INCREMENTAL HAMMERING FORMING OF SHEET METAL AUTOMATED USING CCD CAMERA AND DATABASE

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ABSTRACT
Incremental hammering forming automated using a CCD (Charged-Coupled Device) camera and a database is developed as flexible forming of sheet metals. In this process, the sheets are bent into desired shapes by repeating local deformation due to the hammering. The forming process is divided into roughing and finishing operations. In the roughing operation, the sheet is hammered in accordance with a sequence stored in a database. On the other hand, the roughly formed shape is corrected by hammering at points of large differences of shape in the finishing operation. The three-dimensional shape of the sheet during the forming is calculated from the distortion of grid pattern measured by the CCD camera system by means of the Fourier transform grid method. Aluminum square sheets are formed by an incremental forming machine with a set of a hemispherical punch and rubber die. The sheet is moved by a rectangular coordinate robot to change the position for the blow with the punch. The sheets are successfully formed into a sphere, frustum of cone, paraboloid and hyperboloid.

INTRODUCTION
In incremental forming processes, workpieces are formed into desired shapes by repeating local deformation. These processes are expected as an approach of flexible forming for small lot production because a great variety of shapes are produced by only a set of tools. In addition, the forming load is small due to local deformation. The incremental forming is applied to sheet metal forming, forging, spinning, etc. Hammering forming is the most flexible method among the incremental forming processes and is mainly employed for bending of sheet metals. Since this forming is very skillful, the industrial application has been still limited. Although the hammering forming has the advantage of the flexibility, it is difficult to control the hammering sequence because of a large degree of freedom. The hammering sequences are generally determined according to empirical knowledge of long experienced experts. It is desirable in metal forming industry to develop an approach for determining the hammering sequences instead of human experts.

As a systematical study of the incremental forming, Matsubara et al. (1994) have investigated hammering sequences for spherical, ellipsoidal and hyperboloidal shapes. Hasebe et al. (1996) have analyzed local deformation in the incremental forming by the upper bound method. On the other hand, the authors (1996) have proposed a method using the genetic algorithm for determining the forming sequences. The genetic algorithms have been recently applied as an approach for combinatorial optimization problems in the field of manufacturing. The hammering sequences have been modelled as a combinatorial optimization problem. However, it is not easy to develop an analytical method for determining the hammering sequences because of the large degree of freedom.

CCD cameras are increasingly used as a visual sensor in the field of manufacturing with the decrease in price and the improvement of performance. Liu et al. (1996) have applied the CCD camera to measure the surface deflection of embossed sheets. Oenoki et al. (1996) have employed the CCD camera to control angles of bent sheets for correction of springback. By means of the CCD camera, global data such as workpiece geometries and strain distributions can be measured in a real time. On-line control using the CCD cameras would be effective in automatic forming without human assistant.

In the present study, a CCD camera system and knowledge processing technique are applied to the hammering forming of sheet metals in order to overcome the difficulty in control. By searching into a database, a forming sequence for the rough roughing is generated. The CCD camera is employed to measure the three-dimensional shape of the sheet during the forming necessary for on-line control of the finishing operation.

ROUGHING OPERATION USING DATABASE

Method of Forming

In the hammering forming, a sheet metal is bent into a desired shape by repeating local deformation. Although the control of the hammering sequence is necessary to the achievement of the desired shape, it is not easy to determine the sequence because global deformation caused by repeating local deformation is very complicated. For the determination, the direct application of the finite element method is unrealistic due to an extremely long computing time. To overcome the difficulty, knowledge processing and shape measurement techniques are included in the control of hammering forming in the present study.

The forming process is divided into roughing and finishing operations. In the roughing operation, the sheet is hammered in accordance with a sequence stored into a database. Then, the roughly formed shape is corrected by hammering at points of large differences of shape in the finishing operation. In this operation, the three-dimensional shape of the sheet during the forming is measured with a CCD camera system. The present forming approach emulates that employed by human experts. The experts first form the sheets into rough shapes in accordance with the empirical knowledge, and approach the desired shapes from the observation of the shape during the forming.

Construction of Database

The database for hammering sequence in the roughing operation is constructed. For the sake of simplicity, axi-symmetric parts such as spheres and frustums of cone are handled and the sheet is successively hammered along circular paths as shown in Figure 1. The forming parameters are the order of the circular path number n, the punch stroke u, the distances a and b between the blows and between the paths, etc.

For the spheres and frustums of cone, cross-sectional shapes after the forming stored into the database are acquired from a preliminary experiment by changing the values of the parameters as shown in Table 1. The hammering sequence which starts from the outside of the sheet for the center is employed because the deflection of the formed shape is reduced by the constraint of the periphery of the sheet. In the case of the frustum of cone, however, the hammering sequence turns to that from the center after arriving at the corner of the frustum to form a sharp shape. The starting point in each circular path is rotated by 90° to reduce the deflection.

Determination of Hammering Sequence

The hammering sequence in the roughing operation is determined by finding a similar geometry by means of a pattern recognition approach. The cross-sectional geometry of a desired part is normalized as shown in Figure 2, and whether the geometry is similar to the spheres or frustums of cone is judged from the amount of hatched area. Then, the most similar shape is selected from the database by checking the difference between the desired and stored shapes.

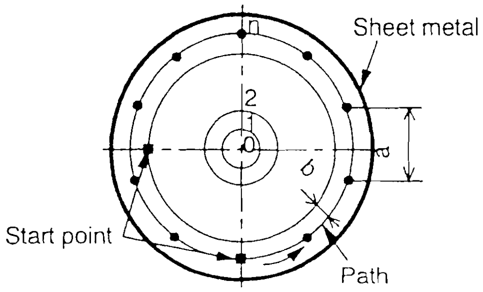

FIGURE 1. HAMMERING PATHS AND PARAMETERS FOR AXI-SYMMETRICAL PART.

TABLE 1. PARAMETERS IN PRELIMINARY EXPERIMENT USED FOR CONSTRUCTION OF DATABASE.

Path sequence Sphere Frustum of cone	 15-11, 9, 7, 5, 3 15-n_c, 0, 3-(n_c-1) n_c=8, 9, 10, 11, 12
Distance between hammering points a /mm	9
Distance between paths b /mm	2
Punch displacement u /mm	1, 1.5, 2.0, 2.5, 3.0

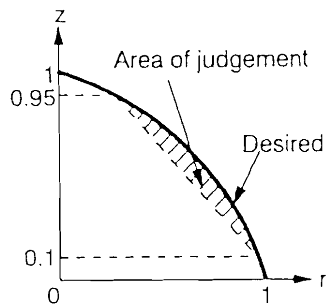

FIGURE 2. NORMALIZATION OF CROSS-SECTIONAL SHAPE OF DESIRED PART.

In the hammering forming, not only local but also global information is necessary to form the sheets into desired shapes. The repeat of local deformation causes wasteful blows, and does not often attain to the desired shapes. In the hammering sequence stored into the database, global deformation caused by repeating local deformation is taken into consideration. It is desirable to include a wealth of knowledge extracted from the human experts in the database.

FINISHING OPERATION USING CCD CAMERA

Finishing Operation

Since the number of stored sequences into the database is limited and the effects of material properties are neglected, the accuracy of the shape formed by the roughing operation is not high. In the finishing operation, the roughly formed shape is corrected by hammering at points of large differences of shape. Unlike the roughing operation, the hammering is not successive but local.

Measurement of Shape Using CCD Camera

In the finishing operation, a three-dimensional shape of the sheet during the forming is measured to obtain the difference of shape. Although the scanning techniques using a touching signal probe and a laser displacement sensor are generally used for measuring three-dimensional shape, the measuring time is not short and the apparatus is not simple. For the measurement, a CCD camera system is employed in the present study. In this system, the three-dimensional shape is obtained by processing images taken by the CCD camera.

In the measurement using the CCD camera, the three-dimensional shape is detected by projecting a grid pattern on the sheet as shown in Figure 3. The projected pattern has no distortion on the standard plane, whereas the pattern is distorted by putting the deformed sheets on the plane. From the difference between the two patterns, namely the displacement, the three-dimensional shape is obtained by means of an image processing technique.

Fourier Transform Grid Method

Since individual pixels in the image taken by the CCD camera have information of brightness, the accuracy of measurement depends on the size of the pixels, and thus the accuracy for the CCD camera is lower than those for the scanning techniques. To improve the accuracy, the distribution of measured brightness is interpolated into a smooth curve like a cosine function as shown in Figure 4, and the distribution of displacement is calculated from the curve (Morimoto, 1991). The interpolation leads to a smaller resolvableness than the direct processing of the pixel information of the CCD camera.

The two-dimensional distribution of measured brightness with the CCD camera is transformed separately for the two orthogonal directions x and y. The Fourier transform of the distribution in the x-direction, f(x), for the standard plane is given by

$$f(x) = \sum_{n=-\infty}^{\infty} C_n \exp\{jn\omega_0(x-x_0)\}, \qquad (1)$$

$$C_n = 2C_0 \sin(n\omega_0 b_0/2)/(n\omega_0 b_0)$$

$$\omega_0 = 2\pi/p_0$$

where p_0 is the pitch of the grid, b_0 is the width of the grid line and C_0 is the half amplitude of the 0th harmonic. The transform of the distribution in the x-direction, g(x), for the deformed sheet is obtained by shifting f(x) given by equation (1) for the displacement u(x);

$$g(x) = f\{x-u(x)\}$$

$$= \sum_{n=-\infty}^{\infty} C_n \exp\{jn\theta(x)\}. \qquad (2)$$

The phase $\theta(x)$ is expressed by

$$\theta(x) = \omega_0\{x-u(x)-x_0\}. \qquad (3)$$

Since the 1st harmonic $g_1(x)$ has the largest amplitude except for the 0th harmonic, the distribution of brightness is interpolated by

$$g_1(x) = C_1 \exp\{j\theta(x)\}. \qquad (4)$$

Since it is difficult to directly extract the 1st harmonic from the distribution of brightness, the Fourier transform is employed. The amplitude spectra are first obtained from the Fourier transform, and then the real and imaginary parts $R\{g_1(x)\}$ and $I\{g_1(x)\}$ of the phase are obtained by taking the inverse Fourier transform for the 1st harmonic;

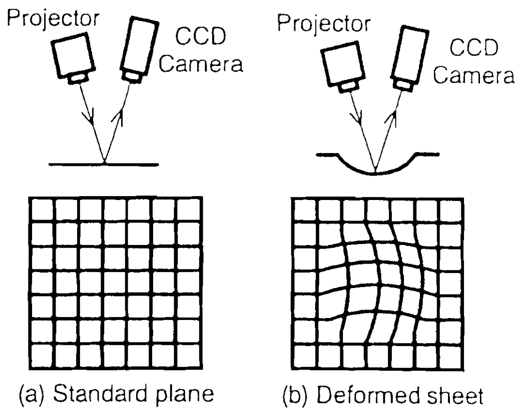

FIGURE 3. DISTORTION OF GRID PATTERN PROJECTED ON DEFORMED SHEET.

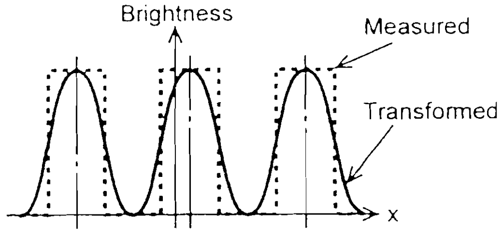

FIGURE 4. TRANSFORM OF DISTRIBUTION OF MEASURED BRIGHTNESS INTO SMOOTH CURVE.

$$\theta(x) = \tan^{-1}\frac{I\{g_1(x)\}}{R\{g_1(x)\}}. \quad (5)$$

By substituting equation (3) into equation (5), the distribution of displacement is given by

$$u(x) = x - x_0 - \tan^{-1}\frac{I\{g_1(x)\}}{R\{g_1(x)\}}. \quad (6)$$

In equation (6), the distribution of brightness is transformed into the continuous distribution of displacement.

Automatic Search of Origin

The origins for the individual images are necessary for the calculation of the distribution of displacement. When the marked image is directly processed, an error is produced due to an additional distortion of the grid around the mark. In addition, it is desirable to search the origin automatically for the control.

A procedure for searching the origin for the image is given in Figure 5. The origin is marked at a point of intersection on the grid pattern. The measured image is represented by a binary form as shown in Figure (a). The transform of black pixels around a white pixel is repeated until a first break of the lines is detected (see Figure (b)). Next, all the lines are narrowed to one pixel as shown in Figure (c), and the position of the origin is determined as the center of the break. Finally, the pixels for the mark of the origin in the original image have the values of brightness around the origin to calculate the distribution of displacement (see Figure (d)). The noises of the measured image are eliminated by this procedure because the sizes of the noises are smaller than that of the origin.

Calculation of Three-Dimensional Shape

From the distribution of displacement obtained by the Fourier transform grid method, the three-dimensional shape of the deformed sheet is calculated. In this case, the positions of the centers of the projector and CCD camera, P_p and P_c, are measured beforehand.

A scheme for calculating the three-dimensional shape from the obtained distribution of displacement is given in Figure 6. For the projected grid pattern, point A for the standard plane is displaced to point B by putting the deformed sheets on the plane, i.e. the difference is the displacement. The two points correspond to points A_I and B_I on the image plane. The positions of points A and C on the standard plane are calculated by the transformation of the co-ordinate system for points A_I and B_I. The position in the z-direction at point B is determined as an intersection point of lines A-P_p and C-P_c. The three-dimensional shape is obtained by processing the whole measured image. For a cylinder with a diameter of 100mm, the maximum error for this method was 0.71mm and the average error was 0.29mm.

METHOD OF EXPERIMENT

Forming Machine

A hammering incremental forming machine having a CCD camera is illustrated in Figure 7. The set of a

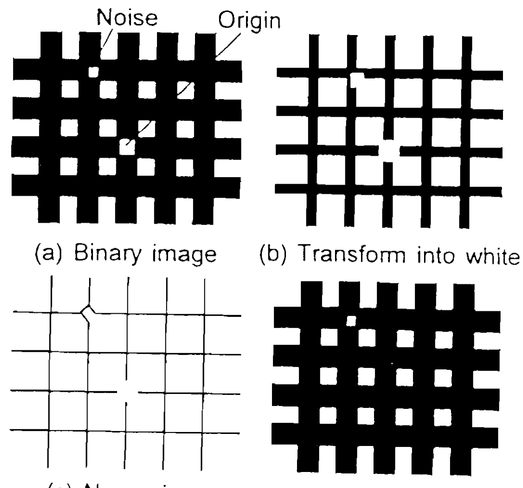

FIGURE 5. TREATMENT FOR SEARCHING ORIGIN OF MEASURED IMAGE.

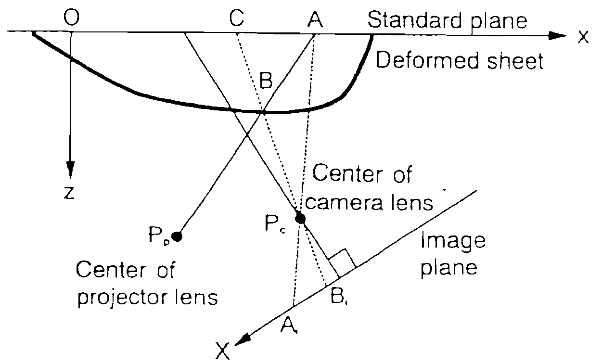

FIGURE 6. METHOD FOR CALCULATING THREE-DIMENSIONAL SHAPE.

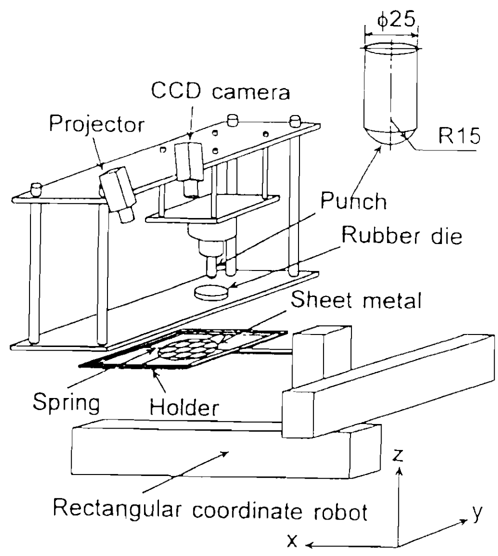

FIGURE 7. INCREMENTAL FORMING MACHINE WITH HEMISPHERICAL STEEL PUNCH AND RUBBER DIE.

the forming tools. The curvature of the deformed hemispherical steel punch and rubber die is used as sheet becomes large by the use of the rubber die. The sheet is flexibly attached to the frame with the springs. The frame is moved by a rectangular coordinate robot to change the position for the blow with the punch. The displacement of the punch driven by hydraulic power is adjustable.

The robot is also employed to carry the sheet to the position of measurement because the space inside the forming machine is too small to measure the image. The conditions of measurement using the CCD camera are given in Table 2. The three-dimensional shape is calculated by a personal computer connected with the CCD camera, and the sheet is moved by the robot to deform the point of the target.

Forming Conditions

The conditions used for the hammering forming of aluminum square sheets are summarized in Table 3. Although the displacement of the punch is controlled in the roughing operation, the displacement of the punch in the finishing operation is fixed to a small value to approach a desired shape.

The procedure for the hammering forming is shown in Figure 8. The forming sequence in the roughing operation is determined by finding a similar shape to the desired shape in the search into the FEM database. The roughly formed shape is corrected by deforming points having large differences of shape detected with the CCD camera system. For the shape measured in each interval of about five blows, the deformed points for the next interval are determined.

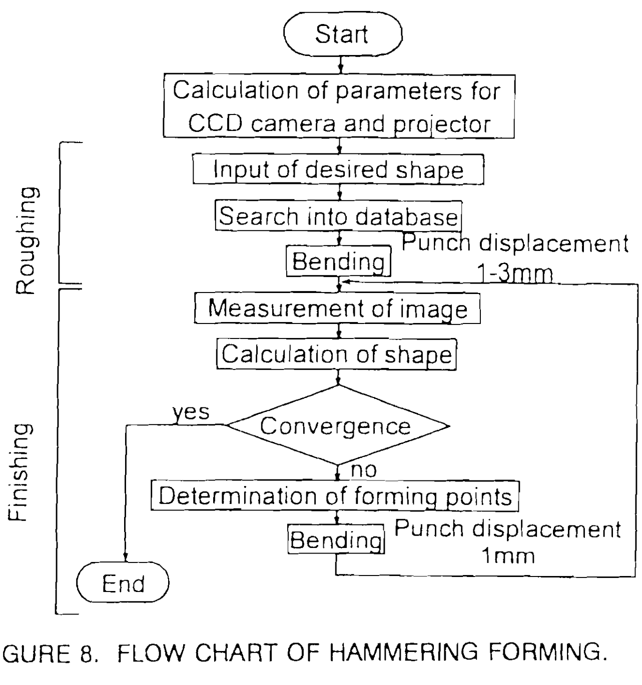

FIGURE 8. FLOW CHART OF HAMMERING FORMING.

HAMMERING FORMING

The formed shapes for the sphere and frustum of cone are illustrated in Figure 9. The overall shapes were measured by the scanning technique using a laser displacement sensor.

The central cross-sectional shape for the frustum of cone obtained by the present method is compared with that by a local modification method in Figure 10.

TABLE 2. CONDITIONS FOR MEASUREMENT OF THREE-DIMENSIONAL SHAPE OF SHEET USING CCD CAMERA.

Grid pitch /mm	2.0
Black and white ratio of grid	1:1
Number of pixels /pixel	256x256
Number of colors	256
Number of measuring points	400

TABLE 3. CONDITIONS USED FOR INCREMENTAL FORMING OF ALUMINUM SQUARE SHEET.

Dimension of sheet /mm	80x80x1
Punch displacement /mm Roughing Finishing	 1.0, 1.5, 2.0, 2.5, 3.0 1.0
Distance between hammering points /mm	3.0
Radius of sphere /mm	67
Frustum of cone /mm (h:height, r_1:upper radius, r_2: lower radius)	h=12, 14, r_1=12, r_2=30
Paraboloid r, z /mm	$z=-0.015r^2$
Hyperboloid r, z /mm	$(r/20)^2-(z/16)^2=-1$

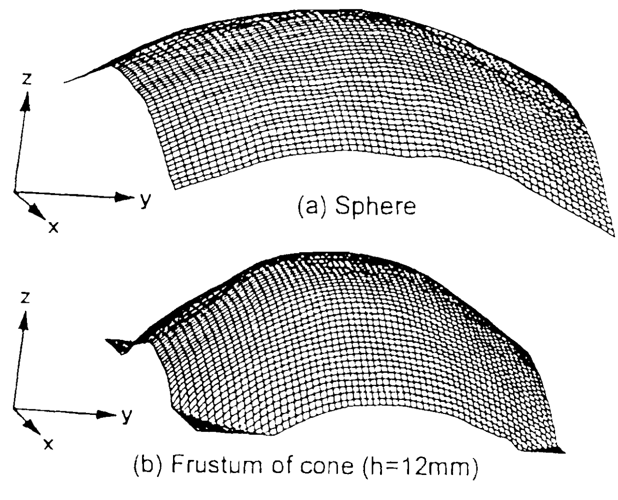

FIGURE 9. MEASURED SHAPES OF FORMED SHEET WITH LASER DISPLACEMENT SENSOR.

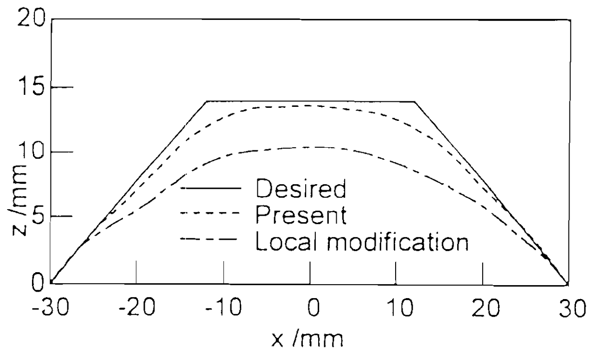

FIGURE 10. CENTRAL CROSS-SECTIONAL SHAPES FOR FORMED FRUSTUM OF CONE OBTAINED BY PRESENT AND LOCAL MODIFICATION METHODS (h=14mm).

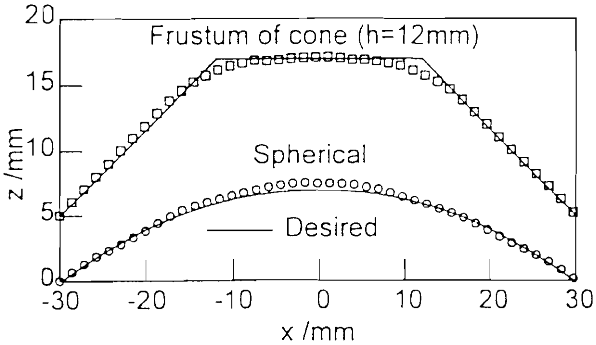

FIGURE 11. CENTRAL CROSS-SECTIONAL SHAPES FOR FORMED SPHERE AND FRUSTUM OF CONE.

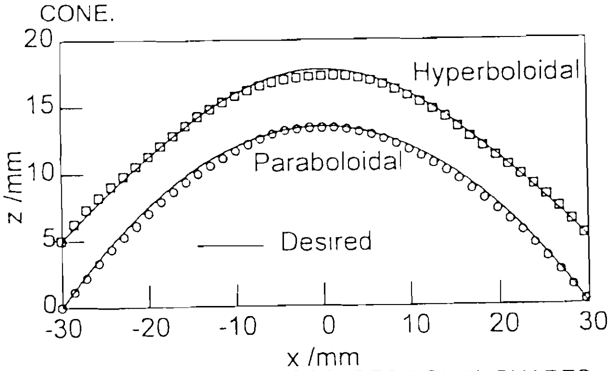

FIGURE 12. CENTRAL CROSS-SECTIONAL SHAPES FOR FORMED PARABOLOID AND HYPERBOLOID.

In the local modification method, the difference between the deformed and desired shapes is detected by means of the CCD camera from the beginning of the forming, and the shape is adjusted by hammering at points having large differences of shape. The local modification method is the same as that for the finishing operation in the present method. The accuracy of the formed sheet by the present method is higher than that by the local modification method. In addition, the number of blows for the present method is considerably smaller than that for the local modification method, about a half. This means requiring the global information for the hammering forming.

The central cross-sectional shapes for the sphere and frustum of cone obtained by the present method are shown in Figure 11. The maximum error for the sphere is 0.34mm and that for the frustum of cone is 1.2mm. Since it is not easy to form the sharp corner in the frustum of cone with the hemispherical punch, the error increases in this portion.

Although the hammering sequences for only the sphere and frustum of cone are stored into the database, the applicability to similar geometries is evaluated as shown in Figure 12. The paraboloidal and hyperboloidal shapes are chosen as examples of forming. The maximum errors for the two shapes are about 0.6mm. The present method has the ability to dealing with similar geometries even if the geometries are not stored into the database.

CONCLUSIONS

Knowledge processing and shape measurement techniques were applied to attain intelligent hammering forming. The rough forming into a desired shape was facilitated by storing the global information for hammering sequences into the database, and the finishing of the shape was heightened by using the CCD camera system for the measurement of three-dimensional shapes. The combination of the CCD camera system and knowledge processing approach emulates the reasoning for human experts, namely the CCD camera system and knowledge processing approach function as eyes and a brain, respectively. This combination is effective in on-line control of forming processes.

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