Crack detection in upsetting of aluminum alloy using acoustic emission monitoring technology

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Research Article

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Abstract

Acoustic emission technology relies on detecting and converting elastic (acoustic) waves from solids undergoing internal structural irreversible changes into electrical signals. This technique represents a non-destructive testing method used in industrial fields such as weld monitoring, proof testing, and flaw detection of pressure vessels. In this study, the applicability of acoustic emission technology for detecting and monitoring defects in a workpiece during a metal forming process was studied. A notch shape was designed using the finite element method to induce a premature crack on the surface of aluminum alloy cylindrical specimens by compressing them using a pair of flat dies. During the upsetting tests, acoustic emission signals and images of the notched specimen were recorded in real time. The obtained acoustic emission signals were analyzed through various parameters such as amplitude, energy, and RMS to determine the crack occurrence. Moreover, the signal results were compared with those from images obtained simultaneously to confirm the crack detection. The experimental results showed that acoustic emission technology could successfully detect crack occurrence in aluminum materials during the upsetting tests. These results imply an opportunity to detect material defects during various metal forming processes using acoustic emission technology.

1. Introduction

Metal forming technology with mass-produced high-quality mechanical properties is widely used in various industrial fields. Nevertheless, this technology requires quality standards while maintaining its manufacturability through a real-time monitoring system to estimate the forming limit due to cracks, internal ruptures, or other defects [1, 2]. Although defect-monitoring techniques using various sensors have been studied, sensors have limitations because of the different material properties and defects during manufacturing. For example, a load cell is typically used to monitor the load change due to manufacturing defects; however, the load change can be insignificant to measure materials with high formability [3, 4].

The acoustic emission method used for a non-destructive inspection is usually implemented to predict and detect fracture of high-pressure containers in the aerospace and nuclear physics fields. Moreover, recent studies showed that cracks could be detected during plastic deformations. For instance, using acoustic emission signal analysis, Behrens et al. [5–7] detected crack formation during the cold forging of steel and aluminum alloys. In particular, the authors analyzed the applicability of the method for real-time implementation. They also monitored the acoustic emission signal during the sheet drawing process and analyzed the change in signal per step. The results focused on comparing and analyzing the properties of the acoustic emission signal measured for a ductile raw material. Furthermore, El-Galy et al. [8] analyzed the signals acquired during a magnesium alloy upsetting experiment and confirmed that the signals differed in forms according to the shape and composition of the material and the manufacturing conditions such as forming speed and temperature. Martínez González et al. [9] monitored the acoustic emission signals during a three-point bending test for advanced high-strength steel. The authors verified the relationship between the carbide fracture and the acoustic emission signal by analyzing the

micromechanical behavior and fracture mechanisms. Seemuang et al. [10] also detected micro-cracks initiation during tensioning in advanced high-strength steel by examining the direct current potential drop (DCPD) and the acoustic emission signal. The author also evaluated an efficient method to detect micro-cracks by comparing the response time of the two methods.

The studies mentioned above monitored the crack initiation from excessive transformations in metal forming such as forging and sheet metal forming through an acoustic emission signal analysis. However, for ductile materials, micro-cracks initiate and propagate through a gradual process of creation, expansion, and merging of micro-voids, making it challenging to specify the time when the cracks initiate. Moreover, various events such as friction, abrasion, and potential shifts might cause the acoustic emission signal; thus, a cross-verification is required to specify the signal due to the crack.

This study verified the crack occurrence in aluminum upsetting using an acoustic emission sensor. Specifically, the time the signal estimated the crack occurrence was compared with that detected by analyzing the specimen's surface image. The cylindrical specimen had a perpendicular V-notch to induce the premature crack for a 6000 series aluminum alloy with a high elongation rate. The notch shape was selected to create the highest damage value. The final notch shape design was obtained by evaluating cylindrical specimens through finite element analysis (FEA), considering the ductile failure theory. In the experiments, the crack behavior around the notch area was observed using an optical camera while measuring the load change and acoustic emission signal to detect the crack occurring during the upsetting test. The analysis of acoustic emission signals and notch images indicated that the crack initiation point was similar to that of the crack occurrence signal in the upsetting test of the cylinder specimen and the acoustic emission waveform analysis.

2. Acoustic Emission

2.1 Acoustic emission method

The acoustic emission method detects and assesses the elastic wave due to the change in the internal structure using a sensor. In general, early acoustic emission methods were used in seismology to detect block faulting. However, since the 1960s, these methods have been applied to engineering fields to evaluate the integrity of large structures or detect pipe leakage [11, 12].

The acoustic emission sensor contains a piezoelectric material that creates an electric charge. Thus, when a force is applied, the energy from the object's surface is transformed into an electric signal [13]. These acoustic emission sensors can be classified into a broadband sensor with a large frequency range and a resonant sensor with high sensitivity in a particular frequency according to whether it has a buffer material or not [14].

Measuring the acoustic emission signal requires: 1) an acoustic emission sensor to convert the elastic wave of the surface to electric signals, 2) a preamp to amplify the original output signal, 3) a signal

processing device to convert analog signals into digital data, and 4) a computer system with an analysis program to interpret and display the results. Such a system is shown in Fig. 1 [15].

2.2 Acoustic emission signal

As shown in Fig. 2, an acoustic emission signal continuously received over time can be classified as separate hits, namely, time parameters peak definition time (PDT), hit definition time (HDT), and hit lockout time (HLT) [16]. The recorded signal can be computed to the specific acoustic emission parameters defined in ISO 12716:2001, such as amplitude, energy, RMS, and count. Moreover, the signal can be analyzed to detect various physical phenomena [17].

Figure 3 shows representative waveforms of selected hits. In particular, the continuous signal waveform (a) can represent a continuous change such as friction and potential shift. In contrast, the burst signal waveform (b) can represent sudden changes such as material yield and crack formation [18–20].

Among the various acoustic emission property parameters, this study considers the amplitude and energy parameters defined using Equations 1 and 2. These parameters are used to detect the crack initiation in the upsetting experiment and analyze the waveforms to determine the sources of the signals.

$$Amplitude = \left\{ 20 \log \left(\frac{V_{max}}{10^{-6}} \right) - (PreamplifierGain) \right\} dB$$

1

where V_{max} is the maximum voltage value in hit duration.

$$Energy = \left\{ \int_{T_1}^{T_2} V_R(t) \right\} \mu Vsecond$$

2

where T_1 and T_2 are the hit start and end points, respectively, and $V_R(t)$ is the rectified acoustic emission waveform.

3. Upsetting Experiment

3.1 Notch specimen design

Due to its high strength, corrosion resistance, and processability, the 6000 series aluminum is widely used as an industrial lightweight metal. This study considered two alloys in the upsetting experiment to evaluate how the acoustic emission signal differs according to the material property. Thus, the high-

strength A6061-T6 aluminum alloy and the relatively lower strength and high elongation A6063-F alloy were considered.

First, the mechanical properties of the A6061-T6 and A6063-F were evaluated through the tensile and compression tests. The tensile test was performed following the ASTM-E8 standard on manufactured round specimens with a gauge length of 24 mm. The test specimen was placed in a 10-ton universal testing machine considering a strain rate of 1/1000. In contrast, the compression test considered a cylinder specimen with a diameter, height, and height-to-diameter ratio of 12 mm, 18 mm, and 1.5, respectively. The cylinder was covered with molykote on the top and bottom sides to minimize barreling. The test specimens were set between the upper and the lower jigs. The speed of the test was 0.1 mm/s. Fig. 4 shows the stress and strain rate relationships obtained from the tensile and compression test. Particularly, the tensile strength and strain rate of A6061-T6 are 400 MPa and 17%, showing a higher strength and lower strain rate than those of A6063-F, 190 MPa and 27%.

In the upsetting experiments of the aluminum alloys, a notch in a V-shape was created to induce a premature crack in an area observable by the experimenter. Subsequently, the FEA was conducted to predict the crack possibility according to the notch design parameters. The FEA analysis was performed using DEFORM-3D, a conventional analysis software. The specimen was modeled as rigid plastic material and the die as a rigid body. Moreover, the upsetting analysis was performed up to a maximum load of 8 tons. The maximum damage value was analyzed according to the ductile failure theory. The shape creating the maximum damage value was found by fixing the height-to-diameter ratio to 1.5, and the specimen diameter (D), the notch depth ratio (N), and the notch angle (A) were designed and analyzed using the conditions set in Table 1 According to the ductile Cockcroft-Latham failure criterion [21, 22], the damage values were obtained as follows:

$$DamageValue = \int \frac{\sigma_1}{\sigma} d\epsilon$$

3

where σ_1 is the maximum normal stress, σ is the effective stress, and ϵ is the effective strain.

Table 1
Design parameters of the notch specimen FEA model

D (mm)	N	A (degree)
10/ 11 / 11.5	0.05 / 0.10 / 0.15	60 / 90 / 120
	0.20 / 0.25 / 0.30	

Figure 6 shows the maximum damage value according to the notch shape. Note that both materials show higher damage values with a smaller specimen diameter and notch angle. As seen in the Figure, the

maximum values occur at a specific depth according to the material property. Specifically, A6061-T6, which has relatively higher strength and lower strain ratio than A6063-F, presents larger maximum damage values than A6063-F.

Figure 7 shows the cumulative damage value distribution of the A6061-T6 (D10, N0.15, A60) and A6063-F (D10, N0.10, A60). In addition, the predicted premature crack positions for both materials are obtained. According to the result, both materials show maximum damage values located in the notch center.

From the analysis presented above, the upsetting experiments for the notch specimen shapes A6061-T6 (D10, N0.15, A60) and A6063-F (D10, N0.10, A60) showing the highest damage values were selected as the notch shapes to induce a premature crack. Therefore, additional specimens were manufactured with heights of 14 mm and 16 mm to analyze different heights. In this regard, six specimens were manufactured, as shown in Fig. 8.

3.2 Acoustic emission monitoring upsetting experiment

Figure 9 shows the 10-ton universal testing machine with parallel upsetting zigs used to perform the upsetting tests. A laser extensometer was used to measure the displacement during the test. Moreover, the crack signal from the specimen was measured using the broadband acoustic emission sensor WSA of MISTRAS installed on the upper side of the low die. This study considered the experimental equipment's noise. Moreover, a sensor with identical specifications was installed into the ram of the machine to measure the noise due to the equipment. Finally, an optical camera was installed in front of the testing machine to observe the changes in the notch area in real time. The upsetting was performed at 0.1 mm/s, and the experiment ended immediately after the load reached 8 tons.

As shown in Fig. 10, the laser extensometer data is exported simultaneously to the acoustic emission monitoring computer and a computer recording the optical camera images. This allowed us to synchronize the optical image of the notch area and the acoustic emission signal according to the displacement. This approach enables observing the notch area at the assumed crack signal.

4. Results And Analysis

4.1 Results of the acoustic emission monitoring upsetting experiment

All manufactured specimens experienced cracks due to excessive tensile strain at the notch center. In particular, the crack in the A6061-T6 specimen initiated at a small compression ratio and continued to be visible at the same maximum pressure due to differences in material formability. In contrast, the A6063-F specimen showed a micro-crack and an orange peel on the surface due to the grain growth during the compression strain, as shown in Fig. 11 [23–25].

The load and acoustic emission signals measured by the load cell and sensor, respectively, during the upsetting test were analyzed and calculated. The maximum amplitude and energy parameters are shown in Fig. 12 and 13. Note that the upsetting load increases continuously according to the displacement in all tests. Moreover, no signs of load change due to micro-crack initiation and development are present.

Figure 12 shows the change in the maximum amplitude parameter according to the compression ratio. The maximum amplitude parameter shows dispersed results even with the presence of cracks in all specimens, failing to show a drastic change indicating the crack initiation point.

Figure 13 illustrates the energy parameter measurements according to the compression ratio and the notch optical image at specific points in time. Contrasting to the maximum amplitude parameter that does not show any drastic change, the energy parameter shows a drastic increase at a specific time (t), assumed as the crack initiation point. To verify whether the drastic change in energy was due to the crack initiation, the results of the energy parameter were synchronized with the compression displacement to compare the specific time (t') where the crack clearly occurred in the recorded optical image of the center of the notched specimen. The results show that the crack initiation point t' from the optical image occurs after the point t measured by the energy parameter in all cases. Note that no evident cracks are present at time t due to the resolution limitations of the optical image.

4.2 Acoustic emission signal source analysis

Figure 14 shows the energy parameter analysis for the acoustic emission signal from tests with similar conditions to that of previous notched specimens. Nevertheless, in this case, the results correspond to a notch-less cylinder specimen with a diameter and height of 10 mm and 15 mm, respectively. Unlike the notched specimens, no cracks were observed on the surface of the specimen post-experiment. Moreover, Fig. 13 and 14 present a comparison of the energy parameter results. In particular, Fig. 13 shows a drastic increase in energy at the later part of the test, whereas there is generally low and consistent energy in the crack-less cylinder specimen.

Therefore, the crack in the notched area rapidly increases the energy parameter recorded in the notched specimen, Fig. 13. The fracture might be initiated within the interior of the specimen and expanded to the surface. Alternatively, a micro-crack not visible due to the low resolution of the optical image might have caused the acoustic emission signal change.

As mentioned above, acoustic emission signals create continuous signal waveforms during continuous changes such as potential shifts. In contrast, these signals create burst signal waveforms for sudden changes such as yielding or crack formation [18–20]. This study analyzes the waveforms to verify the relationship between the change in energy parameters due to micro-crack formation and the measured signals.

Figure 15 shows the waveform of the broadband sensor installed on the lower die of the 15 mm notched specimens for each material at the maximum acoustic emission energy point w_A and a random point w_B .

While the maximum acoustic emission energy w_A detects a burst signal, the random point w_B would detect a continuous signal.

Therefore, the optical image analysis, upsetting experiments with crack-less specimens, and analysis of the acoustic emission waveforms showed that the rapid increase in the acoustic emission energy parameter detected in the aluminum notch-specimen upsetting experiment resulted from the initiation of the micro-crack.

5. Conclusion

This study implemented acoustic emission monitoring technology to detect the development of cracks in the aluminum alloy upsetting test. The acoustic emission signals were analyzed according to the forms and materials of the specimens. The following results were obtained through various methods:

1. The FEA analysis showed that the damage values were higher for a smaller notch angle and specimen diameter. Moreover, the notch depth presented a specific depth where the maximum damage value occurred according to the material property.
2. The acoustic emission parameter analysis indicated that the amplitude parameter did not show any visible changes when the crack was initiated. In contrast, the energy parameter showed large acoustic emission energy compared to the steady-state when the crack was initiated in the aluminum alloy.
3. The upsetting test of the crack-less cylinder specimen through the acoustic emission energy parameter showed that the acoustic emission energy was lower than that in the notched shape specimens.
4. The waveform analysis of the crack initiation signal of the acoustic emission signal showed that burst signals were obtained due to cracks.

This study verified the detection possibility of the 6000 series aluminum based on the acoustic emission monitoring technology. Thus, future work can consider detecting defects due to materials or manufacturing processes using acoustic emission monitoring technology.

Declarations

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Figures

Figure 1

Acoustic emission detection process

Figure 2

Definition of simple acoustic emission waveform parameters

Figure 3

Typical acoustic emission signal waveforms (a) Continuous signal and (b) Burst signal

Figure 4

Stress-strain curves of aluminum alloy (a) A6061-T6 and (b) A6063-F

Figure 5

Design of the notch specimen FEA model

Figure 6

Comparison of the damage value regarding different design parameters (a) A6061-T6 and (b) A6063-F

Figure 7

Results of the numerical modeling considering the Cockroft-Latham fracture criterion (a) A6061-T6 (D10, N0.15, A60) and (b) A6063-F (D10, N0.10, A60)

Figure 8

Manufactured notched specimens (a) A6061-T6 (H14, H15, H16) and (b) A6063-F (H14, H15, H16)

Figure 9

Experimental setup for the upsetting tests with acoustic emission measurements

Figure 10

Figure 11

Photographs of specimens with cracks after the upsetting test (a) A6061-T6 (H14, H15, H16) and (b) A6063-F (H14, H15, H16)

Figure 12

Acoustic emission amplitude evolution during notch specimen upsetting tests (a) A6061-T6 H14, (b) A6061-T6 H15, (c) A6061-T6 H16, (d) A6063-F H14, (e) A6063-F H15, and (f) A6063-F H16

Figure 13

Acoustic emission energy evolution and image during notch specimen upsetting experiments (a) A6061-T6 H14, (b) A6061-T6 H15, (c) A6061-T6 H16, (d) A6063-F H14, (e) A6063-F H15, and (f) A6063-F H16

Figure 14

Acoustic emission energy evolution during cylinder specimen upsetting tests (a) A6061-T6 and (b) A6063-F

Figure 15

Waveform analysis of detected crack signals using acoustic emission energy (a) A6061-T6 H15 and (b) A6063-F H15