529 Experimental and Numerical Simulations of the Riveting Process by Upset Forging

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Abstract: The presentation in the literature of analyses of the riveting process by upset forging is not new. However, based on the results that have been published to date, it is not easy to produce guidelines for the optimum design of the punch shape because each of these analyses was carried out using models of different sizes. In this paper, the riveting process by upset forging using five types of punches under a constant rivet head volume are investigated. This paper presents experimental findings as well as the results of rigid plastic finite element simulations. The results include the relationship between the upset force and the punch stroke as well as a clarification of the deformation characteristics of rivet heads. Moreover, the distributions of the compressive stress on the riveted plate in relation to joint strength were analysed.

Key Words: Fixing Element, Plastic Forming, Numerical Analysis, Riveting, Upset Forging, Rigid Plastic Finite Element Method

1. INTRODUCTION

The application of the riveting process to small parts has been on the increase recently as a result of the increase in demand for products manufactured using lower labor costs and shorter production times [1]. However, the strength of the joints in these products is sometimes inadequate. Therefore, a systematic investigation into the riveting process is required [2-4].

Analysis of the deformation mechanism of the flat head rivet and of the forming process by combined upsetting and shaving [5-7] in relation to the riveting process by upset forging have been reported on in the literature. However, because this research has been limited to flat type punches, the results cannot necessarily be extended to an improvement in joint strength of riveting for all punch types.

The purpose of this paper is to examine the capability of joint strength improvement by changing the head shape of a rivet under a constant head volume.

In the first instance, numerical calculations were carried out on five types of head shapes of constant volume. Punches with the same impression volume were manufactured based on the head shape types.

Next, experiments and rigid plastic finite element simulations of the riveting process by upset forging were carried out using punches with lead as the model material.

The relationship between the punch stroke and the upset force were analyzed, and the deformation characteristics of the rivet heads were quantitatively clarified. Moreover, in order to evaluate the joint strength, compressive stress distributions on the riveted plate were analyzed.

2. EXPERIMENTAL PROCEDURE

2.1 Experimental equipment and test piece

Fig.1 shows a schematic illustration of the experimental equipment used for the upset forging as well as the shape and dimensions of the test piece. The experiment was carried out using a universal testing machine at a punch speed of about 5 mm/min and at a temperature of 20℃. In addition, the punch and test piece were lubricated using machine oil. The shape and dimensions of the lead test piece are shown in Fig.1(C).

Some clearance between the test piece and the rivet hole arose because the experiment was carried out by inserting the test piece into the rivet hole of the experimental equipment. Effort was put into minimizing this clearance.

As shown in Fig.1(C), one test piece and one piece split into two halves along the meridian plane were used in the experiments. The two half test pieces were used to observe deformation after forming. The Visioplasticity method [8][9] was applied, whereby grid lines with 2 mm spacing were marked out on the meridian plane. The two half test pieces were put together inside the

- 196 -
experimental equipment.

The test pieces were created first by casting and then by pressing them into a mold. Next, they were finished to the required size by grinding. Lastly, each test piece was annealed for 2 hours at 100°C. The resulting Vickers hardness of each test piece after annealing was in the range of 6 to 7HV. In order to obtain a flow stress-strain diagram for lead, a uniaxial compression test was carried out under the conditions of constant strain rates of $1.7 \times 10^{-3}$ s$^{-1}$, $8.3 \times 10^{-3}$ s$^{-1}$, $16.7 \times 10^{-3}$ s$^{-1}$ and $33.4 \times 10^{-3}$ s$^{-1}$ and for temperatures of 20°C. Experimental results revealed that the flow stress of the lead did not depend on the strain rate in this range.

The flow stress-strain curve was found to be approximated by

$$\bar{\sigma} = 44.4 \bar{\varepsilon}^{0.285} \text{ (MPa)} \quad (1)$$

2.2 Punch shape

In this paper, five types of head shapes for cold headed rivets were investigated [10]: a sharper-than-round head, a round head, a pan head, and two types of heads with convex and concave faces.

Fig. 2 shows the calculation methodology for the various rivet head shapes. Firstly, because of the axial symmetry of the rivet head, the sectional shape on the meridian plane is approximated by the following equation

$$f(r) = ar^4 + br^2 + c \quad (2)$$

Equation (2) assumes that the following two conditions are met:

1. That the volume around the $z$ axis of

\[
\begin{bmatrix}
\frac{L_1^4}{16} & \frac{L_1^2}{4} & 1 & 0 \\
0 & 0 & 1 & -1 \\
256 & 16 & 0 & 0 \\
S_1 & S_2 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
a \\ b \\ c \\ Z_1
\end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (3)
\]

\text{Fig. 2 Design of various punch shapes}
\[ S_1 = \pi \sum_{i=1}^{N} (r_i^4 - r_{i+1}^4), \quad S_2 = \pi \sum_{i=1}^{N} (r_i^2 - r_{i+1}^2) \]
\[ N = \frac{L}{2 \Delta r}, \quad V_0 = \frac{N}{r} \pi \sum_{i=1}^{N} (f_i - f_{i+1}) \]

Fig. 3 shows five types of punches manufactured based on the rivet head shapes. Type A forms the rivet head into a sharper shape than the round head after forming. Type B forms a round head and Type C forms a pan head. Type D or Type E forms a head with convex and concave faces while Type E produces a head that is more uneven than Type D.

Incidentally, Type A, B and C touch the periphery of the upper side of the test piece at the beginning of forming. Type D and Type E touch in the central part of the head owing to their different impression shape. Because the head volume is held constant, the punch strokes are different.

3. NUMERICAL PROCEDURE

3.1 Simulation method

The penalty function method [11-13] that meets volume constancy by selectively reduced integration was used for the rigid plastic FEM.

3.2 Finite element model and computational conditions

Fig. 4 shows the finite element model. The calculation of the FEM was performed with an axially symmetrical system. The flow stress of lead as given by equation (1) was used in the calculation.

The following initial assumptions were imposed on the calculation:

1. There was no clearance between the rivet hole and the test piece.
2. The node of the finite element which was arranged in the corner of the riveted plate (as shown in A part of Fig. 4) was restrained because the metal flow bifurcates into radial and axial directions.
3. Coulomb's friction law was applied for the friction condition between the test piece and the punch using a frictional coefficient of \( \mu = 0.05 \) [14].
4. It was assumed that the friction condition on the riveted plate was the sticking friction condition.
5. The calculation was carried out using a punch speed of \(-0.1 \text{ mm/s}\).

\[ \begin{align*}
\text{Fig. 3 Various punches} \\
\text{Fig. 4 Finite element model of test piece}
\end{align*} \]
at 1 second time increments. Then, the frictional force between the punch and the test piece was calculated by multiplying the nodal force in a direction perpendicular to the punch boundary surface by the frictional coefficient in the process of iteration in order to solve the nonlinear stiffness matrix.

3. The coordinates of the punch boundary surface and the nodal coordinates of the test piece were updated in every step. When the nodal coordinates of the test piece were inside the punch boundary surface, the node was judged to be newly in contact with the punch. In the following step, the nodal velocity was assigned to the node.

When carrying out this calculation step by step, most of the head surface eventually becomes in contact with the punch.

4. RESULTS AND DISCUSSION

4.1 The upset force during the upsetting process

Fig. 5 shows the relationship between the upset force and the punch stroke. Fig. 5(A) shows the experimental results while Fig. 5(B) shows the calculated results obtained by FEM.

From the results of Fig. 5(A), it is found that the upset force increases gradually at the early stage of the upsetting process and that it increases rapidly at the final stage. This is because in all of the cases the test piece is compressed until the space of the punch cavity essentially disappears.

The upset force versus the same punch stroke becomes the greatest when the punch of Type C (pan head type) is used. When a punch of Type D or Type E with the convex and concave faces is used, it becomes smaller than the others. This is particularly the case when the Type E is used.

The results calculated by FEM shown in Fig. 5(B) agree well with the experimental results. Therefore, it can be considered that the method of approach described previously is applicable.

4.2 The characteristics of metal flow

Fig. 6 shows the nature of the metal flow obtained by the experiments. Fig. 7 shows the distorted FE meshes and the distributions of the effective strain calculated by FEM. The results by FEM represent the state in which the bottom of the punch is situated both 2 mm above the riveted plate and immediately in contact with the riveted plate.

It is found that the distorted grid patterns of simulation shown by FEM are in good agreement with the experimental results. Therefore, the following effective strain distributions are discussed based on the results obtained by FEM.

In all of the cases, the effective strain becomes large in the upper peripheral area of the rivet head and near the corner of the riveted plate. However, when a punch of Type A (sharper than round) is used, the effective strain is large in the peripheral area but small near the z axis. Therefore the distribution is very uneven.

When a punch of Type B (round head type) or Type C (pan head type) is used, the effective strain distribution becomes more uniform because the compression rate in the central part of the head increases. From the above results, it is considered that the sharper the head shape, the more uneven the effective strain distribution becomes.

When a punch of Type D or Type E with concave and convex faces is used, the effective strain becomes large in the upper area of the riveted plate and near the z axis. This is particularly the case when a punch of Type E is used. The effective strain distribution is remarkably uneven because the effective strain becomes very large near the head surface along the z axis.

4.3 Internal stress during the upsetting process

Fig. 8 shows the velocity fields and distributions of the internal stress during the upsetting process obtained by FEM. The figures represent the state in which the bottom of the punch is situated at 2 mm above the riveted plate.

When a punch of Type A is used, the axial stress becomes high along the z axis, and the tensile stress acts near the head surface. It can be considered that the velocity field in the central area of the head is generated in an upward
Type A
Deformed mesh
Effective strain $\varepsilon$

Type B
Deformed mesh
Effective strain $\varepsilon$

Type C
Deformed mesh
Effective strain $\varepsilon$

Type D
Deformed mesh
Effective strain $\varepsilon$

Type E
Deformed mesh
Effective strain $\varepsilon$

Fig. 6 Distorted grid patterns of test piece obtained by experiments

Fig. 7 Distributions of effective strain

Fig. 8 Velocity fields and distributions of internal stress
4.4 Compressive stress on the riveted plate

The compressive stress on the riveted plate is closely related to the joint strength because it corresponds to a tightening force of the plate. Therefore, the distribution of the compressive stress that acts on the riveted plate at the final stage of the upsetting process was analyzed.

Fig.9 shows the distribution of the compressive stress on the riveted plate calculated by FEM. This was calculated by dividing the nodal force of the finite element on the riveted plate by the contact area of the element.

It was found that the pressure on the riveted plate becomes the greatest near the rivet hole and lowest in the peripheral area of head. Moreover, in either case, there is not a clear difference in the magnitude of the compressive stress.

5. CONCLUSIONS

In this paper, experiments and rigid plastic finite element simulations of the riveting process by upsetting were carried out using five types of punches under a constant rivet head volume. From these simulations, the following information on the optimum design of punches was obtained:

(1) The upset force versus the punch stroke is greatest when a pan type of punch is used.

(2) The effective strain distribution after forming becomes the most uniform when a pan type of punch is used. When a sharper-than-round punch or a punch with the concave and convex faces is used, the effective strain distribution becomes uneven.

(3) The compressive stress that acts on the riveted plate at the final stage of the upsetting process is highest near the rivet hole and lowest in the peripheral area of head in either case. There is little clear difference in the magnitudes of the compressive stresses in each of these cases.

REFERENCES