Detection of Damage and Fracture of Forging Die by Fractal Property of Acoustic Emission*

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The detection of damage to and fracture of cold forging tools during forming operation by fractal property of acoustic emission (AE) is performed. First, a tensile test on tool steel is conducted to elucidate the fractal dimensions of deformation-induced and fracture-induced AEs. The resultant fractal dimensions are 1.97 and 1.44. Next, the change in the fractal dimension of AE from a die insert is investigated under cold forward extrusions. Workpieces with a conversion coating film are used to eliminate the effect of friction on AE. After 300 extrusions, no damage and wear is observed on the die surface, and the fractal dimension is almost constant at 2.04 on average. Then, another series of cold forward extrusions under high-friction conditions is performed with mineral oil VG2 and stearic acid to promote the onset of damage to and fracture of the die. A defect on the surface of the workpiece is observed at the 101st extrusion, which resulted from the onset of crack on the die radius. The former average fractal dimension, 2.01, of the onset of the crack changes to 1.52 after the onset of the crack. From the results, the fractal dimension can be concluded to be one of the most effective indicators of the progress of damage to a cold forging tool. Finally, a method of separating the die-induced AE from the total AE based on the Kaiser effect is proposed.

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1. Introduction

The service life of forging tools is often limited by wear, seizure, plastic deformation and fatigue fracture, or their combination, as cold forging tools are subjected to a considerably high stress during forming operations. In particular, in cold forging, the fatigue fracture due to the initiation and growth of the fatigue crack mainly dominates the service life.¹

Under such a situation, the establishment of detection techniques for the progress of the fatigue fracture is important to reduce the production cost of the cold forging.

On the other hand, the acoustic emission (AE) technique is a very effective method for the nondestructive inspection of the progress of material damage and fracture.²⁻⁵ In the field of forming process engineering, the AE technique has been applied to the detection of the lubrication condition,⁶⁻⁷ drawing,⁸⁻⁹ sheet metal forming,¹⁰⁻¹¹ blanking,¹²⁻¹³ hobbing¹⁴ and so on.

AE is a phenomenon caused by the elastic waves generated by the onset of microdefects in materials. Material damage and fracture may result from the various magnitudes of internal microcracks. Therefore, the magnitude that depends on AE amplitude possesses a fractal property. Namely, the AE amplitude distribution is expressed by the power law.¹⁵⁻¹⁶ Therefore, the AE amplitude distribution detected may have a fractal property. In fact, it is reported that the AE amplitude distribution due to the microscopic fracture of several materials has a fractal property.⁴⁻¹⁷⁻²⁰

In the present paper, as a fundamental study of the change in the fractal property of the AE amplitude distribution due to the damage to and fracture of the forging tools, the AE signal detected during cold forward extrusions is investigated. With the progress of damage in tools, the change in fractal dimension is examined.

After the relationship between AE amplitude and its fractal property was explained, the tensile test of tool steel was conducted to elucidate the fractal dimensions of the deformation-induced and fracture-induced AEs. Cold forward extrusions are then performed to investigate the change in fractal dimension during the iteration of extrusions.

Finally, a method of separating the AE generated by a forging tool from the whole AE was proposed using the Kaiser effect for the evaluation of damage to and fracture of the forging tool.

2. Fractal Property of AE Amplitude Distribution

From many research studies, the AE amplitude distribution follows the fractal property; the frequency $f(A)$ of AE amplitude $A$ can be expressed as⁴⁻⁵⁻¹⁵⁻¹⁶

$$f(A) = cA^{-m}$$

where $c$ is a constant, and the exponent $m$ denotes the fractal dimension.

Equation (1) can be described as follows when common logarithm is taken.

$$\log_{10} f(A) = -m \log_{10} A + \log_{10} c$$

Namely, a linear relationship is obtainable on a logarithmic graph by taking the common logarithm of eq. (1).

The fractal dimension $m$ of deformation-induced AE is larger than that of fracture-induced AE, as the small amplitude of AE events is dominant in the case of deformation-induced AE.

The value of $m$ is reported to be larger than 2.0 when AE is caused by material deformation, and less than 2.0 when AE is caused by microfracture of the material.⁴
3. Fractal Property of AE Amplitude during Tension Test of Tool Steel

3.1 Tensile test and AE measurement

AE signals during the tensile test of the tool steel SKD11 (JIS) were detected to clarify the fractal dimension \( m \) due to deformation and fracture. The hardness of the specimen was 60 HRC.

The tensile test was conducted using a universal testing machine Shimadzu AG-100kND. The tensile loading rate was 15 kN/s.

An AE measurement system (MUSIC system in NF Corporation) was used for acquiring AE signals. This system consisted of an AE sensor, a preamplifier and a local processor containing the main amplifier. A broad-band-type AE sensor with a flat frequency response between 150 kHz and 1200 kHz was used. The total gain by the preamplifier and main amplifier was set to 70 dB. The threshold level was set to 140 mV at the output voltage of the main amplifier.

Figure 1 shows the geometry of the specimen for the tensile test of SKD11. The notched specimen was used to specify the region where the fracture occurs.

3.2 Experimental results

Figure 2 shows the changes in the load and AE event rate with tensile displacement in gage length. Although the AE events can be observed at the initial stage, these AE events include the noises due to the initial contact in the gripped part of the specimen. We can also observe many AE events just before and after fracture.

Figures 3(a) and 3(b) show the logarithmic AE amplitude distributions during the deformation and fracture, respectively, as well as their regression lines drawn by the least-squares method. The deformation-induced AE events are collected around the displacement \( S = 0.13 \) mm in Fig. 2, whereas the fracture-induced AE events around the fracture. The deformation-induced and fracture-induced fractal dimensions are 1.97 and 1.44, respectively. These values seem reasonable in comparison with the reported values. Therefore, we can regard the fractal dimensions as good indicators of the deformation and fracture of SKD11.

4. AE and Its Fractal Property during Cold Forward Extrusions

4.1 Apparatus and condition of experiment

A hydraulic press Kyowa KTP-100 (load capacity: 100t) was employed for the cold forward extrusions. The rate of extrusion was set at 3 mm/s.

The AE measurement system used in the present experiment was the same as that used in the tensile test in Chapter 3. The total gain by the preamplifier and main amplifier was set to 70 dB. The threshold level was set to 120 mV at the output voltage of the main amplifier to remove the electric and mechanical noises.

Figure 4 shows the geometry of the die insert used in the present experiment. The die angle \( 2\alpha = 90^\circ \) and the extrusion ratio \( R = 4 \). The die radius \( r = 1 \) mm. The material of the die insert was SKD11 with a hardness of 60 HRC, which was the same as that of the specimen in the tensile test. A shrink ring (material: SKH6, outer diameter: 200 mm) was used to reinforce the die insert by prestressing. The position of AE sensor was also indicated in the figure. The AE sensor was attached on the surface with the adhesive tape and grease.

The material of the workpiece was the low-carbon steel S25C (JIS). The diameter and height of the solid cylindrical workpiece were \( d = 14 \) mm and \( h = 15 \) mm, respectively. The yield stress and hardness were 310 MPa and 157 HB.

The workpiece was applied with a conversion coating film to eliminate the influence of friction as much as possible.
The Coulomb friction coefficient in this extrusion was estimated by fitting the experimental load versus punch stroke curve with that calculated by FEM.

Figure 5 shows the experimental and calculated punch load-stroke curves using the Coulomb friction coefficient $\mu = 0.06$. A very close agreement between the experimental and calculated values can be observed. From the result, the Coulomb friction coefficient can be estimated as $\mu = 0.06$.

### 4.2 AE during single cold forward extrusion

Figure 6 shows AE total event counts $f$ and punch load $P$ as functions of punch stroke $s$ at the extrusion number $N_1 = 212$. As shown in this figure, the nonsteady extrusion process is defined as a process in which load increases and the diameter of the workpiece decreases, whereas steady extrusion process is defined as a process in which the workpiece is extruded in the steady state with a constant diameter. Most of the $f$ are generated during the nonsteady extrusion process.

In the nonsteady extrusion process, the AE event detected can be considered to be attributed to the deformation of the workpiece and the die insert, as well as to the friction at the interface between the workpiece and the die insert. On the other hand, in the steady extrusion process, the AE event will be attributed to the deformation of the workpiece and the friction, because further deformation of the die insert ceases with the decrease of punch load as shown in Fig. 6.

### 4.3 Fractal property of AE detected during cold forward extrusions

Figure 7 shows the change in $m$ with the extrusion number $N_1$. As observed in this figure, the average $m$ is 2.04, which is similar to the deformation-induced fractal dimension of 1.97 obtained in Section 3.

The extrusions under the same condition as mentioned above were conducted at $N_1 = 300$. No cracks, flaws or defects on the surface of the die insert were confirmed.

The slope of the regression line in Fig. 7 is almost zero, even though it is slightly decreased. It can be said that there is no change in fractal dimension in this experiment.

We can conclude that no fracture-induced AE is generated in this experiment. This conclusion seems to be consistent with the change in $m$ as shown in Fig. 7.
5. Detection of Damage to and Fracture of Die Insert under High-friction Conditions

The inspection of damage to and fracture of the die insert under high-friction conditions that promote damage to and fracture of the die insert due to the change in the fractal dimension of the AE is performed.

5.1 Apparatus and condition of experiment

The apparatus used was the same as that described in Section 4. The rate of the punch stroke for this experiments was set at 0.5 mm/s that was lower than the rate in Section 4, in order to prevent the unexpected fracture of the forging tools.

A mixture with mineral oil VG2 and stearic acid is used as a lubricant. Figure 8 shows the experimental and calculated results of punch load-stroke curves for the estimation of the Coulomb friction coefficient. The Coulomb friction coefficient $\mu = 0.7$ is used in the calculation. As observed in this figure, the maximum punch load in the experiment is similar to that in the calculation. However, the experimental punch load increases even during steady state extrusion. This is because the Coulomb friction coefficient may be increasing as the extrusion progresses due to seizure. The maximum punch load is 500 kN that is 1.9 times as large as the maximum load obtained in Section 4.

5.2 Experimental results

Figures 9(a) and 9(b) show the photographs of the surface near the die radius of the workpiece at the extrusion numbers $N_2 = 100$ and $N_2 = 101$, respectively. The defect can be observed inside the circle in Fig. 9(b). This defect is transferred from the die radius. On the other hand, there is no defect observed in Fig. 9(a). It can be considered that the defect in the die radius occurs at $N_2 = 101$.

Figures 10(a) and 10(b) show the logarithmic AE amplitude distributions, as well as their regression lines drawn by the least-squares method at $N_2 = 70$ and $N_2 = 133$, respectively, as examples of the distributions before and after the initiation of the crack. The values of $m$ at $N_2 = 70$ and $N_2 = 133$ are 2.01 and 1.46, respectively. Each value is consistent with that for the deformation-induced and fracture-induced AEs, respectively.

Figure 11 shows the change in $m$ during the extrusions with high-friction conditions.

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Fig. 8 Punch load versus punch stroke during cold forward extrusions under high-friction conditions.

Fig. 9 Surface appearances of workpieces extruded under high-friction conditions.

Fig. 10 AE amplitude distributions and fractal dimensions under high-friction conditions.

Fig. 11 Change in fractal dimension during cold forward extrusions under high-friction conditions.
under high-friction conditions. The cold forward extrusion under the same conditions as mentioned above was conducted at \( N_2 = 155 \). The obvious decrease in fractal dimension can be observed at \( N_2 = 100 \). The average \( m \) from \( N_2 = 1 \) to 100 and from \( N_2 = 101 \) to 155 were 2.01 and 1.52, respectively; these values are similar to those for the deformation- and fracture-induced AEs, respectively, obtained in Chapter 3.

From the above results, it can be concluded that the fractal dimension of AE amplitude from the die insert is capable of detecting the defects in a die insert under circumstances where there are many AE sources such as deformation, fracture and friction, and the superposition of electrical or mechanical noises.

Figure 12 shows the longitudinal sectional area of the die insert after the extrusion number \( N_2 = 155 \). We can observe that the crack propagates from the die radius.

6. Proposal for Method of Separating AE from Die Insert

The AE signals obtained in Chapters 4 and 5 consist of AE events from the die insert, workpiece and AE events due to friction. Therefore, we can assume that the AE predictions of the behavior of the deformation of and damage to the die insert can be more precise if we can calculate the fractal dimension using only the AE events from the die insert.

A possible method of separating the AE of the forging die from the whole AE during cold forward extrusion is proposed using the Kaiser effect.

6.1 Kaiser effect

The Kaiser effect that was first investigated by W. Kaiser describes the phenomenon that a material under load emits AE only after a primary load level is exceeded.\(^4,5\) However, when a change in the property or internal structure of the material occurs due to the initiation of microdefects, phase transformation and so on, the Kaiser effect disappears and AE is generated under a lower load than previously.

Therefore, the Kaiser effect can be useful for the detection of internal defects newly generated in the material.

6.2 Specification of AE from forging die by Kaiser effect

Let us discuss AE behavior during cold forward extrusion under the low-friction conditions described in Section 4.

The punch load is the same for each extrusion. Therefore, the external load applied to the die insert can be considered the same for each extrusion, if the strength of the workpiece and the frictional condition are not changed.

Therefore, if a series of extrusions are performed in a relatively short period, no deformation-induced AE from the die insert will be detected during the extrusion.

As an example, let us examine the AE signal obtained at \( N_1 = 212 \) and 213 as shown in Fig. 13. The time interval in the experiment between \( N_1 = 211 \) and 212 is 5 days. Therefore, the Kaiser effect at \( N_1 = 212 \) can be regarded as having disappeared sufficiently.

The AE event count \( f \) at \( N_1 = 213 \) is 114, which is less than \( f = 496 \) for the previous extrusion at \( N_1 = 212 \). This is because no deformation-induced AE from the die insert at \( N_1 = 213 \) is generated due to the Kaiser effect as the external load does not exceed that in the previous extrusion at \( N_1 = 212 \).

Therefore, the AE obtained for \( N_1 = 213 \) may contain the deformation-induced AE of the workpiece and the friction-induced AE that may be very small.

Figures 14(a) and 14(b) show the AE amplitude distributions and \( m \) values at \( N_1 = 212 \) and 213, respectively. The fractal dimension in Fig. 14(b) can be regarded as that of the deformation of the workpiece and friction.

Figure 15 shows the AE amplitude distribution and its fractal dimension of the deformation-induced AE in the die insert obtained by eliminating the AE amplitude at \( N_1 = 213 \) from that at \( N_1 = 212 \), respectively. In this case, the fractal dimension \( m \) is 2.04, which is close to \( m = 2.03 \) obtained using the whole AE detected. From this result, we may conclude that it is sufficient to evaluate the fractal dimension by the whole AE during cold forward extrusion.

On the other hand, many AE events were obtained during cold forward extrusion under the high-friction conditions described in Section 5, and the Kaiser effect could not be observed. This may be because the damage-induced AE in the die insert and the AE due to the seizure are constantly generated in each extrusion process under the high-friction conditions.
7. Conclusions

The fractal dimension \( m \) of AE generated during the forming process, which predicts the damage to and fracture of a forging die, was investigated during cold forward extrusion.

The conclusions obtained in the present study can be summarized as follows:

1. The \( m \) of the deformation- and fracture-induced AE amplitude during the tensile test of SKD11 are 1.97 and 1.44, respectively.

2. The \( m \) during cold forward extrusion with the conversion coating film is 2.03 in average, and it is almost constant during the experiment. This result is consistent with the surface appearances of the die insert in which no defect is found.

3. In the case of the cold forward extrusions under high-friction conditions, the average \( m \) after the initiation of the crack is 1.52, which is considerably lower than the value of 2.01 before the initiation of the crack. This decrease is in good agreement with the crack initiation in the die insert.

4. A possible method of separating of the AEs in the die insert is proposed. The resulting \( m \) by this method is 2.04, which is close to the \( m \) of all AE events. Therefore, it is sufficient to calculate the \( m \) using all AE events.

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