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Method of Evaluation of Distribution Characteristics of Flaky Inclusions*

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Метод оценки характеристик распределения хлопьевидных включений

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Для определения максимального размера хлопьевидных включений в литом магниевом сплаве с добавками кремния предложен метод оценки характеристик распределения указанных включений. Применимость метода проверена путем компьютерного моделирования с произвольными распределениями включений. Метод позволяет прогнозировать максимальный размер хлопьевидных включений в произвольном объеме материала.

Ключевые слова: включение, дефект литья, концентрация напряжений, масштабный фактор, статистический метод, дефект материала, негорючий магниевый сплав.

Introduction. A Si-added noncombustible Mg casting alloy [1] has flaky inclusions. The flaky inclusions are larger than the defects in a normal casting material and the number of the flaky inclusions in this material per unit volume is much less than the inclusions in a normal casting material. Figure 1 shows an example of a flaky inclusion (oxidation).

A mechanical structure has many stress concentration areas. However, the stress concentration volumes of the mechanical structure made by this alloy are usually small. In order to put this material into practical use, it is necessary to control the inclusions so as not to include them in a stress concentration volume. In order to control the inclusions, it is necessary to evaluate the maximum size of the flaky inclusions. It seems effective to apply statistics of extreme [2, 3] to this material, although for such a small volume like a stress concentration volume, it is important that the control volume should be smaller than the stress concentration volume. However, the control volume cannot be small due to the properties of the flaky inclusions. Thus, the statistics of extreme are not effective in this case.

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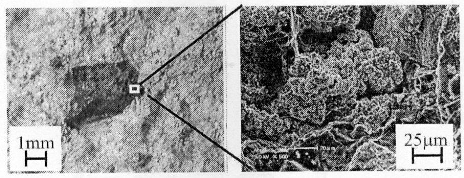


Fig. 1. Oxide inclusion appeared on fracture surface [1].

In this study, we propose an evaluation method of the size distribution characteristics not only of extreme values, but also all the size regions of the flaky inclusions. The sizes of the inclusions are measured from the fracture surfaces obtained from the tensile tests. Alternately, the results of fatigue tests can be used instead of tensile tests, since in both cases the material fracture start from the inclusion. The validity of this method is verified through simulations with materials that have arbitrary inclusion distributions. The proposed method enables prediction of the maximum size of the flaky inclusions in an arbitrary volume.

1. **Proposed Evaluation Method**.

1.1. ***Repetitive Tensile Test***. When a tensile test is performed using a material, which obeys the weakest link theory, the fracture sourcen is the maximum size inclusion in the control volume. The inclusion appears on the fracture surface. With this phenomenon, the repetitive tensile test is proposed by the authors as the method to evaluate the size distribution characteristics of the inclusions. Figure 2 shows the schematic diagram of the repetitive tensile test. For the first test, the fracture source should be the maximum size inclusion in the specimen, and the inclusion appears on the fracture surface. After the first test, the inclusions, which are fracture sources emerging on the fracture surfaces, are smaller than the inclusion which is a fracture source of the first test. In this way, the sizes of the inclusions are measured from the fracture surfaces. The size distribution of the inclusions can then be estimated by the repetitive tensile testing.

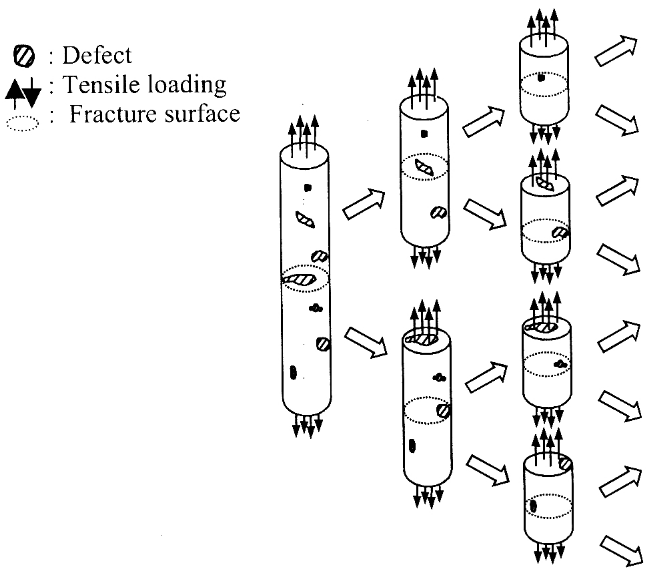


Fig. 2. Schematic diagram of the repetitive tensile test.

A tensile specimen usually has grip sections. The diameter of the specimen grip section is greater than that of the control volume. However, since the total volume of the specimen for the repetitive tensile test must be treated as the control volume, specimens with no grip section should be used for the tests. The cross section of the specimen has a uniform shape. In order to apply a tensile load to the specimen, its edge must be gripped. However, the inclusions in the grip sections will not be the fracture origin because no load is applied to the grip sections. The true size distribution of inclusions may not correspond to the distribution obtained from the repetitive tensile tests. Therefore, in order to estimate the size distribution of inclusions from the result with the specimen with grip sections, the repetitive test results need to be refined.

1.2. ***Correction Method of the Test Results***. In this paper, $\sqrt{area}$ is used as the size of the flaky inclusions similar to the Murakami method [4]. Figure 3 shows the definitions of $\sqrt{area}$.

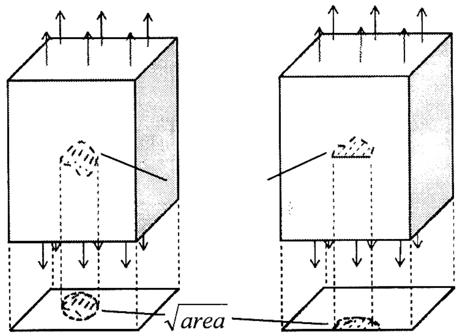
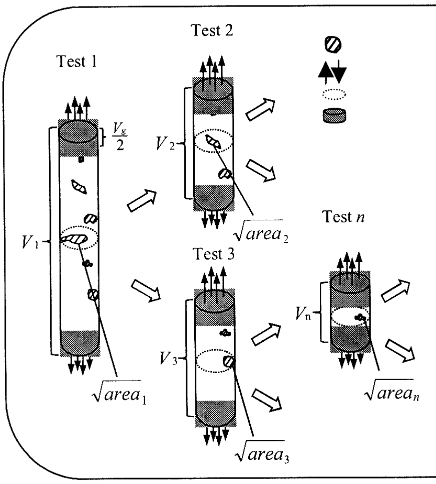


Fig. 3. Definitions of $\sqrt{area}$.

Figure 4 shows the correction method of the repetitive tensile test considering the grip sections. The expected value of the inclusion whose size is $\sqrt{area_1}$ in the control volume V_1 is estimated as follows. A tensile test is carried out using the specimen whose volume is V_1 in Test 1. The fracture origin size is $\sqrt{area_1}$. When the total grip section volume is V_g, the tested volume is $(V_1 - V_g)$. The Test 1 result is that the maximum inclusion size in the volume $(V_1 - V_g)$ is $\sqrt{area_2}$. Considering the ratio of volume V_1 to volume $(V_1 - V_g)$, the expected value of the inclusions whose size is $\sqrt{area_1}$ in the volume V_1 is $1 \times V_1/(V_1 - V_g)$.

The expected value of the inclusion whose size is $\sqrt{area_2}$ in the control volume V_2 is considered as follows. The tensile test is carried out using the specimen whose volume is V_2 in Test 2. The fracture origin size is $\sqrt{area_2}$. The Test 2 result is that the maximum inclusion size in the volume $(V_2 - V_g)$ is $\sqrt{area_2}$. The expected value of the inclusions whose size is $\sqrt{area_2}$ in the volume V_2 is $1 \times V_1/(V_1 - V_g)$. The number of inclusions whose sizes are over $\sqrt{area}$ is defined as $F_V(\sqrt{area})$. The expected value of the inclusions whose size is $\sqrt{area_2}$ in the



Defect size	Cumulative number, $F_V(\sqrt{area})$	
	Test result	Correction result
$\sqrt{area_1}$	1	$1\times\frac{V_1}{V_1-V_g}$
$\sqrt{area_2}$	2	$1\times\frac{V_1}{V_1-V_g}+1\times\frac{V_2}{V_2-V_g}$
$\sqrt{area_3}$	3	$1\times\frac{V_1}{V_1-V_g}+1\times\frac{V_2}{V_2-V_g}+1\times\frac{V_3}{V_3-V_g}$
⋮	⋮	⋮
$\sqrt{area_n}$	n	$\sum_{k=1}^{n}(1\times\frac{V_k}{V_k-V_g})$
⋮	⋮	⋮

Fig. 4. Correction method.

volume V_1 is $F_{V_1}(\sqrt{area_2}) = 1\times V_1/(V_1 - V_g) + 1\times V_2/(V_2 - V_g)$ when considering the Test 1 result because $\sqrt{area_1} \geq \sqrt{area_2}$.

Test n is carried out using the specimen whose volume is V_n. The expected value of the inclusions whose size is $\sqrt{area_n}$ in the volume V_n is

$$F_{V_n}(\sqrt{area_n}) = \sum_{k=1}^{n}\left(1\times\frac{V_k}{V_k - V_g}\right). \qquad (1)$$

Based on the correction to the test result by considering the grip sections volume, the size distribution of the inclusions can be predicted. The specimen becomes shorter after every tensile test. When the specimen cannot be gripped, the repetitive tensile test ends.

2. **Validation by Simulation**.

2.1. ***Validation Method***. Real materials have an unknown inclusion distribution. Therefore, corrected distributions and real distributions cannot be compared by repetitive tensile tests using real materials, and.the validity of the proposed repetitive tensile test cannot be verified. In this paper, numerical simulations of repetitive tensile tests are performed on a computer with an assumed inclusion distribution. The following expression based on the expression proposed by Hashimoto et al. [5] is used as the assumed inclusion distribution.

$$F_V(\sqrt{area}) = \overline{M}_V \exp\left[-\left(\frac{\sqrt{area}}{\lambda}\right)^{\nu}\right], \qquad (2)$$

where $\overline{M}_V$ is average number of all inclusions in the specimen, and λ and ν are constant number depending on particle characteristic.

At the start, λ and ν are assumed. In order to confirm that the proposed method does not depend on a distribution characteristic, simulations are performed for three materials that have different λ and ν values. Table 1 shows the assumed λ and ν values.

T a b l e 1

Assumed Constants for Simulation

Material	$\overline{M}_V$	λ	ν
Material I	10	93	0.3
Material II	10	651	1.0
Material III	10	1136	3.0

The length of the specimen is assumed to be a unit length. Random numbers are allocated to the inclusions. The random numbers are the position coordinates of the inclusions in a specimen. The coordinate uses one axis parallel to the loading direction. With this specimen, operations to break the specimen from the maximum size inclusions are repeated. However, some constant length from the edge of the specimen is the grip section. When the maximum size inclusion is in the grip section, the specimen is broken from the maximum size inclusion in the volume without grip sections.

Test results may vary according to the proportion of grip section volume to specimen volume. The grip section volume is prepared of 2 proportions, and the differences in both are compared. The prepared proportion of the grip sections to the specimen volume are 10 and 20%.

2.2. ***Simulation Results and Discussion***. Figures 5 and 6 show the repetitive tensile test simulation results and the refined results in which the grip sections are assumed to be 10 and 20% of the specimen volume, respectively.

All figures show ten simulation results with the changing positions of the inclusions. The reason why more than one simulation result is shown is that $F_V(\sqrt{area})$ is the mean distribution of the inclusion sizes and the number in a certain volume material. The simulation results for the same material differ because inclusions are randomly placed in a specimen. The simulation results and refined results are case studies. It is expedient to compare the assumed distributions and corrected results by more than one simulation result. The test results are lower than assumed distributions in Figs. 5 and 6 because the inclusions in the grip sections do not originate from a fracture. However, the refined results are distributed around the assumed distributions. The refined results agree with the assumed distributions. The scatter of the refined results in Fig. 5 is wider than that in Fig. 6 because the grip section volume of the specimen in Fig. 5 is larger than that in Fig. 6. However, the refined results in Fig. 5 and Fig. 6 agree with the assumed distributions. Consequently, the proposed correction method for the repetitive tensile test result is considered to be adequate and invariant to the grip section length.

Conclusions. The repetitive tensile test and the correction method are proposed as the method to evaluate the inclusion distribution for the all size ranges. The

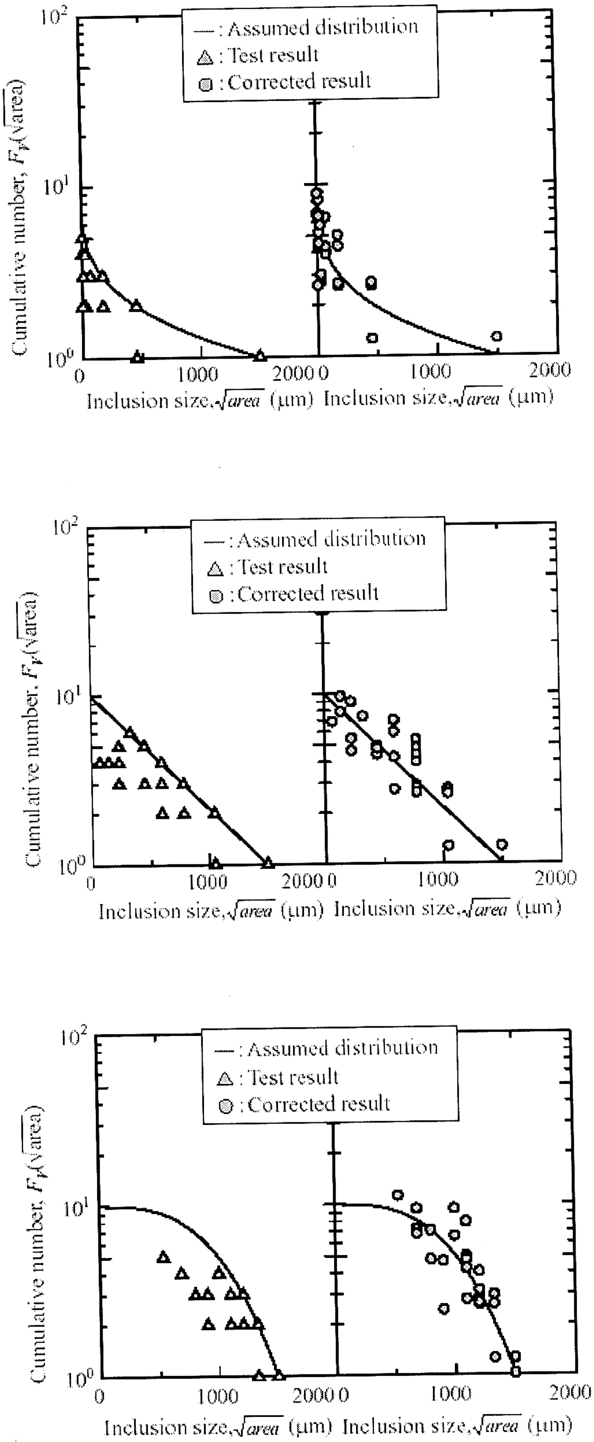


Fig. 5. Simulation results. (The grip volume is 10% of the specimen volume.)

validity of the proposed correction method is verified by the simulation using the proposed evaluation method.

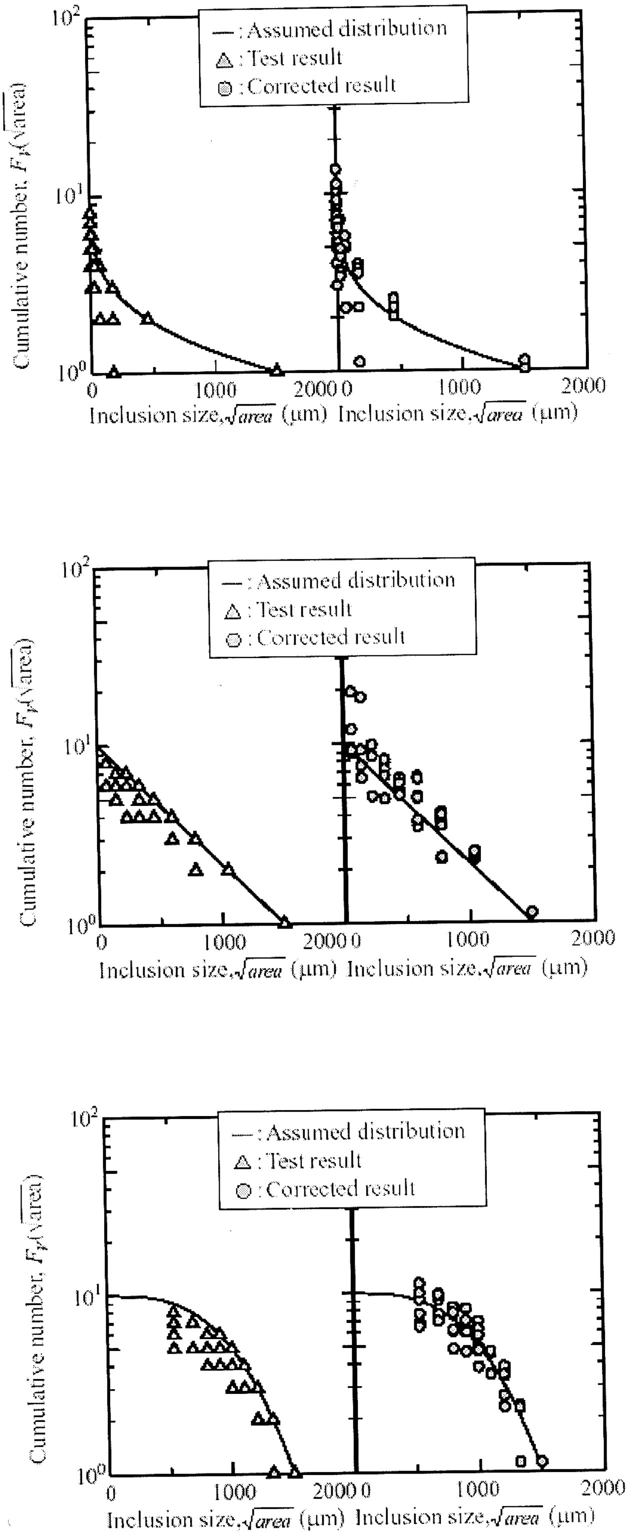


Fig. 6. Simulation results. (The grip volume is 20% of the specimen volume.)

Р е з ю м е

Для визначення максимального розміру пластівчастих включень у литому магнієвому сплаві з домішками кремнію запропоновано метод оцінки характеристик розподілу вказаних включень. Робота методу перевірена шляхом комп'ютерного моделювання з довільним розподілом включень. Метод дозволяє прогнозувати максимальний розмір пластівчастих включень у довільному об'ємі матеріалу.

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