Ultrasonic Reflection Characteristics of Wrinkle in Sheet Metal Forming
—Evaluation by FDTD Analysis and Ultrasonic Measurement Using Model Specimen—

Yuji Segawa, Takuya Kuriyama, Yasuo Marumo, Taekyung Lee, Yasuhiro Imamura, Tomohiro Nonaka and Yutaka Sakata

1Department of Mechanical Engineering, National Institute of Technology, Miyakonojo College, Miyakonojo 860-8555, Japan
2Faculty of Advanced Science and Technology, Kumamoto University, Kumamoto 860-8555, Japan
3Magnesium Research Center, Kumamoto University, Kumamoto 860-8555, Japan
4Technical Division, Faculty of Engineering, Kumamoto University, Kumamoto 860-8555, Japan
5Department of Integrated System Engineering, Nishinippon Institute of Technology, Fukuoka 800-0394, Japan

Ultrasonic reflection characteristics that vary with wrinkling enable the detection of wrinkles during press forming. In this study, we investigated the influence of wrinkles on ultrasonic reflection characteristics by Finite-Difference Time-Domain (FDTD) analysis and experiments with model specimens. The wrinkle shape on the model specimen was made into a trapezoid by electric discharge machining. FDTD analysis was performed using the analysis model that reproduces experimental situations. The first reflection wave occurring at the lower surface of the upper die affected the ultrasonic characteristics, which changed with wrinkle wavelength. The effective diameter of the ultrasonic probe and the irradiation diameter of the ultrasonic wave also affected the ultrasonic reflection characteristics. In the region where the ratio of the irradiation diameter of the ultrasonic wave to the wrinkle wavelength is 0.3 or more, the reflection intensity depends on the irradiation position of the ultrasonic wave. The irradiation position at the maximum reflection intensity varies depending on the fraction of the effective diameter of the ultrasonic probe and the wrinkle wavelength.

1. Introduction

Various measures are taken to prevent defects that occur during metal press working. However, the causes of these defects vary widely and their complete prevention is difficult. Therefore, product inspection is carried out so that defective products do not proceed to later processes of production. At actual production sites, sampling inspection is generally adopted taking cost into consideration. There is always a risk of an outflow of defective products because not all products are inspected during sampling inspection. To completely prevent the outflow of defective products and minimize related losses, the development of in-process techniques of monitoring all products using sensors has been underway.

For in-process monitoring of the contact state between dies and a material, ultrasonic measurement is effective. We have developed dies with an embedded ultrasonic probe, carried out in-process monitoring of wrinkles generated during deep drawing, and found that the reflection characteristics of ultrasonic waves change as a result of the generation of wrinkles. The reflection characteristics of ultrasonic waves change depending on the wrinkle height and wrinkle wavelength, which poses a problem to realize high-precision detection of defects.

In this study, to address the above problems, ultrasonic measurement and numerical analysis were carried out using specimen models simulating periodic wrinkles to examine the effect of wrinkles on the reflection characteristics of ultrasonic waves.

2. Measurement Principles

As reported previously, when the acoustic impedances of two media that come into contact with each other are different, ultrasonic waves occur reflection and transmission at the interface. These phenomena are used in the evaluation of the state of wrinkles. Figure 1 shows schematics of the detection of wrinkles generated during sheet metal forming.
using ultrasonic waves. Ultrasonic waves are irradiated from an ultrasonic probe placed above the upper die toward the workpiece. When the lower surface of the upper die is in contact with air, as shown in Fig. 1(a), ultrasonic waves are nearly totally reflected at the lower surface of the upper die. The maximum amplitude of reflected ultrasonic waves is assumed to be the reflection intensity $I$ and the reflection intensity in Fig. 1(a) is denoted as $I_0$. When wrinkles are generated in the workpiece sandwiched between the upper and lower dies, as shown in Figs. 1(b) and 1(c), the reflection intensity changes to $I_1$ in the case of Fig. 1(b) and $I_2$ in the case of Fig. 1(c) in proportion to the decrease in contact area. In a situation where wrinkles do not occur due to good processing as shown in Fig. 1(d), the reflection intensity is denoted as $I_3$. The acoustic impedance of the workpiece with respect to that of the die is the highest, which is followed by those of the lubricant and air. Therefore, $I_0 > I_1 > I_2 > I_3$. From the change in reflection intensity, the generation of wrinkles and the change in wrinkle state can be estimated. In this study, the relative reflection intensity $I/I_0$ defined the ratio of the reflection intensity $I$ at a certain contact state to $I_0$ was used as the index to evaluate wrinkles.

3. Experiment for Evaluating Reflection Characteristics of Ultrasonic Waves

Figures 2 and 3 show schematics of the experimental apparatus and Fig. 4 shows a schematic of a specimen used in this study. The experimental apparatus (Fig. 2) and the specimen are explained in detail in a previous report\(^\text{10}\) and only a summary is given here. The experimental apparatus consists of three units made of S50C: a storage box for an ultrasonic probe, an upper die, and a lower die. These three units are assembled together with bolts. The storage box for an ultrasonic probe was used to fix the position of the ultrasonic probe. The upper die has a punch and its height is set to 30 mm so that the irradiation distance of the ultrasonic waves used is larger than the near-field length. The dimensions of the punch are 50 (width) × 60 (length) mm\(^2\) so that the presence of the punch does not affect the propagation of ultrasonic waves. To clarify the relationship between the shape of wrinkles and the reflection intensity of ultrasonic waves, the gap between the dies and the specimen was filled with glycerin, which is frequently used as a contact medium in the nondestructive test. The groove for glycerin was formed by assembling two parts in the lower die. The O-ring prevents the leakage of glycerin from between the two parts. The gap between the upper and lower dies where a specimen is placed was set to be 5% lower than the height of the specimen so that the dies and the specimen come into sufficient contact. The apparatus can accommodate specimens with different heights by changing the height of the convex part in the lower die. The relationship between the irradiation position and the reflection intensity of ultrasonic waves was determined precisely by finely adjusting the position of the lower die by rotating the positioning bolt. Figure 3 shows the peripheral equipment required in the ultrasonic measurement. A pulsar receiver transmits and receives ultrasonic waves via an ultrasonic probe. The waveforms of reflected ultrasonic waves are recorded on a PC via an oscilloscope. Ultrasonic measurement for a length corresponding to that of two wavelengths of wrinkles was repeated three times at different irradiation positions. The mean of the measurements was calculated and used as the measured value at each irradiation position.

An A1050 sheet was formed into a specimen with trapezoidal wrinkles [50 (width) × 80 (length) mm\(^2\)] by electro-discharge machining, as shown in Fig. 4. The sheet thickness $t_w$, wrinkle height $h$, angle of wrinkle inclination $\alpha$, contact width $c_w$, and wrinkle wavelength $\lambda_w$ were used as the parameters of wrinkle shape. The surface roughness $Ra$ of the specimen was 3.89 µm after machining (before machining, $Ra = 0.14 \mu$m). Table 1 shows a summary of experimental conditions. To examine the relationship between $\lambda_w$ and reflection intensity, three specimens with different values of $\lambda_w$ and the same $t_w$, $h$, and $c_w$ values (1.0 mm) were fabricated. A vertical ultrasonic probe made by Olympus was used in the measurement at different frequency $f$. The effect of $f$ on reflection intensity was also examined. In this experiment, the irradiation diameters ($D_t$, the diameter of the irradiation when the ultrasonic waves reach the lower surface of the upper die) were 19.83, 11.40, and 7.84 mm for ultrasonic probes with frequencies of 2.25, 5, and 10 MHz, respectively.
4. Analysis of Reflection Behavior of Ultrasonic Waves by Finite-Difference Time-Domain (FDTD) Method

4.1 Equations and calculation method

From the change of the waveform of reflected ultrasonic waves, the relationship between the wrinkles and the reflection intensity was examined. If the reflection behavior of ultrasonic waves is observed, the effect of wrinkles on reflected ultrasonic waves can be examined in more detail. Thus, the reflection behavior of ultrasonic waves was analyzed to visualize the reflection of ultrasonic waves. The details of the calculation method have been explained in a previous report and are briefly outlined here. In this study, the FDTD method was used for the analysis. The FDTD method was originally developed for the analysis of electromagnetic fields. In recent years, the FDTD method has been used in the analysis of elastic waves for the nondestructive test of materials and plastic working.

For the FDTD method applied to elastic waves, Hooke’s Law (eq. (1)) and the equation of motion (eq. (2)) were used, assuming that elastic waves propagate in an isotropic medium in an acoustic field and are thus uniform in the y direction.

\[
\begin{align*}
\frac{\partial}{\partial t} \begin{bmatrix} T_{xx} \\ T_{zz} \\ T_{xz} \end{bmatrix} &= 
\begin{bmatrix}
  c_{11} & c_{13} & 0 \\
  c_{13} & c_{33} & 0 \\
  0 & 0 & c_{55} 
\end{bmatrix}
\begin{bmatrix}
  \frac{\partial u}{\partial x} \\
  \frac{\partial v}{\partial x} \\
  \frac{\partial u}{\partial z} + \frac{\partial v}{\partial x} 
\end{bmatrix} \\
\rho \frac{\partial}{\partial t} \begin{bmatrix} u \\ v \end{bmatrix} &= 
\begin{bmatrix}
  \frac{\partial T_{xx}}{\partial x} + \frac{\partial T_{xz}}{\partial z} \\
  \frac{\partial T_{xz}}{\partial x} + \frac{\partial T_{zz}}{\partial z} 
\end{bmatrix}
\end{align*}
\]

Here, \( T_{xx} \) and \( T_{xz} \) are the vertical stresses in the x and z directions, respectively, \( T_{zz} \) is the shearing stress, \( u \) and \( v \) are the particle velocities in the x and z directions, respectively, \( c_{ij} \) is the component of a stiffness matrix, and \( \rho \) is the density of the medium. In the FDTD method, central difference approximation is applied to convert eqs. (1) and (2) into equations that can be used to calculate sound pressure and particle velocity. Here, the sound pressure and particle velocity are arranged in a lattice interval, as shown in Fig. 5.

4.2 Analysis model and conditions

Figure 6 shows the analysis model. In the analysis, we assumed that the specimen was completely in contact with the upper and lower dies. The shape of the wrinkles of the specimen was trapezoidal, which is the same as that of the model specimen. In addition, the same parameters of wrinkles shape as those in the experiment were used. It was assumed that the gap between the specimen and the dies was filled with glycerin. The boundary at the inclination of wrinkles was set in a stepwise manner so that practical solutions can be obtained. At the outer periphery of the analysis model, the Mur first-order absorbing boundary condition was applied to enable the calculation for an infinitely continuous medium even in a finite domain. The diameter of the ultrasonic probe was assumed to be the same as that used in the experiment. Ultrasonic waves with the waveform shown in Fig. 7 were used as input waves. Table 2 shows a summary of physical properties of each medium. The distances between particles of sound pressure and particle velocity were set 1/10–1/20 the wavelength of ultrasonic waves to guarantee the accuracy of calculation.

5. Experiment and Analysis Results

5.1 Relationship between \( I/I_0 \) and irradiation position

Figure 8 shows the relationship between \( I/I_0 \) and the irradiation position. The irradiation position is the horizontal distance from the left end of a specimen to the center of the ultrasonic probe. The shapes of specimens are also shown at

<table>
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<th>Table 1: Experimental conditions.</th>
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<tr>
<td>Specimen thickness ( t_s ) [mm]</td>
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<tr>
<td>Wrinkle height ( h ) [mm]</td>
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<tr>
<td>Contact width ( c_w ) [mm]</td>
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<tr>
<td>Wrinkle wavelength ( \lambda_w ) [mm]</td>
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<tr>
<td>(Wrinkle slope angle ( \alpha ) [deg])</td>
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<td>Frequency ( f ) [MHz]</td>
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<tr>
<td>(Effective diameter ( D ) [mm])</td>
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the top of Fig. 8 for ease of understanding the relationship between $I/I_0$ and the irradiation position. For $\lambda_w = 4$ mm shown in Fig. 8(a), $I/I_0$ negligibly changed with the irradiation position. However, for $\lambda_w = 8$ or $12$ mm, $I/I_0$ changed with the irradiation position. From this finding, the irradiation position affects the reflection intensity under a certain condition, the details of which are discussed in the next section.

5.2 Relationship between $I/I_0$ and contact state between dies and wrinkles

The change in $I/I_0$ shown in Fig. 8 was induced because the contact state between the dies and the wrinkles in an area irradiated with ultrasonic waves changed depending on the irradiation position. Figure 9 shows the results of sound pressure distribution analyzed by the FDTD method when the center of the convex part of wrinkles was irradiated with ultrasonic waves and the waves reached the lower surface of the upper die. Among the reflected waves, the first reflected waves generated when ultrasonic waves reached the lower surface of the upper die were dominant. The reflection ratio at the contact interface between the lower surface of the upper die and glycerin was about 90%, whereas the reflection ratio at the contact interface between the lower surface of the upper die and the specimen was about 46%. Thus, the reflected waves were non-uniform. The sound pressure distribution differed depending on $\lambda_w$, as shown in Fig. 9, which affects the first reflected waves. From this finding, $\lambda_w$ changes the contact state between the lower surface of the upper die and the wrinkles, which then affects the reflection intensity. For $\lambda_w = 4$ mm shown in Fig. 8(a), the irradiation diameter $D_1$ was the largest (19.83 mm) and $\lambda_w$ was the smallest. When $\lambda_w$ was small with respect to $D_1$, $I/I_0$ negligibly changed because the change in the contact state in the irradiated area was small even when the irradiation position changed. With increasing $\lambda_w$ to 8 or 12 mm, $I/I_0$ changed because the change in the contact state in the irradiated area was large when the irradiation position changed. Therefore, $D_1$ is considered to also affect the reflection intensity.

For $\lambda_w = 4$ mm shown in Figs. 8(b) and 8(c), $I/I_0$ tended to be the largest and smallest at the convex and concave parts of wrinkles, respectively. However, for $\lambda_w = 8$ or 12 mm, $I/I_0$ shows the opposite trend; it is the largest and smallest at the concave and convex parts of wrinkles, respectively. Figure 10 shows schematics of the contact state between the dies and the specimen when the centers of the convex and concave parts were irradiated with ultrasonic waves with a frequency of 5 MHz. For $\lambda_w = 4$ mm, the horizontal distance from the center of the concave part to the contact part between the upper die and specimen $L$ was 1.5 mm [Fig. 10(a)]; for $\lambda_w = 8$ mm, $L$ was 3.5 mm [Fig. 10(b)]; and for $\lambda_w = 12$ mm, $L$ was 5.5 mm [Fig. 10(c)]. Because the effective diameter $D$ of the ultrasonic probe with a frequency of 5 MHz is 6 mm, the contact part located 1.5 mm from the center of the ultrasonic probe fell within the effective diameter, meaning that the contact state significantly affects...
Fig. 9 Sound pressure distribution of ultrasonic wave after reaching lower surface of upper die \((t_w = 1.0 \text{ mm}, \ h = 1.0 \text{ mm}, \ c_w = 1.0 \text{ mm}, \ f = 2.25 \text{ MHz}, \ t = 5.89 \mu s)\).

For \(\lambda_w = 4 \text{ mm}\), the regions of the contact part within the effective diameter at the convex and concave parts were 1 and 2 mm, respectively. Thus, \(I/I_0\) becomes large when the convex part, which had a smaller contact part than the concave part, was irradiated with the ultrasonic waves. For \(\lambda_w = 8\) or 12 mm, when the concave part was irradiated with ultrasonic waves, the contact part existed outside the effective diameter, leading to an increase in \(I/I_0\) because of a small effect of the contact part. In contrast, when the convex part was irradiated with the ultrasonic waves, the region of the contact part within the effective diameter was 1 mm regardless of \(\lambda_w\) (4, 8, or 12 mm), as shown in Figs. 10(d), 10(e), and 10(f), respectively. Thus, for \(\lambda_w = 8\) or 12 mm, larger \(I/I_0\) was observed when the concave part was irradiated with ultrasonic waves because there was no contact part within the effective diameter. This tendency is opposite that in the case of \(\lambda_w = 4 \text{ mm}\) and is also observed when ultrasonic waves with a frequency of 10 MHz are used. Figure 11 shows the relationship between the changes in \(I/I_0\) and \(\lambda_w\) using \(I/I_0\) at \(\lambda_w = 4 \text{ mm}\) as a reference when concave and convex parts were irradiated with ultrasonic waves. The change in \(I/I_0\) in the concave part became larger than that in the convex part when \(\lambda_w\) increased from 4 to 8 or 12 mm. This finding indicates that the contact state in the concave part changes more significantly than that in the convex part.

5.3 Region where \(I/I_0\) changes depending on irradiation position

In some cases, \(I/I_0\) is almost constant regardless of the irradiation position, whereas in other cases, \(I/I_0\) changes depending on the irradiation position. In addition, the maximum \(I/I_0\) is observed in some cases when the convex part is irradiated with ultrasonic waves, whereas in other cases, the maximum \(I/I_0\) is observed when the concave part is irradiated with ultrasonic waves. These results are affected by \(\lambda_w\), \(D\), and \(D_1\). Here, a new parameter \(\lambda_w/D_1\) is defined. Because \(c_w\) of any specimens is 1 mm, the contact part between the dies and the specimen depends on \(\lambda_w\). Thus, \(\lambda_w/D_1\) represents the degree of change in the contact part within the irradiated area. With increasing \(\lambda_w/D_1\), the change in the contact part upon changing the irradiation position increases. Figure 12 shows the relationship between the difference in relative reflection intensity and \(\lambda_w/D_1\). The difference in relative reflection intensity is given by \((I_{\text{max}}/I_{0\text{F}}-I_{\text{min}}/I_0)/(I_{\text{max}}/I_0)\). When the maximum \(I/I_0\) is observed at the convex part, the plots are represented by a black dot. When the irradiation position where the maximum \(I/I_0\) is
observed changes from the convex part to the concave part, the plots are connected by a dashed line. At around \( \lambda_w/D_1 = 0.2 \), the difference in relative reflection intensity is as small as about 0.01, indicating no difference in relative reflection intensity regardless of the irradiation position. At around \( \lambda_w/D_1 = 0.3–0.4 \), the difference in relative reflection intensity increases and relative reflection intensity changes depending on the irradiation position. However, for \( \lambda_w/D_1 \geq 0.3 \), two parts, namely, the part where maximum \( I/I_0 \) is observed when the convex part is irradiated and the part where maximum \( I/I_0 \) is observed when the concave part is irradiated, coexist. Here, \( \lambda_w/D \) is defined. Because \( \lambda_w \) affects \( L \), \( \lambda_w/D \) is the parameter that represents the contact state between the dies and the specimen when the convex part is irradiated with ultrasonic waves. Figure 13 shows the relationship between \( (I_{\text{max}}/I_0-I_{\text{min}}/I_0)/(I_{\text{max}}/I_0) \) and \( \lambda_w/D \) for \( \lambda_w/D_1 \geq 0.3 \). The irradiation position where the maximum \( I/I_0 \) is observed is the convex part for \( \lambda_w/D \leq 0.7 \); however, it is the concave part for \( \lambda_w/D \geq 1.2 \). From this finding, the irradiation position where the maximum \( I/I_0 \) is observed is considered to change from the convex part to the concave part in the range of \( \lambda_w/D_1 = 0.7–1.2 \).

5.4 Effect of \( f \)

Figure 14 shows the relationship between \( I/I_0 \) and \( f \). To avoid the effect of the shape of wrinkles, the mean \( I/I_0 \) values of each specimen were used. \( I/I_0 \) negligibly changes with increasing \( f \). Figure 15 shows the relationship between the difference in relative reflection intensity and \( f \). When ultrasonic waves \( f = 2.25 \text{ MHz} \) were used, the change in \( I/I_0 \) was observed for wrinkles with a large \( \lambda_w \); however, no change in \( I/I_0 \) was observed for wrinkles with a small \( \lambda_w \), leading to a small difference in relative reflection intensity. When \( f \) increased to 5 and 10 MHz, the directivity of ultrasonic waves increased. Namely, the change in the contact state between the dies and the specimen was detected even for wrinkles with a small \( \lambda_w \), leading to a large difference in relative reflection intensity.

6. Conclusions

To investigate the wrinkles on the reflection characteristics of ultrasonic waves during sheet metal press forming, ultrasonic measurement using wrinkle model specimens and a numerical analysis by the FDTD method were carried out. The following results were obtained.

1. The reflection intensity of ultrasonic waves is markedly affected by the first reflected waves generated when ultrasonic waves reach the lower surface of the upper die. The reflection intensity of the first reflected waves depends on \( \lambda_w \). In addition, the reflection intensity of ultrasonic waves is affected by \( D \) and \( D_1 \).

2. For \( \lambda_w/D_1 < 0.3 \), \( I/I_0 \) negligibly changes with irradiation position because the change in the contact state between the dies and the wrinkles according to the irradiation position is small. For \( \lambda_w/D_1 \geq 0.3 \), \( I/I_0 \)
changes with the irradiation position because the change in the contact state between the dies and the wrinkles, which depends on the irradiation position, is large.

(3) For $\lambda_w/D_1 \geq 0.3$, the irradiation position where maximum $I/I_0$ is observed changes from the convex part to the concave part in the range of $\lambda_w/D = 0.7$–1.2. This is because the contact state between the dies and the wrinkles in the effective diameter changes when the convex and concave parts are irradiated with ultrasonic waves.

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