the oxide layer of the cold flake to maximize the intensity of the reflection echoes.

3. Results and Discussion

3.1 Influence of oxide layer of cold flake on tensile strength

Typical stress-strain curves for specimens with and without a cold flake are shown in Fig. 4. For specimens containing the cold flake of the considerable size, the strength and the elongation at fracture were significantly smaller than those of the specimen without the cold flake.

Typical acoustic images were taken with the specimen containing the embedded cold flake before and after tensile testing, as shown in Fig. 5. Two coarse cold flakes were observed in the figure before tensile testing, but a crack propagated through the oxide layer of the cold flake directing perpendicular to the tensile direction. This was confirmed by the fracture surface shown in Fig. 5(c). In the figure, a path of the crack propagation was not clear, but the crack initiated from the embedded oxide layer and propagated in the matrix. A typical example of crack propagation is shown in Fig. 6, in which radiating ridges expand from the oxide layer of the cold flake.

Fig. 5 Comparison of acoustic image and fracture surface of specimen with embedded cold flakes. Crack propagated through oxide layer directing transversely to tensile direction. (a) Acoustic image before testing (b) Acoustic image after break (c) Fracture surface.

Fig. 6 Fracture surface showing radiating ridges from embedded cold flake.

Figure 7 shows the case of the exposed cold flake. The crack propagated through the oxide layer as shown in Fig. 7(c), in which the radial pattern spreads from the oxide layer.

As was shown in Fig. 5, when the oxide layer was parallel to or slightly inclined from the tensile direction, it did not act as the crack initiation site no matter if the cold flake was embedded or exposed, but the crack initiated at the other exposed cold flake directing perpendicular to the tensile direction.

In Fig. 8, a relation between the nominal tensile strength and the area of the oxide layer of the cold flake is shown. In the figure, regression solid lines for specimens with the embedded and the exposed oxide layers were obtained by the least square fitting, and the dotted line shows the tensile strength σ_B (about 285 MPa) of the sound specimen without cold flake or with a small one comparable to the silicon particle. The figure also includes results obtained by Iwahori *et al.*²⁴⁾ and Okayasu *et al.*²⁵⁾ measured with aluminum alloy die-casts ADC12 and ADC10 for comparison. The area of the oxide layer had a deleterious effect on the tensile strength, and the tensile strength of the specimen with the exposed cold flake took a far smaller value than the specimen with

Fig. 7 Comparison of acoustic image and fracture surface of specimen with exposed cold flake directing transversely to tensile direction. (a) Acoustic image before testing (b) Acoustic image after break (c) Fracture surface.

Fig. 8 Change in nominal tensile strength σ_N with area A_{OL} of oxide layer of cold flake.

the embedded cold flake. The tensile strength obtained in the present work was lower than the strengths obtained by Iwahori *et al.*²⁴⁾ and Okayasu *et al.*²⁵⁾ This difference is due to difference in the estimated area of the cold flake. In the present work, the tensile strength was related to the area of the cold flake from where the crack initiated. On the other hand, Iwahori *et al.* and Okayasu *et al.* related the strength with the total area of cold flakes appeared in the fracture surface, and hence the area of the oxide layer was over-estimated.

Figure 9 shows a relation between the effective tensile strength and the area of the oxide layer. The effective tensile strength was raised to some extent from the nominal tensile strength, but still shows a tendency to decrease with the area of the oxide layer.

The tensile strength took lower value when the oxide layer was exposed to the surface. Figure 10 compares typical two specimens containing exposed cold flakes of different areas and exposed lengths. Even if the area of the oxide layer was larger, when the exposed length of the oxide layer was

Fig. 9 Change in effective tensile strength σ_E with area A_{OL} of oxide layer of the cold flake.

smaller, the tensile strength took a higher value, as tabulated in the figure. Therefore, the influence of the exposed length of the cold flake on the tensile strength was examined. As shown in Fig. 11, the tensile strength decreased with increasing exposed length of the oxide layer.

3.2 Crack opening during tensile testing

It is said that the oxide layer acts as a nature of cracks.¹⁰⁾ However, as shown in Fig. 12, the cold flake tightly joins with the matrix through the oxide layer. Therefore, the in-process ultrasonic measurement was carried out during tensile testing to examine detaching of the cold flake from the matrix before final failure. Figure 13 shows a typical change in the ultrasonic wave (R_{CF} in the figure) reflected from the oxide layer of the cold flake during tensile testing. In this case, the intensity of the echo R_{CF} did not change up to a stress of about 200 MPa, and at about 205 MPa, the echo

Specimen	Area of oxide layer, A_{OL}/mm^2	Exposed length, L_{OL}/mm	Tensile strength, σ_E/MPa
A	1.0	1.9	170
B	2.0	1.6	208

Fig. 10 Comparison of fracture surface and tensile strength of specimens with cold flakes of different exposed lengths of oxide layer.

Fig. 11 Relation between effective tensile strength σ_E and exposed surface length L_{OL} of cold flake.

Fig. 12 Typical boundary between cold flake and matrix.

Fig. 13 Typical change in ultrasonic wave (R_{CF}) reflected from oxide layer of embedded cold flake. S and B show echoes reflected from surface and bottom, respectively.

intensity decreased. At a stress of about 216 MPa, the echo intensity increased again, but a sign of the echo was changed from negative (downward in the figure) to positive (upward). At this stage, it was thought that the oxide layer was detached from the matrix to form a crack.

3.3 Criterion for final failure

In the tensile testing, the oxide layer of the cold flake was detached from the matrix to form a crack before final failure.

Fig. 14 Comparison of critical value K_{IC}^* at failure obtained with equations given by Murakami, Ishida and Newman.

Therefore the criterion for failure was discussed from the standpoint of the fracture mechanics. Since the stress-strain curve showed nonlinearity as shown in Fig. 4, the nonlinear fracture mechanics, such as the J-integral approach, should be applied in the analysis.³²⁾ However, the specimen was broken in a brittle manner with a small deformation, and hence as a simple treatment, the linear fracture mechanics was applied to obtain the critical stress intensity factor at failure as the critical value K_{IC}^* at failure.

For embedded and exposed cold flakes, critical stress intensity factors were calculated with equations given by Murakami^{33,34)} and Ishida and Noguchi,³⁵⁾ and those given by Murakami^{33,34)} and Newman and Raju,^{36,37)} respectively. See Appendix for precise representation of the stress intensity factors.

The critical value K_{IC}^* at failure for embedded and exposed cold flakes is represented in Fig. 14 as a function of the area of the oxide layer. In the figure, K_{IC}^* obtained with different equations are plotted in the same range, but distributed in a range of 6–10 MPa·m^{1/2}. When the area of the oxide layer was lower than 2.5 mm², K_{IC}^* tended to decrease with decreasing area of the oxide layer, but it took almost a constant value in a range of 8–10 MPa·m^{1/2} for the oxide layer of the area above 2.5 mm². K_{IC}^* of 8–10 MPa·m^{1/2} was slightly lower than the fracture toughness K_{IC} of 11–14 MPa·m^{1/2} measured by Kanazawa *et al.*³⁸⁾

The decrease in K_{IC}^* at smaller area of the oxide layer is caused by nonlinearity of the stress-strain curve. The specimen containing the coarse cold flake was broken after small deformation with a slight nonlinearity of the stress-strain curve. To the contrary, the specimen containing the small cold flake deforms largely before breaking to show a considerable nonlinearity of the stress-strain curve. In this case, the parameter is underestimated.

When the specimen contains the coarse cold flake, K_{IC}^* took a constant value of 8–10 MPa·m^{1/2}, but this value is slightly smaller than the fracture toughness K_{IC} of 11–14 MPa·m^{1/2}. This discrepancy can be due to some causes such as:

- (1) Nonlinearity of the stress-strain curve
- (2) The rigidity effect of the oxide layer

The first term is mentioned in the above section. The second term is as follows: when the crack is formed by detaching of the cold flake from the matrix, one side of the crack surface was covered by the oxide layer. Since the Young's modulus of the aluminum oxide (Al_2O_3) is about 300 GPa, and is significantly greater than that of the matrix of 70 GPa, the interfacial crack deforms asymmetrically with increasing tensile stress, because the oxide layer restricts opening of the crack, to reduce the criterion for failure. It has been also reported that the fracture toughness of Al/ Al_2O_3 sandwich specimen takes a value between the fracture toughness of the monolithic aluminum and the alumina,³⁹⁾ which supports the smaller value of K_{c}^* than the fracture toughness of the matrix.

From these discussions, it can be said that the strength of the die-cast products containing cold flakes is roughly predicted: when the area A_{OL} of the cold flakes directing transversely to the tensile direction is evaluated by the nondestructive method such as the ultrasonic microscopy, the tensile strength is evaluated by substituting K_{c}^* and the area A_{OL} or the size of the oxide layer of the cold flake in the equation of the stress intensity factor.

4. Conclusion

The effect of the cold flake on the tensile strength of the aluminum alloy die-cast (ADC12) was examined, and following conclusions are drawn.

- (1) The tensile strength linearly decreases with the area of the oxide layer of the cold flake directing perpendicular to the tensile direction. The exposed cold flake decreases the tensile strength more severely than the embedded one. When the oxide layer is parallel to or slightly inclined from the tensile direction, the cold flake has no major effect on the tensile strength.
- (2) The in-process ultrasonic measurement was conducted during tensile testing, and it was found that the oxide

layer of the cold flake detached from the matrix to form a crack before failure.

- (3) The linear fracture mechanics approach was employed, and the critical stress intensity factor at failure was obtained to be 8–10 $\text{MPa}\cdot\text{m}^{1/2}$ as the critical value K_{c}^* at failure, and the value was slightly lower than the fracture toughness of 11–14 $\text{MPa}\cdot\text{m}^{1/2}$.

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Appendix

Murakami^{33,34)} gave the following stress intensity factor for the exposed and embedded cracks:

$$K_{\text{I,Murakami}} = \sigma_0 \alpha \sqrt{\pi \sqrt{A_{\text{c}}}}, \quad (\text{A.1})$$

where σ_0 is the stress at fracture, A_{c} is the area of the crack, and α is 0.65 and 0.50 for the exposed and embedded cracks, respectively.

Ishida and Noguchi³⁵⁾ gave the stress intensity factor for the embedded elliptical crack suffering a tensile force given by

$$K_{\text{I,Ishida}} = \frac{\sigma_0 \sqrt{\pi b}}{\phi} M_{\text{A}}, \quad (\text{A.2})$$

where

$$\phi = \left[1 + 1.464 \left(\frac{b}{a} \right)^{1.65} \right]^{\frac{1}{2}} \quad (b \leq a), \quad (\text{A.3})$$

$$\phi = \left[1 + 1.464 \left(\frac{a}{b} \right)^{1.65} \right]^{\frac{1}{2}} \quad (b > a), \quad (\text{A.4})$$

$$\begin{aligned} (M_{\text{A}})_{\varepsilon=0} &= 1.0000 + \lambda(0.1786 - 0.0396\mu - 0.8255\mu^2 + 0.8897\mu^3) \\ &\quad + \lambda^2(-0.6985 - 0.3101\mu + 3.3302\mu^2 - 3.1085\mu^3) \\ &\quad + \lambda^3(1.9715 - 2.4531\mu + 0.0386\mu^2 + 1.3748\mu^3), \end{aligned} \quad (\text{A.5})$$

$$\begin{aligned} M_{\text{A}} &= 0.9995 + 0.0005\mu - 0.0001\mu^2 - 0.0001\mu^3 \\ &\quad + \lambda(0.2038 - 0.3856\mu + 0.5519\mu^2 - 0.2746\mu^3) \\ &\quad + \lambda^2(-0.7489 + 0.6965\mu - 0.9850\mu^2 + 0.5678\mu^3) \\ &\quad + \lambda^3(1.3763 - 1.0266\mu + 0.4242\mu^2 - 0.1049\mu^3), \end{aligned} \quad (\text{A.6})$$

where M_{A} is the so-called stress intensity magnification factor showing the free surface effect, $2a$ and $2b$ are principal diameters of the elliptical crack, d is the plate thickness, $\mu = b/a$, $\lambda = b/d$. The range of applicability is $0.125 \leq b/a \leq 1.0$, $b/d \leq 0.8$ for the center crack, and $0 \leq b/a \leq 1.0$, $0 \leq b/d_1 \leq 0.8$ for the eccentrically located crack, where d_1 is the distance of the crack from the surface.

Newman and Raju^{36,37)} gave the stress intensity factor for the surface crack under tension given by

$$K_{\text{I,Newman}} = \frac{\sigma_0 \sqrt{\pi b}}{E_{\text{K}}} F\left(\frac{b}{a}, \frac{b}{d}, \frac{a}{w}, \theta\right), \quad (\text{A.7})$$

where, $2w$ is the plate width, and θ is the parametric angle ($\pi/2$ in the present calculation).

$$E_{\text{K}} = \left[1 + 1.464 \left(\frac{a}{b} \right)^{1.65} \right]^{\frac{1}{2}}, \quad \text{for } b/a > 1 \quad (\text{A.8})$$

$$E_K = \left[1 + 1.464 \left(\frac{b}{a} \right)^{1.65} \right]^{\frac{1}{2}}, \quad \text{for } b/a \leq 1 \quad (\text{A}\cdot 9)$$

$$F = \left[M_1 + M_2 \left(\frac{b}{d} \right)^2 + M_3 \left(\frac{b}{d} \right)^4 \right] f_\theta g f_w, \quad (\text{A}\cdot 10)$$

$$\left. \begin{aligned} M_1 &= 1.13 - 0.09 \left(\frac{b}{a} \right), \quad \text{for } b/a \leq 1 \\ M_1 &= \sqrt{\frac{a}{b}} \left(1 + 0.04 \frac{a}{b} \right), \quad \text{for } b/a > 1 \end{aligned} \right\} \quad (\text{A}\cdot 11)$$

$$\left. \begin{aligned} M_2 &= -0.54 + \frac{0.89}{0.2 + b/a}, \quad \text{for } b/a \leq 1 \\ M_2 &= 0.2 \left(\frac{a}{b} \right)^4, \quad \text{for } b/a > 1 \end{aligned} \right\} \quad (\text{A}\cdot 12)$$

$$\left. \begin{aligned} M_3 &= 0.5 - \frac{1}{0.65 + b/a} + 14 \left(1 - \frac{b}{a} \right)^{24}, \quad \text{for } b/a \leq 1 \\ M_3 &= -0.11 \left(\frac{a}{b} \right)^4, \quad \text{for } b/a > 1 \end{aligned} \right\} \quad (\text{A}\cdot 13)$$

$$\left. \begin{aligned} f_\theta &= \left[\left(\frac{b}{a} \right)^2 \cos^2 \theta + \sin^2 \theta \right]^{\frac{1}{4}}, \quad \text{for } b/a \leq 1 \\ f_\theta &= \left[\left(\frac{a}{b} \right)^2 \sin^2 \theta + \cos^2 \theta \right]^{\frac{1}{4}}, \quad \text{for } b/a > 1 \end{aligned} \right\} \quad (\text{A}\cdot 14)$$

$$\left. \begin{aligned} g &= 1 + \left[0.1 + 0.35 \left(\frac{b}{d} \right)^2 \right] (1 - \sin \theta)^2, \quad \text{for } b/a \leq 1 \\ g &= 1 + \left[0.1 + 0.35 \left(\frac{a}{b} \right) \left(\frac{b}{d} \right)^2 \right] (1 - \sin \theta)^2, \quad \text{for } b/a > 1 \end{aligned} \right\} \quad (\text{A}\cdot 15)$$

$$f_w = \left[\sec \left(\frac{\pi a}{2w} \sqrt{\frac{b}{d}} \right) \right]^{\frac{1}{2}}. \quad (\text{A}\cdot 16)$$

The range of applicability is $0 < b/a \leq 2.0$, $a/w < 0.5$ and $0 \leq \theta \leq \pi$.

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