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Forming Limit and Its Improvement in Thin-Walled Tube-End Flaring Using Orbital Rotary Forming with Cylindrical Tools

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The possibility of the tube-end flaring using orbital rotary forming with a cylindrical tool has been experimentally investigated from the viewpoint of forming limit by using thin-walled copper tubes. The forming limit is determined by occurrence of rupture and various kinds of bucklings. The diameter of a cylindrical tool has a major influence on the forming limit in orbital rotary flaring. The flaring limit of tube in orbital rotary forming with a cylindrical tool is greater than that with a conical tool. Furthermore, to prevent buckling a pass schedule of a cylindrical tool is proposed and experimentally examined. The buckling mode is prevented under the proposed preventing condition so that the forming limit is dramatically improved. Therefore, the proposed orbital rotary flaring with a cylindrical tool is likely to be a hopefully practical working process from the viewpoint of forming limit.

1. INTRODUCTION

The conventional press forming is a process in which a sheet metal is formed to fit on a die surface. Due to this fitting necessity, the conventional press forming is not so flexible for production of small lots. In consideration of this problem of manufacture flexibility, the, concept of orbital rotary forming was first introduced in 1986 by Kitazawa *et al.*[1] and shortly afterwards was applied to tube-end forming and sheet metal forming by Kitazawa *et al.*[2)~6)]. Orbital rotary forming is a process in which a tube end or sheet metal is formed to fit on a tool-envelope-surface made by a relative motion of a tool around the sheet metal or tube. In orbital rotary flaring and nosing of a tube end, the tube end fits well on the tool-envelope-surface.[2] Therefore, orbital rotary forming seems to be a hopeful process for flexible manufacture from the viewpoint of die-less or tool-less operation. It has also

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been clarified that the forming limit of a tube end in orbital rotary forming is greater than that in press forming.[3] Recently, a computer-controlled orbital rotary forming machine has been developed which has a mechanism capable of forming continuously an appropriate tool-envelope-surface corresponding to a product shape during a stroke of forming[6]. Also, an orbital rotary flanging of tube ends has been carried out by using this machine, and it is found that the metal-flow behavior is dependent on the pass schedule of the tool during the forming stroke.[6] There exist such a large number of degrees of freedom of this pass schedule that the method for optimizing the pass schedule of the tool has not yet been found.

The orbital rotary forming process and the so-called "potter's wheel" process are alike in the relative motion of tool or finger around a thin-walled material such as a cup. It may be possible that the sight of the motion of fingers in the potter's wheel process, when observed carefully, will lead to a new idea for optimizing the pass schedule of a tool in the orbital rotary forming process. One of the more interesting problems in the application of the motion of fingers to orbital rotary forming is the to devise a method for preventing the buckling in orbital rotary flaring of thin-walled tubes.

In the present work, thin-walled copper tubes are subjected to an orbital rotary flaring using a cylindrical tool, designed to imitate the finger, in an attempt to study on the flaring limit in pursuit of its improvement method.

2. EXPERIMENTAL PROCEDURE

To clarify the forming limit, orbital rotary flaring tests were carried out on a modified lathe. As shown in Fig. 1, the proposed orbital rotary forming is a process in which the tool-envelope-surface made by the relative motion of a cylindriacl tool around the tube moves in the axial direction while the tube rotates, and thus, the tube-end is flared to flow along the tool-envelope-surface. The tube held by a chuck rotates at a constant speed of 315 rpm, and the cylindrical tool and its holder mounted on a tool rest which is swiveled to a required angle γ equal to the half apex angle of the tool-envelope-surface, travels in the axial direction at a constant feed of f mm/rev. The materials used are two kinds of seamless copper tubes (outer diameters 35 mm; lengths 70 mm; wall thicknesses 1.0 and 1.5 mm). The length of flaring zone is equal to the outer diameter of the tube so that Euler buckling should not occur. The mechcanical properties of the tube are given in Table 1. Pasty molybdenum disulphide (M_oS_2) and machine oil are used as lubricant and are coated on both the tool and the tube. The tube is flared with the cylidrical tool until a failure such as buckling or rupturing

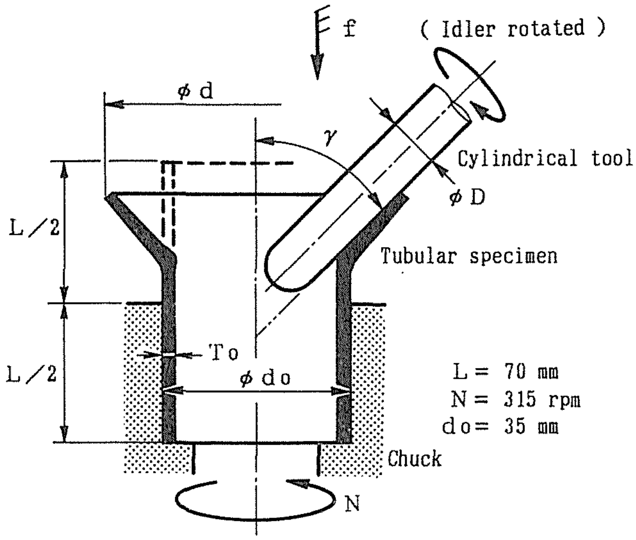


Fig. 1 Orbital rotary flaring with a cylindrical tool.

Table 1 Mechanical properties of the materials used.

Material (JIS)	Outer Dia. do/mm	Thickness To/mm	Work hardening exponent n	Plastic coefficient F/MPa
Hard copper (C1220-H)	35	0.6	0.02	450
		0.8	0.02	460
Soft copper (C1220-O)	35	0.6	0.46	600

takes place. Then, the magnitude of the limiting flaring ratio λ_c[7] defined by Eq. 1 at buckling or rupturing can be obtained by measuring the final outer diameter, d, of the tube end and comparing it with the initial outer diameter, d_o, of the tube end:

$$\lambda_c = (d - d_o)/d_o. \quad (1)$$

Effects on limiting flaring ratio λ_c were investigated of the diameter, D, of the cylindrical tool, the half apex angle, γ, of the tool-envelope-surface, the feed displacement, f, of the tool per revolution, the lubrication, the wall thickness, T_o, of the tube, and the work-hardening exponent, n, of the tube material over the range shown in Table 2. To confirm the advantage of using a cylindrical tool over using a conical tool, λ_c for a cylindrical tool have been compared with that for a conical tool. Furthermore, a comparison

Table 2 Experimental conditions.

Factors	Conditions
Half apex angle of tool-envelope-surface $\gamma/°$	15, 20, 30, 45, 60, 75
Feed displacement of tool per revolution $f/mm \cdot rev^{-1}$	0.0125, 0.05, 0.1, 0.7
Lubrication	Pasty molybdenum disulphide, Machine oil
Tube wall thickness T_o/mm	0.6, 0.8 (d_o=35 mm)
Diameter of cylindrical tool D/mm	15, 20, 25, 30

has also been made between λ_c for the proposed rotary forming and that for the conventional press forming.

3. EXPERIMENTAL RESULTS

3.1 Unfavorable deformation modes

For the orbital rotary flaring with a cylindrical tool, forming limits were determined by the occurrence of several unfavorable deformation modes such as various kinds of bucklings and rupturings, as shown in Fig. 2. The photo in Fig. 3 shows the defects formed on thin-walled hard copper tubes when flared to rupture or buckle with a cylindrical tool.

When $\gamma \leqq 20°$, necks occurred and propagated in the direction parallel to the axis of tube as shown in Fig. 3 (a), and finally, a rupturing occurred along the necked regions. It should be stressed that this necking mode is a characteristic mode in orbital rotary flaring. In press flaring, it is well

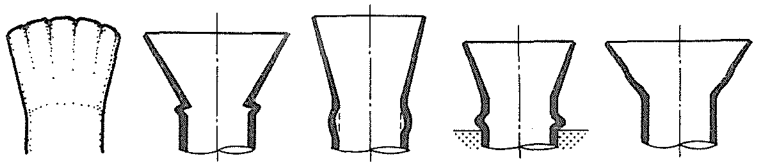


Fig. 2 Unfavorable deformation modes for tube-end flaring by orbital rotary flaring with a cylindrical tool.

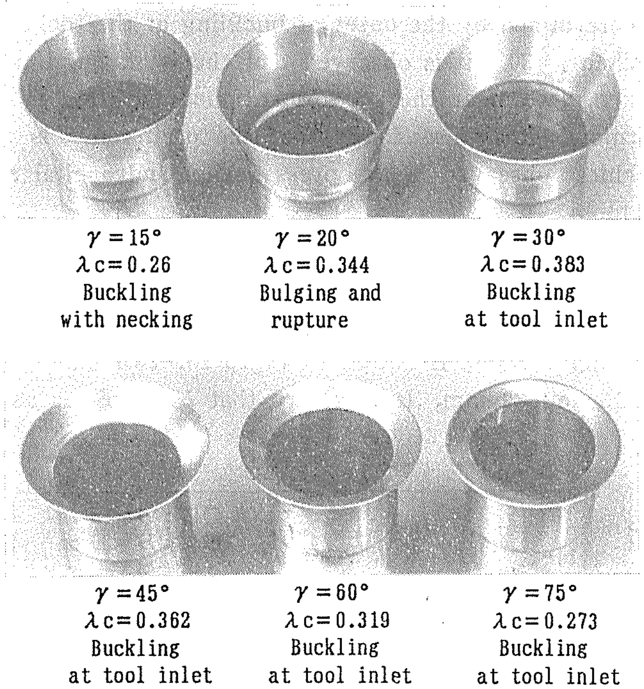


Fig. 3 Unfavorable deformation modes in the process of orbital rotary flaring with a cylindrical tool. (Hard copper tube: Outer diameter 35 mm; Wall thickness 0.6mm; D=15mm; f=0.1mm/rev. Lubricant: Pasty molybdenum disulphide)

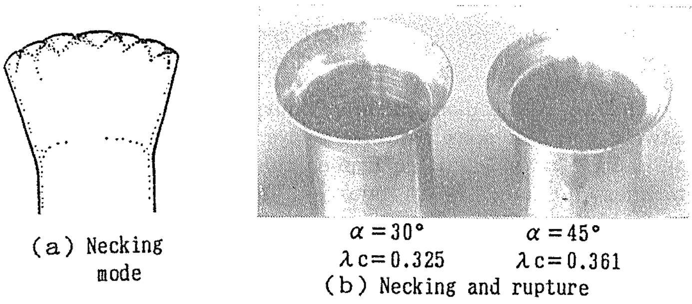


Fig. 4 Necking and rupture originated at the tube end and developed at about 45° to the meridional direction in press flaring. (Hard copper tube: Outer diameter 35mm; wall thickness 0.6mm. Lubricant: Pasty molybdenum disulphide)

known that necks started at the tube end and developed at about 45° to the meridional direction as shown in Fig. 4(a).

On the other hand, in the range $\gamma \geqq 30°$, no necks occurred, and the forming limit was determined by the onset of buckling at the tool inlet as shown in Fig. 2 (b). When $\gamma=30°$, it is observed that the weak bulging mode shown in Fig. 2 (e) takes place after the above-mentioned buckling mode has taken place. Furthermore, it is also found that the occurrence is restrained of curling or waviness observed in the press flaring and orbital rotary flaring with a conical tool.

3.2 Forming limit

The relationship between the half apex angle of tool-envelope-surface γ and limiting flaring ratio λ_C is shown in Fig. 5 for two diameters of cylindrical tool D: 15 and 30 mm. It is shown that λ_C increases as γ decreases,

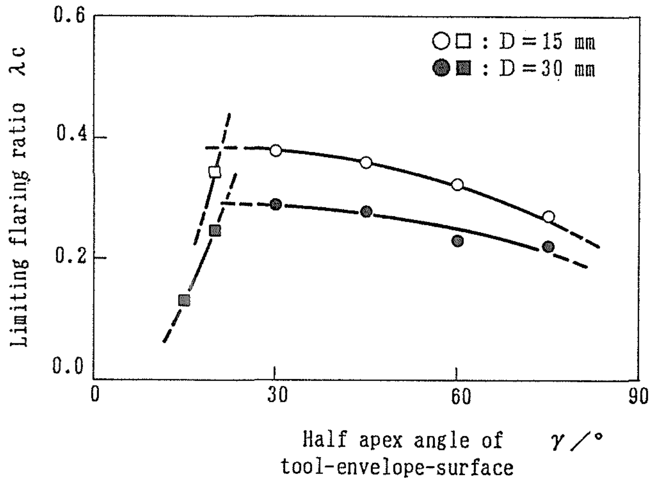


Fig. 5 Influence of the diameter of cylindrical tool D on the relationships between the half apex angle of tool-envelpe-surface γ and the limiting falring ratio λ_C. (Hard copper tube: Outer diameter 35mm; wall thickness 0.6 mm; f=0.1 mm/rev. Lubricant: Pasty molybdenum disulphide. ○●: Buckling mode at tool inlet. □●: Other modes)

reaching a maximum value at $\gamma=30°$, and then decreases as γ further decreases. As has been discussed above, in the range $\gamma \geqq 30°$, it is noted that the occurrence of neck and rupture observed in the range $\gamma \leqq 20°$ is restrained. The shape of the λ_C curve in the case of D=30 mm is similar to that in the case of D=15 mm, although λ_C for D=15 mm is grater than that for 30 mm. Figure 6 shows the dependence of tool diameter D on limiting flaring ratio λ_C. It is shown that λ_C increases as D decreases and approaches a maximum

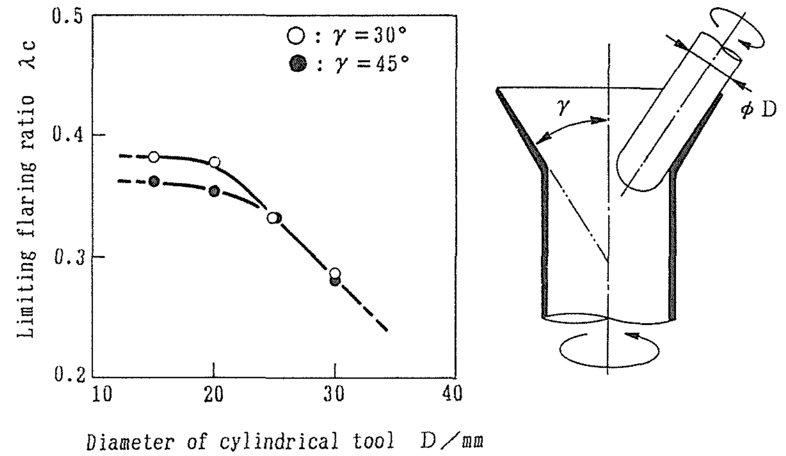


Fig. 6 Relationships between the diameter of cylindrical tool and limiting flaring ratio λ_C. (Hard copper tube: Outer diameter 35 mm; wall thickness 0.6 mm; f=0.1 mm/rev. Lubricant: Pasty molybdenum disulphide. ○●: Buckling mode at tool inlet)

value at about D=20 mm. In the case of annealed copper tubes, the buckling mode (Figs. 2 (c) and (d)) occurs in an early stage of flaring. The effect of tube wall thickness T_0 on limiting flaring ratio λ_C is shown in Fig. 7. λ_C increases as T_0 incerases. The effect of the feed displacement of tool per revolution, f, on λ_C is shown in Fig. 8. From this figure, it is seen that λ_C increases as f increases.

4. DISCUSSION

From these experimental, results it is found that higher limiting flaring ratios are obtainable with cylindrical tools having smaller diameters, smaller work-hardening exponents of tube materials, smaller half apex angles of tool-envelope-surfaces, larger wall thicknesses of tubes, and larger feed displacements of tool per revolution as shown in Table 3. Considering production cost, it is desirable that limiting flaring ratio increases as the feed displacement of tool per revolution increases. It is recommended that the diameter of the cylindrical tool is half the outer diameter of the tube, considering both the rigidity of cylindrical tool and the experimental results shown in Fig. 7. As shown in Fig. 8, it is obvious that the limiting flaring ratio in orbital rotary flaring increases as the feed displacement of tool per revolution increases, although the limiting flaring ratio for the proposed rotary forming in Fig. 3 and those for the conventional press forming in Fig. 4

Table 3 Method for improving flaring limit.

D/mm	f/mm rev	To/mm	γ/°	n
↘ (~0.5do)	↗	↗	↘ (30≦)	↘

↗ :High value, ↘ :Low value

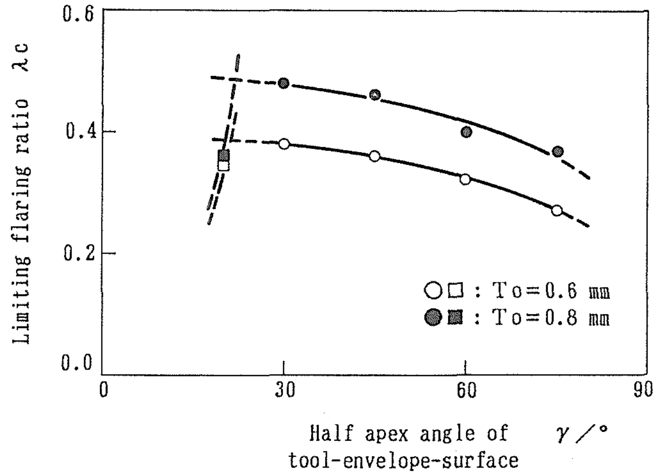


Fig. 7 Influence of tube wall thickness To on limiting flaring ratio λ_C. (Hard copper tube: Outer diameter 35 mm; wall thickness 0.6 mm; D=15 mm; f=0.1 mm/rev. Lubricant: Pasty molybdenum disulphide. ○●: Buckling mode at tool inlet. □■: Other modes)

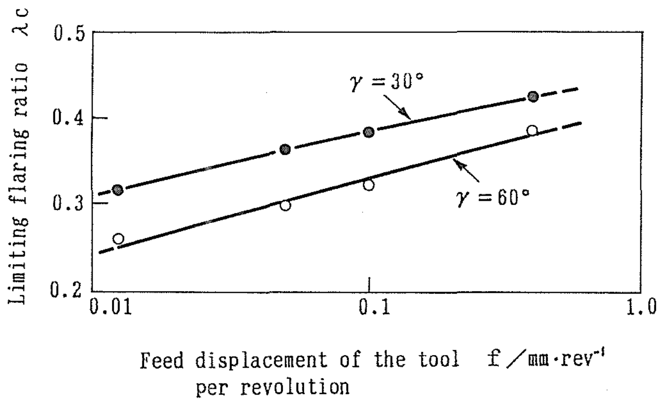
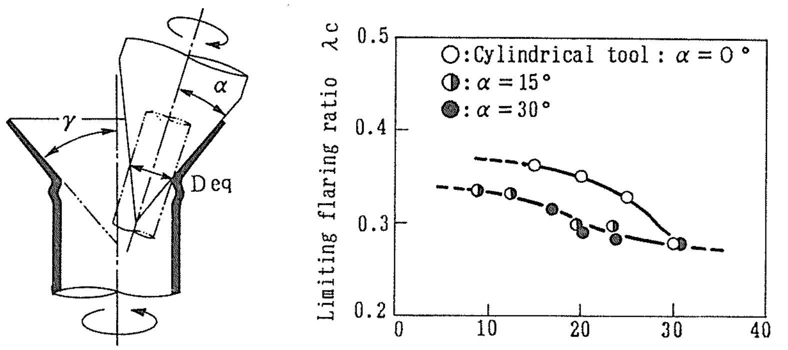


Fig. 8 Influence of the feed displacement of tool per revolution f on limiting flaring ratio λ_C. (Hard copper tube: Outer diameter 35 mm; wall thickness 0.6 mm; D=15 mm. Lubricant: pasty molybdenum disulphide. ○●: Buckling mode at tool inlet)



(a) Equivalent diameter of tool Deq

Equivalent diameter of tool Deq/mm

(b) $\gamma = 45°$

Fig. 9 Influence of the equivalent diameter of tool Deq on limiting flaring ratio λ_c. (Hard copper tube; Outer diameter 35 mm; Wall thickness 0.6 mm. Lubricant: Pasty molybdenum disulphide)

are approximately the same. Thus, it is suggested that the forming limit of orbital rotary forming is higher than that of press forming.

In Ref. 3, orbital rotary flaring and nosing with a conical tool are described and forming limits are reported except for the range $\gamma < 45°$. From the results of Ref. 3, the effects of D, γ, f, T_0, and n on λ_c are similar to the above experimental results. One of the main differences between the orbital rotary forming with a cylindrical tool and that with a conical tool is in the tool shape. To compare forming limits of both cylindrical and conical tools, we have introduced the concept of "equivalent diameter of tool Deq" defined in Fig. 9 (a). Figure 9 (b) compares flaring limits of cylindrical and conical tools by transforming results for conical tools into those for cylindrical tools using Deq. It is found that the limiting flaring ratio for a cylindrical tool is greater than that for a conical tool. Furthermore, the limiting flaring ratio increases with decreasing equivalent diameter of tool for both cylindrical and conical tools. It is suggested that the equivalent diameter of tool Deq has a major effect on the forming limit in orbital rotary forming.

The fitting behavior of tube to tool-envelope-surface is controlled by contact area ratio defined as the ratio of the contact area to the total deformed area of the tube.[2] As has been discussed above, λ_c increases with increasing f and with decreasing Deq. On the other hand, the contact area ratio decreases as both f and Deq decrease. Thus, it is suggested that the contact area ratio does not seem to be a factor affecting λ_c: the onset of buckling at the tool inlet is independent of the contact area ratio. This burkling which occurred at the tool inlet is a local buckling of the mode, and propagated in the circumferential direction of tube.[3] It was observed by Kitazawa *et al.*[3] that it is difficult to predict the occurrence of the above buckling mode by means of buckling load, and that the onses of buckling is affected by local meal flow. Thus, it is suggested that the effect of Deq on λ_c is connected closely with this local metal-flow phenomenon.

As has been mentioned above, from the viewpoint of how to improve the forming limit in orbital rotary flaring of thin-walled tubes, the method for preventing buckling is the most important problem. In a previous paper,[3] Kitazawa *et al.* have proposed the continuous inclination method of the pass schedule of conical tool in tube end flanging but we point out a difficulty in applying this method to preventing buckling that occurs at the tool inlet. The motion of fingers in the potter's wheel process suggests a new idea, the mothod for preventing buckling shown in Fig. 10, for the pass schedule of a cylindrical tool in the orbital rotary forming process. Then, we introduced the modified inclination method of the pass schedule of a cylindrical tool shown in Fig. 10 (b). This method is a process in which the tube at the tool inlet is repeatedly flared to prevent buckling by using a cylindrical tool

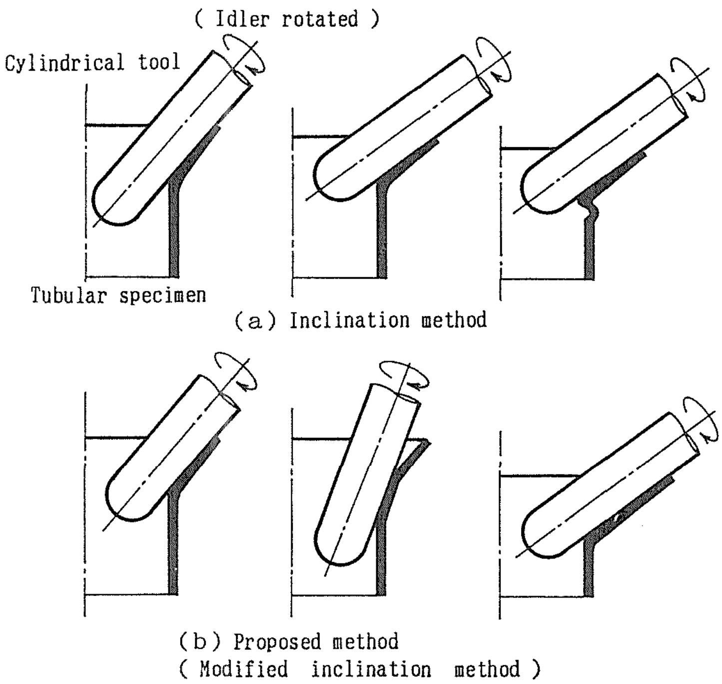
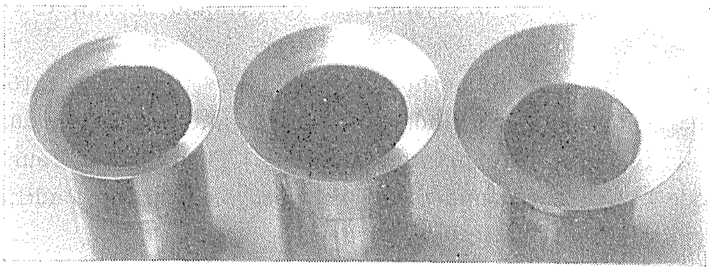


Fig. 10 Proposed method for the preventing of the buckling at tool inlet.



Single process ($\lambda c=0.319$) Inclination method ($\lambda c=0.455$) Proposed method ($\lambda c=0.692$)

Fig. 11 Effect of the proposed method on forming limit. ($\gamma=60°$. Hard copper tube: Outer diameter 35 mm; Wall thickness 0.6 mm; D=15 mm; f=0.1 mm/rev. Lubricant: Pasty molybdenum disulphide)

with a small angle γ under application of the above inclination method. Figure 11 shows that the buckling mode is prevented under the proposed preventing condition so that the forming limit is dramatically improved.

Therefore, the proposed orbital rotary flaring with a cylindrical tool is likely to be a hopefully practical working process from the viewpoint of forming limit.

5. CONCLUSION

The possibility of the tube end flaring using orbital rotary forming with a cylindrical tool has been experimentally investigated from the viewpoint of forming limit by using thin-walled copper tubes. The results are summarized as follows:

1) Forming limits were determined by the occurrence of several unfavorable deformation modes such as various kinds of bucklings and rupturings. In the range $\gamma \leqq 20°$, a rupture mode occurred and propagated in the direction parallel to the axis of tube. On the other hand, in the range $\gamma \geqq 30°$, the forming limit was determined by the onset of buckling at the tool inlet.

2) It was found that higher limiting flaring ratios are obtainable with cylindrical tools having smaller diameters, smaller work-hardening exponents of tube materials, smaller half apex angles of tool-envelope-surfaces, larger wall thicknesses of tubes, and larger feed displacements of tool per revolution. The forming limit of orbital rotary forming is higher than that of press forming.

3) It was found that the limiting flaring ratio for a cylindrical tool is greater than that for a conical tool. The equivalent diameter of tool Deq has

a major influence on the forming limit in orbital rotary forming. It is recommended that the diameter of cylindrical tool should be half the outer diameter of tube.

4) A modified inclination method in which the tube at the tool inlet is repeatedly flared by using a cylindrical tool with a small angle γ during tube-end flaring, is introduced to prevent buckling. Then, it was found that the bucklng mode is prevented under the proposed preventing condition so that the forming limit is dramatically improved.

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