Proposed Strength Evaluation Method for Casting Material with Defects
(Using Non-combustible Mg Alloy with Added-Si)*

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Abstract
In order to evaluate a casting material which had a variable tensile strength, a strength evaluation method was proposed. Tensile tests were carried out on a specimen with a particular artificial defect as the fracture origin. The fracture origin size could be controlled using the proposed evaluation method. Therefore, the tensile test results, which had slight scatter, were obtained. However, the shape of the artificial defect was different from the casting defect, thus the effects of each defect on the tensile strength might be different. Both the critical stress intensity factors at the beginning of the unstable fracture were then compared, and it was clarified that the artificial defect and the casting defect had the same effect on the tensile strength. By this method, a non-combustible Mg alloy with added-Si, which contained large casting defects, could be evaluated. It was clarified that there was no difference of tensile strength between the noncombustible Mg alloys with 1% and 2% Si, and the relationship between the tensile strength and temperature was obtained.

Key words: Tensile Strength, Material Flaw, Stress Intensity Factor, Casting Material, Non-Combustible Magnesium Alloy, Artificial Defect, Nonferrous Metal, Unstable Fracture

1. Introduction
Reducing the weight of transport machinery, such as cars, is now required to solve the global warming issue and energy problems. It is well-known that magnesium alloys have a high specific strength, are excellent for recycling and the damping characteristic is excellent. Therefore, body lightening by the reduction of the sound insulator and the acoustic material based on the decrease in the engine noise can be expected by applying the magnesium alloy casting material to the engine materials of the car to replace the current aluminum alloy casting materials. However, the tensile strength of ordinary magnesium alloy remarkably decreases (1) at about 200 °C which is the typical temperature range of the engine materials. Moreover, because magnesium is quite active, and it ignites (2), (3) in air atmosphere at high
temperature. Thus, it is difficult for ordinary magnesium alloys to be cast-worked in air; therefore, a special protective atmospheric gas and flux should then be used in the casting procedure. The ignition point was raised by adding about 2% calcium to the magnesium alloys, then the alloy allowed the foundry operation in the open atmosphere called. It was a non-combustible magnesium alloy\(^{2,3}\). However, the strength at elevated temperature is insufficient for use as an engine material as well as the previous magnesium alloys.

The present authors paid attention to silicon addition for following non-combustible magnesium alloys as the engine material. The following were reported as an example of adding silicon to light metals.

1. A silicon phase that shows a high Vickers' hardness compared to the mother phase is formed with the addition of silicon to the magnesium alloys, and the strength at elevated temperature is improved\(^{1}\).

2. The abrasion resistance is improved by adding silicon to the aluminum-based alloy\(^{4,5}\).

In this study, silicon was experimentally added to the non-combustible magnesium alloy AZX912(X=Ca) aimed at an improved abrasion resistance and high temperature strength\(^{1,6}\), thus the non-combustible magnesium alloy with Si was produced.

However, because this new material should be kept at high temperature to dissolve the silicon, the cast defect such as oxides, which influences the tensile strength, increases compared to ordinary magnesium alloys. Therefore, the tensile strength at elevated temperature varies\(^ {7,8}\) caused by the scatter in the maximum defect size included in the specimen, thus it is speculated that the scatter hide the essential strength property.

Yamada et al.\(^ {8}\) proposed a method for a strength evaluation of the cast materials with a varying tensile strengths in which the defect was equivalent to a crack whose projected area on the plane perpendicular to the principal stress was

\[
\sigma_B = \pi^{\frac{1}{2}} \beta \sigma \sqrt{\text{area}}
\]

and the critical stress intensity factor \(K_\text{cr} = \beta \sigma \sqrt{\text{area}}\) with the tensile strength \(\sigma\) was introduced. They showed the validity of the method. However, when the fracture surface of the present cast material was observed, it was difficult to specify the fracture origin, and then the method of Yamada et al., which used \(\sqrt{\text{area}}\), could be applied to the present material.

Therefore, we propose a strength evaluation method for the cast material with an indefinite fracture origin in this study. In addition, the following investigations on the non-combustible magnesium alloy with added-Si were carried out using the strength evaluation method proposed in this study, and useful results were obtained.

1. Comparison between tensile strengths of two kinds of magnesium alloys with different silicon contents.

2. Temperature dependence of tensile strength.

### 2. Proposed evaluation method

In this study, we proposed a method of controlling the defect size of the fracture origin by introducing an artificial defect of the same size that becomes the fracture origin. It is expected that there is no scatter by arranging the defect sizing of the fracture origin. Moreover, the time when the defect sizing is measured from the fracture surface can be saved, and one can eliminate the measurement error of the defect sizing of each specimen. Therefore, a cast material can be more promptly and accurately evaluated, compared to the method of measuring the defect size from the fracture surface for each specimen after it breaks.

Because the shape of the artificial defect was different from that of the cast defect, one could assume that the influence by both defects was different. In this study, attention was paid as to when both broke, and the equivalence of both was confirmed.
In the tension test on the cast material, a crack is generated and stably grows from a defect that becomes the fracture origin and as not immediate fracture. The crack does not require an increase in the load, then it grows and breaks unstably. when the Stress Intensity Factor (SIF) that acts on the occurring stable growth crack reaches a certain critical value (we introduces the SIF that acts on the stable growth crack when breaking as $K_{IB}$, although the small-scale yielding condition is not satisfied in this material).

In this study, the side surface and the fracture surface were observed in the specimen in which the artificial defect and the cast defect became the fracture origin, the areas (stable fracture region) where the stable growth crack progresses were specified, and the $K_{IB}$ values of both were measured. It is thought that the introduced artificial defect cannot depend on the difference in the initial shape of the cast defect and be considered to be equivalent to the cast defect when $K_{IB}$ of both coincide.

3. Material and test procedure

The materials used were two kinds of experimental alloys, AZX912(X=Ca), in which silicon was added to the non-combustible magnesium alloy at 1% and 2%. Table 1 shows the chemical composition of each material. Figure 1 shows the specimen configuration. After machining, the specimen was ground to the examination part. The 12 mm diameter specimen was ground with # 1,200 emery paper. It was then polished with alumina powder (0.05 $\mu$m grain diameter) to make a 5 mm diameter specimen of for the crack observation on one side of the examination side. Figure 2 shows the shape of the artificial defect. The artificial defect was introduced at the specimen center using a $\phi$ 2 mm drill after polishing and a hole of 2 mm depth was made perpendicular to the specimen axis.

The $\phi$ 12 specimen was used for the plain material and the holed material for the tensile test to measure the tensile strength. The universal testing machine was used for the test. The test temperature was a room temperature, 100 °C, 150 °C, 175 °C, 200 °C and 250 °C. To specify the stable fracture region after it had been examined, height information in the fracture surface was acquired by a fractographic study and laser microscopy.

The $\phi$ 5 specimen was used for the tensile test to observe the crack growth process. The test was carried out by the universal test machine (Autograph made by the Shimadzu Co.). The crack gradually developed from the artificial defect by gradually raising the tensile load added to the specimen. The crack growth process was successively observed by using the replica technique. After it had been examined, the replica observation by an optical microscope and the direct observation on the one side of the examination side were carried out.

Table 1 Chemical composition (wt%)

<table>
<thead>
<tr>
<th>AZX912(X=Ca)+1%Si</th>
<th>Al</th>
<th>Ca</th>
<th>Si</th>
<th>Mn</th>
<th>Zn</th>
<th>Mg</th>
</tr>
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<td></td>
<td>8.82</td>
<td>1.90</td>
<td>0.93</td>
<td>0.26</td>
<td>0.65</td>
<td>Bal</td>
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<table>
<thead>
<tr>
<th>AZX912(X=Ca)+2%Si</th>
<th>Al</th>
<th>Ca</th>
<th>Si</th>
<th>Mn</th>
<th>Zn</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.14</td>
<td>1.71</td>
<td>1.41</td>
<td>0.24</td>
<td>0.68</td>
<td>Bal</td>
</tr>
</tbody>
</table>
4. Results and consideration

4.1 Tensile test results of plain specimen

Figure 3 shows the tensile test results of the plain specimen. It is understood from Fig. 3 that the tensile strengths of the materials with 1% silicon and 2% silicon vary by about 20%. Both tensile strengths cannot be compared because of the scatter as the test uses only a few of specimens as shown in Fig. 3. The scatter factor will be described in Section 4.3.

The cast defects which were the oxide, the shrinkage and cold shut, were confirmed for the fracture as a result of the fractographic study after it had been examined. Figure 4 shows examples of the cast defect confirmed in the fracture surface. Figure 4(a) shows the cast defect (oxide) observed in the fracture of the holed specimen will be described later, and Figs. 4(b) and 4(c) show the cast defect (shrinkage) and cast defect (cold shut) observed in the fracture surface of the plain specimen.

![Fig.1 Shapes and dimensions of the specimen (unit:mm)](image1)

![Fig.2 Artificial defect (unit:mm)](image2)

![Fig.3 Tensile strength of plain specimen for non-combustible Mg alloy with added-Si](image3)
4.2 Tensile test results of holed specimens

Figure 5 shows the results of the holed specimen. The open plots and solid plots show the test results that the artificial defect and the cast defect became the fracture origin, respectively. It was found from Fig. 5 that eight specimens in 24 fractured from a cast defect and their strengths were lower than that of specimens which fractured from an artificial defect. The cast defect was observed in all eight specimens based on the fractographic study.

Moreover, the difference between the tensile strength of Mg alloys with 1% Si and that with 2% Si was within about 10% at each temperature in Fig. 5 when the artificial defect was the fracture origin. Therefore, it can be said that both do not have any difference in
tensile strength. It is considered that the tensile strength of the Mg Alloy with 1% Si is equivalent to the Mg alloy with 2% Si.

4.3 Scatter of tensile strengths of plain specimen

The difference in the maximum size of the cast defect included in each specimen is thought to be a factor that causes the scatter in the plain specimen tensile strength. The scatter in the area rate of the defect included in the fracture surface is considered to be another factor.

The plain specimen and the holed specimen of the present materials had a fracture elongation of less than 1% and the fracture behavior was brittle. Moreover, the artificial defect area introduced into the specimen used for the holed specimen was the same as the biggest cast defect area that appeared to the plain specimen, and was about 3% versus the sectional area of the specimen. Because the cast defects other than the fracture origin that existed in the fracture surface could not be confirmed, the size was very small size compared to the area of the defect in the fracture origin and an increase in the true stress by the existence of the defect was low. The tensile strength in this material, which shows a brittle fracture, depends on the maximum defect size, and the scatter of the tensile strength in the plain specimen is caused by the scatter of the maximum defect size included in the plain specimen.

4.4 Confirmation of stable growth crack

Figure 6 shows the stable growth crack that occurred from the artificial defect was confirmed by the replica technique. It can be confirmed that the stable growth crack occurs by stress below half the tensile strength, and grows with the increasing load. Therefore, it is able to be confirmed that the stable growth crack occurred due to the artificial defect.

Fig.6 Stable crack propagation from an artificial defect

(σB=136MPa, the arrows indicate a crack tip.)
4.5 Determining the stable fracture region

The stable fracture region was specified for the specimen in which the artificial defect became the fracture origin by the observation of the fracture surface and one side of the specimen. Figure 7 shows the contour plot of the fracture surface obtained using scanning laser microscopy, and the boundary of the specified stable fracture region and the unstable fracture is shown by the broken line. The fracture surface of Fig. 7 corresponds to that shown in Fig. 10(a) that is described later. It turned out that a big step existed in the fracture
surface, the fracture surface consisted of the two kinds of big steps based on the contour plot shown in Fig. 7 and the fracture surface morphology was visually observed. Figure 8 shows pattern diagrams of the big step formed to the fracture surface. Hereafter, considering the formation mechanism of the step shown in Figs. 8-① and 8-②, the reason for the broken line shown in Fig. 7 is the boundary of the stable fracture region, and the unstable fracture region is described as follows.

The step shown in Fig. 8-① was not formed in a specific location, but in various places of each specimen. Figure 9 shows the observation results in all surroundings on one side of the specimen after the tests. The cracks (sub-crack) other than a main crack that became the final fracture side could be confirmed. There is the possibility of forming a big step, if a main crack connects it with the sub-crack. Therefore, it is thought for the big step shown in Fig. 8-① to be formed by the connection of the main crack with the sub-cracks nucleated during the stable growth of the main crack. This step is formed in an irrelevant direction along with the direction in which the crack progresses.

The step shown in Fig. 8-② could be radially confirmed from a fracture origin, and not confirmed in the surroundings of the origin. The crack growth does not have the acceleration during the stable propagation, thus it is thought to be a basic selection of one plane. However, because an unstable crack propagates with acceleration, a crack propagates on two or more planes and a macroscopic river pattern appears in the fracture surface from the starting point. Therefore, it is thought that the step shown in Fig. 8-② is the one caused by the unstable growth crack that propagates with acceleration.

(a) Clear stable fracture area of specimen  
(b) Unclear stable fracture area of specimen  
Fig.10 Fracture surface of non-combustible Mg alloy with added-Si (Fracture origin is artificial defect.)

(a) Clear stable fracture area of specimen  
(b) Unclear stable fracture area of specimen  
Fig.11 Fracture surface of non-combustible Mg alloy added-Si (Fracture origin is casting defect.)
Based on the formation mechanism of the two kinds of steps in Figs. 8-① and 8-②, the stable fracture region can be specified by connecting the starting point of the big steps which were formed in the direction of the crack growth. The stable fracture regions could be specified in the 12 of 24 specimens as a result of the fractographic study. Figures 10 and 11 show the fracture surface of a specimen in which the artificial defect and cast defect became the fracture origin, respectively. Figures 10 and 11 show the boundary of the stable fracture and unstable fracture in the specimen with the broken lines whose stable fracture region could be specified. The stable fracture region could not be specified in the fracture surface with an indefinite step as shown in Fig. 8-②. Many sub-cracks occur because the material had a lot of internal cast defects, and many steps in the fracture surface shown in Fig. 8-① are generated, then it became difficult to confirm the steps shown in Fig. 8-②.

The stable growth crack using the replica technique for the cast defect was not observed in this study. However, many cast defects were confirmed from the fractographic results in the fracture surface of the plain specimen. Therefore, this material has many cast defects in the specimen, and it is thought that the fracture origin of the sub-crack confirmed in Fig. 9 is a cast defect. Therefore, it can be said that a stable growth crack will occur from the cast defect, and that it is appropriate to specify the stable fracture region by connecting the starting point of the step formed according to the crack propagation direction.

4.6 Comparison of $K_{IIb}$ for artificial defect and cast defect

Because the specimen size cannot be disregarded compared to the defect size in this study, the modification coefficients $F_I$ were introduced using the following equation, and $K_{III}$ was obtained.

$$K_{III} = F_I \sigma \sqrt{\pi b} \left(b_i \cdot \text{depth of stable fracture region}\right)$$

Shiratori's analytical results (11) were used for the modification coefficients $F_I$. It is necessary to evaluate the surface crack as a semi-ellipse crack in order to use Shiratori’s analytical results. The stable fracture region shape was approximated in this study using the semi-ellipse that was circumscribed in the stable fracture region, and whose major axis corresponds to the tangent on the specimen surface. Figure 12 shows an example of the semi-ellipse made from the fracture surface. The modification coefficients $F_I$ were obtained using the value of Shiratori's analytical results, assuming the major axis of the obtained semi-ellipse to be $2a_i$, and the minor axis to be $2b_i$. Figure 13 shows the numerical result from Eq. (1) of the specimen that was able to specify the stable fracture area. It can be confirmed from Fig. 13 that there is no temperature dependence in $K_{III}$ between the normal temperature and the test temperature of 250 ℃. Moreover, the $K_{III}$ value of the cast defect, which becomes the fracture origin in each temperature region, is compared to the $K_{III}$ value of the artificial defect, which becomes the fracture origin, and it was found that both do not have any difference. Therefore, the difference between the shape of the artificial defect and the cast defect does not influence the tensile strength, and the tensile strength of the specimen with the artificial defect is equal to that of the specimen with a cast defect whose size is the same as the size of the artificial defect.
There is no temperature dependence in $K_{II}$ in Fig. 13, although the tensile strength gradually decreases at a temperature higher than 150 °C and there is a temperature dependence in Fig. 14. This is because the stable fracture region expanded with the temperature increase.

### 4.7 Tensile strength when the artificial defect size is changed

The tensile strength can be obtained by the following equation by transforming Eq. (1).

$$\sigma_{\text{f}} = \frac{K_{\text{II}}}{F_1 \sqrt{2b_f}}$$

(2)

$K_{\text{II}}$ obtained by Eq. (1) depends on the size of the artificial defect, because the region depth $b_f$ of the stable fracture may depend on the artificial defect size that becomes the fracture origin. Therefore, a specimen with an artificial defect whose size is different from the artificial defect shown in Fig. 2 cannot be predicted by the result obtained in the present study. The $b_f$ and $K_{\text{II}}$ values of a specimen with an artificial defect of an arbitrary size are clarified by obtaining a crack progress resistance curve ($R$-curve). The $R$-curve of this material will be obtained and the artificial defect of an arbitrary size will be clarified in the
future.

5. Conclusion

The tensile strength of the casting material has scatter, because the size of the cast defect, which becomes the fracture origin, has scatter. The tensile test using the specimen that introduced the artificial defect was carried out, and the side surface of the specimen and the fracture surface were observed by using the non-combustible magnesium alloy AZX912(X=Ca) as an example of new magnesium alloys with added silicon aiming to rationally evaluate the tensile strength of the casting material. The following results were then obtained. Because the unstable crack propagated with acceleration, the step radially appeared from the fracture origin. The stable fracture region in which the cast defect originates can be specified by connecting the starting point of the step.

1. The critical stress intensity factors $K_{II}$ that act on the crack that contains the stable fracture region was used for the artificial defect of 2 mm diameter and 2mm depth introduced into the specimen using a drill, and the cast defect was equal in size to the artificial defect, were compared. It was found that the $K_{II}$ of both was equal. Therefore, the difference in shape of both does not influence the tensile strength, and the artificial defect and the cast defect are thought to be considered as equivalent.

2. A testing method without any scattered results was proposed using the specimen that introduced an artificial defect equivalent to the cast defect based on above results.

3. This proposed method was applied to a new magnesium alloy, and it was found that two kinds of new magnesium alloys with different silicon contents had the same tensile strength. Moreover, new magnesium alloys showed an excellent strength at elevated temperature when compared to an ordinary material.

References


