Fatigue Strength Analysis of Magnesium Alloys

Hiromitsu Watanabe

Keywords Metal fatigue, Nonferrous metal, Magnesium alloy, Finite element method, Molecular dynamics

Abstract

In our research, a basic study was made applying high specific strength and almost-rare-metal-free-magnesium alloys to our products.

In particular, we conducted a series of mechanical fatigue tests in order to analyze fatigue life, a key factor in product design. As a result, we could clarity the fatigue limit, a basic strength characteristic. Next, we determined by test the (fatigue) notch factor which is a reduction rate of fatigue limit by shapes. This factor is used for the application to mechanical parts of arbitrary shapes. Further, by stress analysis using the finite element method, we reviewed the method of estimating fatigue notch factors.

Lastly as a consideration, we examined the behavior of changes in stress and strain through the calculation of molecular dynamics when repeated loads are applied.

Through these basic study programs, we are working on promoting further improvement of product reliability and compact and light-weight design.

1 Preface

Due to the concerns over climate change and energy saving, there are strong demands of compact product design and product life evaluation techniques in the market. As one of these measures, it became necessary to adopt new rare-metal-free materials with high specific strength characteristics.

In our research, we conducted mechanical fatigue tests on magnesium alloys[1] (which are considered to be promising materials with high specific strengths). As a result, we clarified S-N curves (relationship between stress intensity and the number of cycles to failure) and notch factors (fatigue strength reduction rate of caused by stress concentration). This paper introduces the method of notch factor estimation based on the result of stress analysis by the finite element method.

2 Test Method

2.1 Test Piece

The test piece adopted for this test is an extruded material of magnesium alloy as defined by JIS H4204: 2011 as AZ31. Its chemical components and mechanical properties are shown in Table 1.

Table 1 Chemical Components of Magnesium Alloy Extruded Material (JIS H 4204)

Chemical components of magnesium alloy extruded material (JIS H 4204) are shown.

(wt. %)

Al	Zn	Mn	Si	Fe	Cu	Ni
2.9	0.9	0.38	0.026	0.004	0.002	0.001

Regarding the mechanical characteristics of this material, tensile strength is 200MPa or above, which is lower than that of low carbon steel according to the relevant standard specifications, but it is at the same level of non-heat-treatable aluminum alloy such as A7075, etc.

The specific weight of magnesium alloy is 1.7, about 1/5 of iron (7.9), and the lowest among practical metals. This metal is the 6th most abundant element in the Earth's crest. There has been general concern regarding this material in recent years.

2.2 Fatigue Testing Machine

For our repeated load (stress) test, a plane bending fatigue testing machine (Model PBF30 by TOKYO KOKI CO., LTD.) was used. This machine can load a forced displacement at the arbitrary constant amplitude at 1500min^{-1}. A load cell mounted on the affixed test piece part was used to measure the moment of bending during the test.

Stress σ for this test is a value determined from the moment M that is measured at the load cell divided by section modulus calculated on the basis of test piece size before the test. Since this moment can change with the repeat cycles to be described later, the initial value for the bending moment is set at 200 cycles when testing is stabilized. Since the value of moment is reduced even at a constant displacement due to the effect of damage in material, judgment for fracture is based on a criterion that fracture life should be determined when the moment reduction rate clearly appears at 10% of the initial value.

Table 2 **Combinations of Notch Shapes Used for the Material Strength Test**

Combinations of hole diameters in notch test pieces and the number of holes n are shown.

	No. of holes n		
	1	2	3
Hole diameter d (mm)	3.0	1.5	1.0
	6.0	3.0	2.0

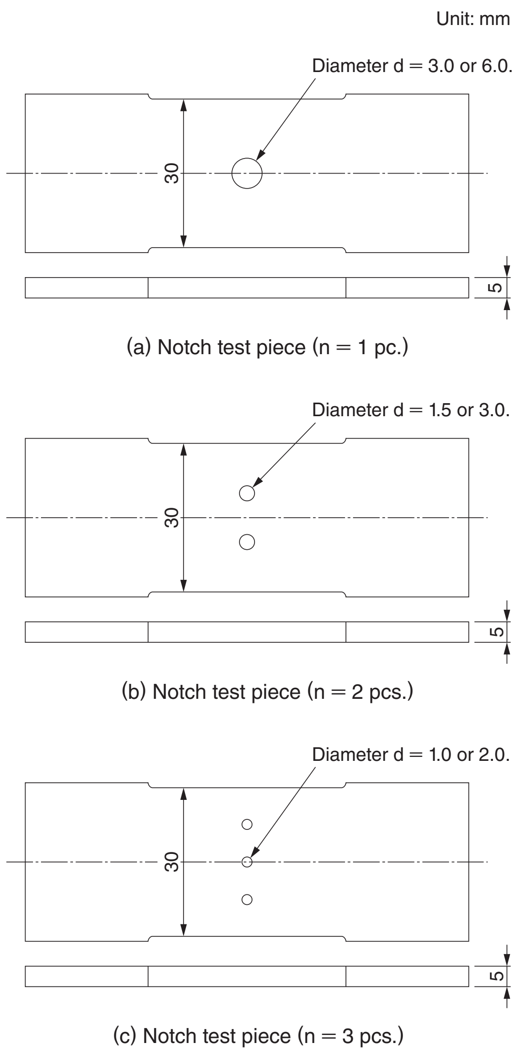


Fig. 1 **Shapes and Dimensions of Test Piece**

Section modulus of bending is the same, but notch sizes and the number of notches are different.

2.3 Contents of Fatigue Test

First, the fatigue test was conducted on a flat test piece and its fatigue strength was measured when there was no concentration of stresses. Subsequently, a test piece with a small hole simulating a stress concentrated part of the bolt hole, was tested in order to obtain the fatigue strength reduction rate empirically. Table 2 shows combinations of notch shapes used for the material strength test. Fig. 1 shows the shapes and dimensions of test piece.

3 Result of Fatigue Test

3.1 Change in Moment Based on Repeat Numbers

Fig. 2 shows the relationship between repeat bending moment amplitude M and repeat number N in cases when the initial value of repeat stress amplitude σa is 147MPa, 126MPa, and 102MPa, respectively. For 147MPa (Mark ◆) where σa is large, Value M increases with an increase in Value N and this trend continues until the repeat number N attains 1×10^4 cycles.

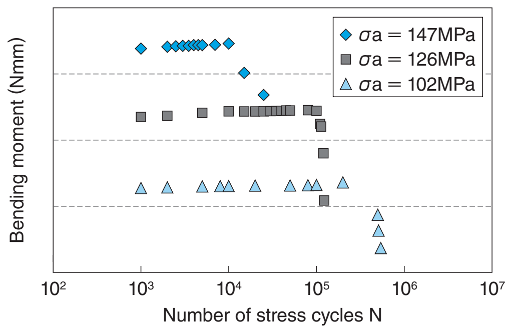


Fig. 2 **Changes in Load (Moment of Bending) Observed during Fatigue Test at a Constant Displacement Amplitude**

When a repeated deformation was applied and the amount of deformation (applied stress) was large, the bending moment slowly increase and then decreased. When the load stress was small, however, the bending moment was kept constant and then suddenly decreased at a certain repeated number.

After that, at the time when Value N exceeds 1×10^4 cycles, Value M sharply decreased from 13,000Nmm to 12,000Nmm; this fact implies that the material properties were changed. When the rate of decrease in Value M exceed 10%, the repeated cycle was 2.5×10^4 cycles and this cycle was defined as the fracture cycle. In the case of 126MPa (Mark ■) where σa was small, Value M slightly increased to 1×10^4 cycles and then decreased suddenly. At 102MPa (Mark ▲) where σa was smaller, there was almost no increase in Value M and this value decreased suddenly when Value N increased.

3.2 S-N Curves of Smooth Specimen

Fig. 3 shows the result of a fatigue test (relationship between stress amplitude σa and number of cycles Nf to failure). The arrow mark in the figure indicates no fracture (discontinued). At 1×10^7 cycles in (a), there was no fracture when σa was below 90MPa. According to this fact, the fatigue limit of this material is known to be approximately 90MPa.

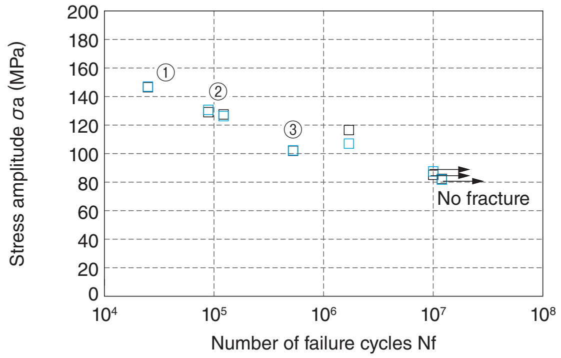
Compared with an aluminum alloy the specific weight of which is about 2.8 and the fatigue strength[2] being 5×10^8 cycles, this material possesses almost the same strength as that of corrosion-resistant aluminum alloy (Series A6000) although the value is lower than that of an extra super duralumin (Series A7075). Judging from the above, the strength of this material is not inferior to that of aluminum alloys, provided that the mass is kept equal.

3.3 S-N Curves of Notched Specimen

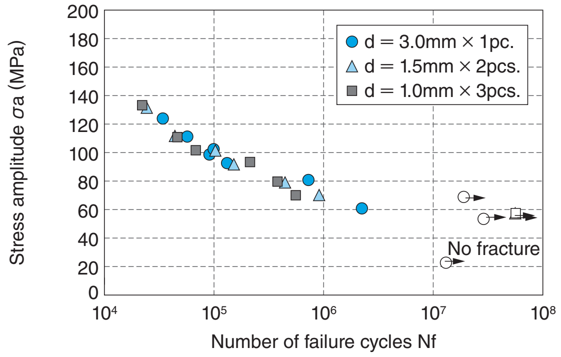
Apart from the fatigue characteristics of smooth specimen as mentioned in the previous section, actual products involve parts and sections where shapes are changed like bolt holes and corner parts. In a section where its shape is greatly changed, stresses are generally concentrated and local stress as a whole becomes high even though the same load is applied. For this reason, it is necessary fo actual design to presume quantitatively the strength r the reduction rate due to stress concentration.

Then, we conducted fatigue test under the condition that there was a small hole in the smooth specimen test piece used for the aforementioned test. This was to obtain the fatigue strength lowering rate (fatigue notch factor).

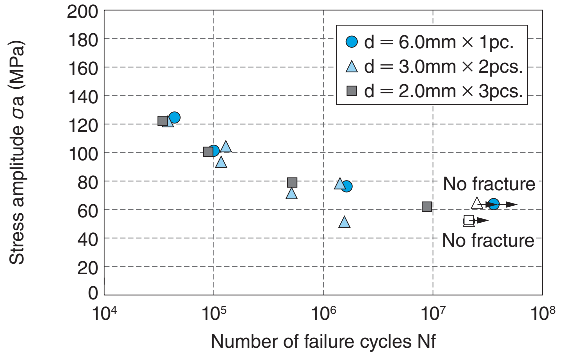
Under the notch condition shown in Table 2,



(a) Smooth specimen



(b) A total of hole diameters of 3mm



(c) A total of hole diameters of 6mm

Fig. 3 Results of Fatigue Test (Relationship between Stress Amplitude σa and Number of Failure Cycles Nf)

Assuming that when the lowering rate of the bending moment shown in Fig. 2 becomes 10% or more at a certain cycle, such number of cycles is defined as a point of fracture. The graphs above show the relationship between the intensity of repeated stress amplitude and number of failure cycles. This is called "S-N curve." When the stress amplitude is large, fatigue fracture occurs soon because of its short life. When the stress is small, there is a limit point causing no fracture. The stress value at this limit point is called the "fatigue limit." Useful information will be available and this limit value will be the basis for strength design.

(b) shows the result of testing conducted with the condition that a total of small hole diameters in a single test piece was 3.0mm which was kept the same, and that the apparent cross-sectional coefficient was also kept the same. Where d = 3.0mm

(Mark ●), the fatigue limit σwk was 69MPa. When the obtained value was compared with the fatigue limit σw of the above smooth specimen, the strength reduction rate or the notch factor β was given by the following expression:

$$\beta = \sigma w / \sigma wk = 90/69 = 1.3 \cdots\cdots (1)$$

Similarly, under the condition that a single notch was small with two holes and d = 1.5mm (Mark ▲), σwk = 57MPa and β = 1.6 indicating that the strength was lowered as compared with the case of d = 3.0mm. Furthermore, when d became as small as 1.0mm and there were 3 holes (Mark ●), σwk = 58MPa and β = 1.6. The latter figure was almost same as in the case of d = 1.5mm.

Item (c) shows the result under the condition that the hole diameter was doubled and that a total of small hole diameters was kept at the same value of 6.0mm and the apparent cross-sectional coefficient was also kept the same. When d = 6.0mm (Mark ●), the fatigue limit σwk was 64MPa and β became 1.4. When the notch was small, d = 1.5mm, and there were 2 holes (Mark ▲), σwk = 65MPa and β became 1.4, which is almost the same condition as in the case of d = 6.0mm. When d became smaller and became 2.0mm and there were 3 holes (Mark ●), σwk = 53MPa and β = 1.7. It showed a tendency of lowering strength.

Table 3 shows a calculation of the fatigue strength lowering rate (notch factor) defined by the fatigue test.

Table 3 Calculation of Fatigue Strength Lowering Rate (Notch Factor) by Fatigue Test

The fatigue limit is obtained from the S-N Curve shown in **Fig. 3**. The notch factor is a value defined on the basis of comparison between a smooth specimen and notch specimen in regard to the fatigue limit to be determined from Expression (1). It can be said that the reduction of strength becomes great if this value is large.

Shape			Fatigue limit σw (MPa)	Notch factor β
Smooth			90	–
Notch	Hole diameter (mm)	No. of holes		
	3.0	1	69	1.3
	1.5	2	57	1.6
	1.0	3	58	1.6
	6.0	1	64	1.4
	3.0	2	65	1.4
	2.0	3	53	1.7

4 Prediction of Fatigue Strength by Stress Analysis

Regarding the result of our past research[(3)~(5)], non-linear stress analysis was carried out for medium carbon steel and low alloy steel used to produce shafts of rotary machines. This analysis was based on the stress to strain curves in consideration of the cyclic stress effect. As a result, it was clarified that there is a reasonable relationship between stress concentration factor computed in conjunction with the Misses equivalent stress and the notch factor obtained from the fatigue test.

For this material in various shapes of its test pieces used for the fatigue test, we made a comparison of stress concentration factors by using non-linear (elastic-plastic) finite element method. **Table 4** shows the presumed fatigue strength lowering rate (notch factor) calculated by using the stress analysis. This table shows the stress concentration factors obtained from stress distribution of the respective test pieces compared with the case when the hole diameter was 3mm and there was only one hole. Compared with the case when there was only one hole, the stress concentration factor becomes as large as 1.1 times when there were multiple holes. In regard to the notch factor obtained from the fatigue test, the stress concentration factor

Table 4 Prediction of Fatigue Strength Lowering Rate (Notch Factor) Calculated by Using Stress Analysis

Stress distribution was obtained by using the finite element method. It became clear that there is a reasonable relationship with the notch factor when a comparison is made among shapes of the respective test specimens in regard to stress concentration factors (maximum stress value/nominal stress value of distribution in the Table) computed in conjunction with the Misses equivalent stress.

Shape			Ratio of notch factor prediction by analysis (Based on a hole diameter of 3.0mm and only one hole)	Ratio of notch factor obtained from experiments (Based on hole diameter of 3.0mm and only one hole)
Notch	Hole diameter (mm)	No. of holes	1.0 	1.0
	3.0	1		
	1.5	2	1.1 	1.2
	1.0	3	1.1 	1.2

became as large as 1.2 times when there were multiple holes, compared with the case of only one hole. This fact suggests that trends are almost the same as the result of the analysis. Thus we concluded that the notch factor, or the rate of fatigue strength reduction limit, can be roughly estimated from the result of stress analysis even in the case of magnesium alloys.

For the examination of the cause of strength reduction in the case of multiple holes, we examined the distribution of stresses in the thickness direction from front surface to rear surface of the small hole section. The result indicates that stress at a shallow point from the surface toward the neutral axis side (center) in the case of only one hole. In the case of multiple holes, maximum stress appeared in the vicinity of the surface layer and this maximum stress was generated in a wider area. It can be considered that the difference in stress distribution is a possible cause of strength reduction.

5 Examining the Results

We examined the reason for an increase of bending moment in fatigue test described in **Fig. 2** with the repeat cycles.

A general deflection curve of beams is given by Expression (2).

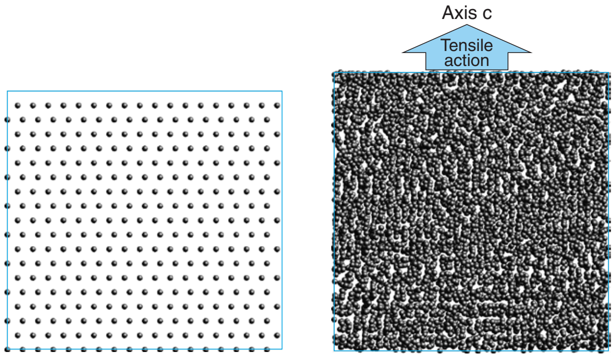
$$1/\rho = -M/EI \cdots\cdots\cdots\cdots (2)$$

Where, ρ = radius of curvature in beam neutral axis, M = bending moment, E = Young's modulus, I = second moment of area

According to this expression, ρ is a constant because displacement is constant. For this reason, the denominator on the right side is thought to change. Since the secondary moment of area I is a dimension of a test piece, this value is considered to be constant until a fatigue crack appears.

Following the aforementioned, we estimated changes in Young's modulus E by calculation based on molecular dynamics simulation. For the calculation of molecular dynamics, we used computational science software SCIGRESS ME (2.1) by Fujitsu. As shown in **Fig. 4**, the atomic structure of magnesium in the closest hexagonal packing structure is modeled with 5832 atoms in all, arranged with 18 atoms vertically, 18 atoms horizontally, and 18 atoms in the depth direction. In regard to the cyclic load, a forced displacement was repeatedly applied in the state of a triangular waveform in the Axis-c direction of model's initial stress-free structure. The velocity of this displacement is devised to reduce the real time of reproduction as short as possible because the velocity of an actual fatigue test is comparable to a phenomenon to be completed in a scale of a few seconds. The volume of calculation by molecular dynamics, however, is enormously large and it is necessary to raise the ambient temperature of the material slightly higher.

Fig. 5 shows the relationship between the stress and strain observed when a forced displace-



(a) Before deformation (b) After deformation

Fig. 4 **Study on Changes in Moment of Bending during Fatigue Test (Calculation Based on Molecular Dynamics)**

Diagram (a) shows an unstressed atomic arrangements before the start of a fatigue test. Diagram (b) shows atomic arrangements when a repeated deformation was applied to several cycles. In this case, atomic arrangements were disorganized and it showed a complicated arrangement.

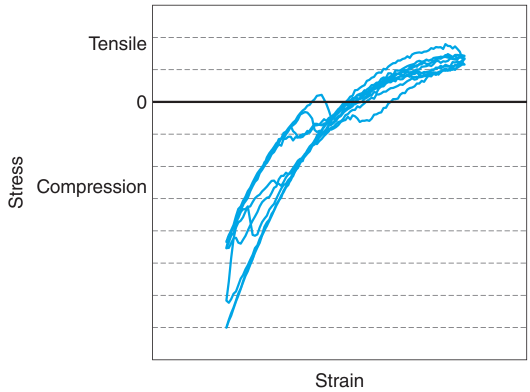
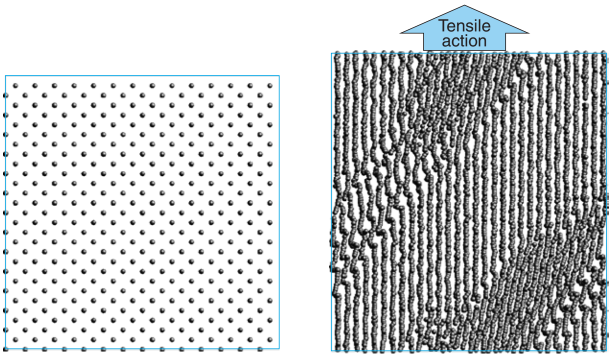


Fig. 5 **Relationship between Stress and Strain Observed when a Cyclic Displacement was Applied According to Calculation by Molecular Dynamics**

Based on the relationship between internal stresses and strain causing molecular deformation as shown in **Fig. 4**, a hysteresis loop due to stress and strain was determined. Tensile stress and compressive stress are in asymmetrical relationship and it is obvious that the gradient (elastic modulus) on the compressive stress side is greater. Since currently, the analysis scope is limited, quantitative comparison is our future challenge.



(a) Before deformation (b) After deformation

Fig. 6 Study on Changes in Moment of Bending during Fatigue Test (Calculation Based on Molecular Dynamics with the Use of Iron)

For comparison, the test result using iron is shown. The occurrence of dislocation was found in the direction of shearing stress (tilted by 45° against the axis of deformation). We could reproduce the condition of plastic deformation.

ment was repeatedly applied according to the calculation by molecular dynamics. Although the Young's modulus on the tension side coincided with the theoretical value, the gradient of the curve on the compression side tended to become large. This suggests that the Young's modulus apparently rises on the compression side.

Since this is a bending test, the surface (and rear surface) received a tensile and compressive stress reciprocally. We saw that the overall width (mean value) of bending moment was raised as a result of an increase in Young's modulus on the compression side.

We conducted a similar test on iron atoms for comparison. The dislocation was found in the direction of the shearing stress as shown in Fig. 6. Unlike the above magnesium, the deformation behavior showed a relatively simple one. The crystalline structure of the iron is a body-centered cubic structure and it is considered that due to the difference in crystalline structure, the deformation behavior after plastic deformation differs.

Since this time the calculation was aimed to reproduce the central part of a single crystal, the effect of material surface and grain boundary was not factored. In order to realize an estimation on the occurrence of fatigue cracks and deterioration diagnosis, we are planning on working on more large-scale and high-speed computation.

6 Postscript

In order to produce environmentally conscious and economically attractive products, we clarified by the test the fatigue characteristics of Magnesium Alloys with a high specific strength. In so doing, we predicted the reduction factor of fatigue strength by the finite element method.

Going forward, we will work on clarifying characteristics of materials through tests. By utilizing the latest analytical techniques, we would like to contribute to society with our products and technologies.

Lastly, we would like to express our sincere gratitude to Professor Haruo Yamamoto, the Mechanical Engineering Course, the Department of General Science and Engineering, Meisei University and Mr. Masato Kogane, the Master's Course for Mechanical Engineering, the Department of Life Science and Engineering, and the Postgraduate Course of Meisei University. We thank you for your cooperation on various tests as well as your precious advice and guidance.

《References》

(1) Kogane, Yamamoto, Watanabe: "Fatigue properties when the aperture number of Magnesium alloy AZ31 of the section coefficient uniformity is different," The Soc. of Materials Sci., Japan, 63rd Ordinary General Meeting, Scientific Lecture, Lecture Miscellany, 2014

(2) The Light Metals Society, Japan, Aluminum Handbook

(3) Yamamoto, Watanabe: "Prediction of Notch Factor with Elastic-Plastic Analysis," The Japan Society of Mechanical Engineers, Yamanashi district conference 2003, pp.147-148, 2003

(4) Watanabe, Yamamoto: "Prediction of Notch factor with Elastic-Plastic Stress Analysis," The Japan Society of Mechanical Engineers, Yamanashi district conference 2004, pp.161-162, 2004

(5) Watanabe, Yamamoto: "Fatigue Life Prediction of Lead-free Solder by Non Linear Finite element method," Soc. of Materials Sci., Japan, Scientific Lecture Miscellany 56, pp.123-124, 2007