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A Lower Upper-bound Solutions for Shear Spinning of Cones

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圓錐體의 剪斷스피닝 加工에 對한 上界解析

崔　　載　　燦

抄　錄

圓錐體의 剪斷스피닝 加工에서 加工物의 半徑과 두께 方向의 相對 위치가 變化하지 않는다는 조건아래서 흐름 函數에 依하여 速度場을 求하고, 接觸係數에 對하여 變形에너지의 極小値를 구함으로써 相當히 낮은 上界値를 얻었으며, 이를 Al-1100-0, Al-1100-H14, Al-6061-0 等 여러가지 材料에 對한 實驗値와 비교한 結果, 定量的으로 一致하였다.

1. Introduction

The rolling Process which uses a roller and a mandrel to deform metal plates, plastically, into conical or other shapes of circular cross section, such as hemispheres, may be technically described as spinning.

Conventional spinning or hand-spinning requires a blank which has the same wall thickness as the finished part.

However, the shear-spinning differs from the conventional spinning in that the blank diameter is the same as the finished part and the thickness of the finished part is determined by the blank thickness mutiplied by the sine of half the included angle of the finished part.

This "Sine law" expresses the conditions that any circular elements retain its original diameter during spinning and that total volume of metal in a certain diameter will not change.

In contrast, the term of conventional spinning is also used for the spinning process when the radial position of an element in the blank reduces appreciably while the blank is deformed.

The spinning process is an example of a new trend which exists in metal working operations. This trend is toward localizing the deformation zone to a small region of the work piece in order to reduce the forming forces and consequently make it possible to reduce the size of machine required to carry out such processes.

Because of the importance of the spinning process in the forming of aircraft and missile

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components, a number of investigations on the spinning process, both theoretically and experimentally, have appeared in the previous literatures.

For example, Colding[1] considered cone spinning as a combination of rolling and extrusion process, whereas Kalpakcioglu[2] assumed a simple shear mechanism for the analysis of the working forces.

The complex straining effect was introduced into the solution of cone spinning by Avitzur and Yang[3] Kobayashi et al.[4] and Hayama et al.[5].

But their equations for predicting the tangential component force are of a complex nature and require the long computation time for its solution.

Recently, Hayama and Amano[6,7] studied the form of contact between blank and roller during shear spinning by experimental and theoretical procedure. Moreover Hayama[8] estimated concretely the three components of working force using the contact area between blank and roller obtained from his previous work.

A test method for determining the spinability of cones was proposed by Kegg[9]. This consists of shear spinning a blank on an ellipsoidal mandrel. On the other hand, Kalpakcioglu[10] proposed the stress system to get the maximum allowable reduction in shear spinning process.

Sortais et al.[11] studied the cone wall thickness variation in conventional spinning of cones and derived the theoretical tangential force component by the deformation energy method.

Kobayashi[12] established the condition of flange wrinkling in conventional spinning of cones by modifying the theory of instability in deep-drawing of cups.

And Slater[13] gives the approximate upper-bound estimates for tangential force during shear spinning of cones assuming the ideal axi-symmetric deformation. But this assumption is not good enough for the shear spinning process.

As a result, it is concluded that each previous theory for the working forces agreed with the experimental data for only limited range of process variables, and did not give good results for other working conditions.

2. Mechanics of Shear Spinning of Cones

2.1. Deformation Mode

Deformation mechanism of shear spinning of cones from flat blank is shown schematically in Fig. 1 (a), (b).

α is the half cone angle of the mandrel, and t_0 is the thickness of the blank.

The process is characterized by the fact that the r-position of an element in the blank rem-

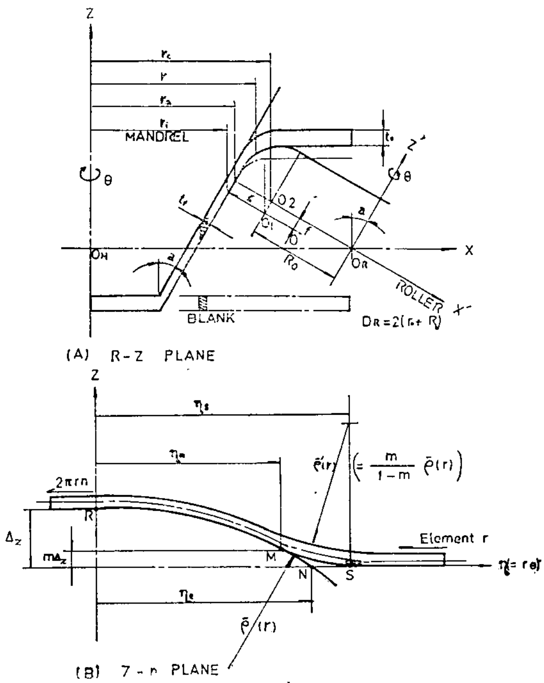


Fig. 1 Schematic description of the deformation in shear spinning of cones.

ains the same during deformation and the angular velocity is constant through whole work piece.

Moreover, for simplicity, it was assumed that during one revolution of the die and blank the roller holds the same position, and after one complete revolution of the die the roll feeds f sin α to X-direction and f cos α to Z-direction. This demands that the initial blank thickness t_0 and the final thickness of the cone t_f for the die slope angle α are related by the equation.

$$t_f = t_0 \sin\alpha \tag{1}$$

2.2. Velocity Fields and Strain Rates

To solve our particular deformation field, the velocity field in the deformationzone was computed first.

Because of the deformation mode, the flow line has to be of the form[17].

$$\phi(x,y,z) = x^2 + y^2 = C_1 \tag{2}$$

$$\chi(x,y,z) = z - z_D = C_2 \tag{3}$$

where z_D is the z-value of the curve SMR in Fig. 1 (b). RM is the contacted portion of the roller z_D with the blank and MS is composed like as Fig. 1 (b) to get the same shear strain $\epsilon_{\theta z}$ along the both side of point M.

When S and M approaches to N, the flow model becomes the similar one proposed by B. Avitzur[3] for shear spinning of cones.

In this case velocity discontinuity exists at N and shear loss term which is neglected by B. Avitzur should be involved in the power.

The components of the velocity field v_x, v_y and v_z assume the form[17],

$$\left.\begin{aligned} v_x &= \lambda\left(\frac{\partial\phi}{\partial y}\cdot\frac{\partial\chi}{\partial z} - \frac{\partial\phi}{\partial z}\cdot\frac{\partial\chi}{\partial y}\right) \\ v_y &= \lambda\left(\frac{\partial\phi}{\partial z}\cdot\frac{\partial\chi}{\partial x} - \frac{\partial\phi}{\partial x}\cdot\frac{\partial\chi}{\partial z}\right) \\ v_z &= \lambda\left(\frac{\partial\phi}{\partial x}\cdot\frac{\partial\chi}{\partial y} - \frac{\partial\phi}{\partial y}\cdot\frac{\partial\chi}{\partial x}\right) \end{aligned}\right. \tag{4}$$

and from Fig. 2, one gets

$$\left.\begin{aligned} v_\theta &= v_y\cdot\cos\theta - v_x\sin\theta = 2\pi rN \\ v_R &= v_y\cdot\sin\theta \times v_x\cos\theta \end{aligned}\right\} \tag{5}$$

Inserting equations (2) and (3) into equations (4) and (5), one gets

$$\lambda = -\pi N \tag{6}$$

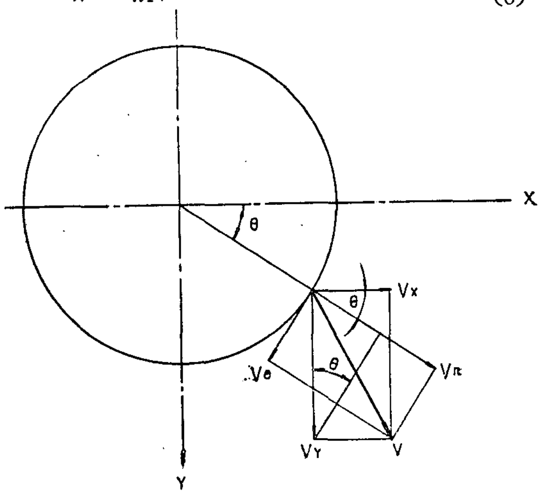
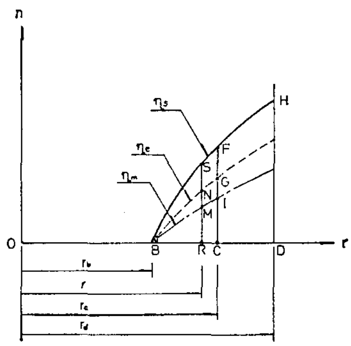
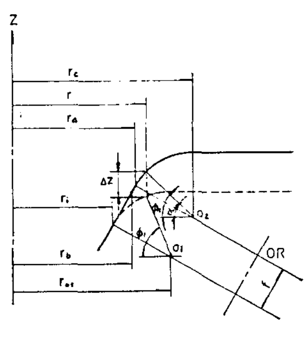


Fig. 2 Velocity components in X-Y plane.



(a) Deformation region in η-r plane.



(b) Shear deformation.

Fig. 3 Model of deformation.

$$\left.\begin{aligned} v_R &= 0 \\ v_\theta &= 2\pi r N \\ v_z &= -2\lambda\left(x\frac{\partial z_D}{\partial y} - y\frac{\partial z_D}{\partial x}\right) \\ &= -2\lambda\frac{\partial z_D}{\partial \theta} \\ &= 2\pi N\frac{\partial z_D}{\partial \theta} \end{aligned}\right\} \quad (7)$$

Noting that $x=\frac{\partial y}{\partial \theta}$ and $-y=\frac{\partial x}{\partial \theta}$.

From the velocity fields of equation (7), one gets the strain rates in cylindrical polar coordinates as follows.

$$\left.\begin{aligned} \epsilon_{RZ} &= \frac{1}{2}\frac{\partial v_Z}{\partial r} = \pi N \cdot \frac{\partial^2 z_D}{\partial r \partial \theta} \\ \epsilon_{\theta Z} &= \frac{1}{2}\frac{\partial v_Z}{r\partial \theta} = \pi N \cdot \frac{1}{r}\frac{\partial^2 z_D}{\partial \theta^2} \end{aligned}\right\} \quad (8)$$

all other $\epsilon_{ij}=0$

The deformation zone is BSFCRBin Fig. 3. BMI is the contact line of the roller with the blank.

2.3. The Power

The rate of total work done on metal under the deformation zone becomes

$$\dot{W} = \int_{vol.} \frac{\bar{\sigma}}{\sqrt{3}} \sqrt{\left(\frac{\partial v_z}{\partial r}\right)^2 + \left(\frac{1}{r}\frac{\partial v_z}{\partial \theta}\right)^2} \cdot dV \quad (9)$$

Inserting equation (8) into equation (9), one gets

$$\begin{aligned} \dot{W} &= \frac{2\pi N t_0 \bar{\sigma}_m}{\sqrt{3}} \cdot \int_S \sqrt{\left(\frac{\partial^2 z_D}{\partial r \partial \theta}\right)^2 + \frac{1}{r^2}\left(\frac{\partial^2 z_D}{\partial \theta^2}\right)^2} \cdot dS \quad (10) \\ &= \frac{2\pi N t_0 \bar{\sigma}_m}{\sqrt{3}} \cdot \left[\int_{S_1} \sqrt{\left(\frac{\partial^2 z_D}{\partial r \partial \theta}\right)^2 + \frac{1}{r^2}\left(\frac{\partial^2 z_D}{\partial \theta^2}\right)^2} \cdot dS_1 + \int_{S_2} \sqrt{\left(\frac{\partial^2 z_D}{\partial r \partial \theta}\right)^2 + \frac{1}{r^2}\left(\frac{\partial^2 z_D}{\partial \theta}\right)^2} \cdot dS_2\right] \\ &= \frac{2\pi N t_0 \bar{\sigma}_m}{\sqrt{3}} \left[\int_{S_1} \sqrt{\left(\frac{\partial^2 z_D}{\partial r \partial \theta}\right)^2 + \left(\frac{r}{\bar{\rho}}\right)^2} \cdot dS_2 + \int_{S_2} \sqrt{\left(\frac{\partial^2 z_D}{\partial r \partial \theta}\right)^2 + \left(\frac{1-m}{m}\right)^2\left(\frac{r}{\bar{\rho}}\right)^2} \cdot dS_2\right] \end{aligned}$$

Where S = Area BSFCRB, S_1 = Area BMICRB, S_2 = Area BSFIMB, and $\bar{\sigma}_m$ is the mean effective stress.

To get a lower upper-bound on energy, one obtains

$$\frac{\partial \dot{W}}{\partial m} = 0 \quad (11)$$

Differentiating equation (10) with respect to m and inserting into equation (11), one obtains

$$m=1 \text{ and } S_1=0,\ S_2=S \quad (12)$$

Inserting equation (12) into equation (10), one obtains

$$\begin{aligned} \dot{W} &= \frac{2\pi N t_0 \bar{\sigma}_m}{\sqrt{3}} \int_S \frac{\partial^2 z_D}{\partial r \partial \theta} dS \\ &\doteq \frac{2\pi N t_0 \bar{\sigma}_m \bar{R}}{\sqrt{3}} \int_\theta \frac{\partial z_D}{\partial \theta}\Big|_{r=r_b}^{r=r_c} \cdot d\theta \\ &= \frac{2\pi N t_0 \bar{\sigma}_m \bar{R}}{\sqrt{3}} \cdot \Delta z_D\Big|_{r=r_c} \\ &= \frac{2\pi N t_0 \bar{\sigma}_m \bar{R}}{\sqrt{3}} \cdot f\cos\alpha \quad (13) \end{aligned}$$

where $\bar{R}=\frac{r_c+r_{01}}{2}$, $\frac{\partial z_D}{\partial \theta}\Big|_{r=r_b}=0$

and $\Delta z_D|_{r=r_c}=f\cos\alpha$

Equation (13) was proposed by B. Avitzur and C. T. Yang[3]. They derived it by a simplified model of pure shear deformation, and did not understand it as an upper-bound on energy. In this analysis, the frictional losses between blank and roller was neglected, because of the small discontinuity of the tangential velocity on the roller.

From equation(13) one obtains the tangential component of forces as follows

$$\dot{W} = 2\pi N \bar{R} \cdot F_t \quad (14)$$

$$F_t = \frac{\bar{\sigma}_m}{\sqrt{3}} \cdot t_0 \cdot f\cos\alpha \quad (15)$$

$$\frac{F_t}{\bar{\sigma}_m} = \frac{1}{\sqrt{3}} \cdot t_0 \cdot f\cos\alpha \quad (16)$$

3. Experimental Procedure

In order to test the validity of the foregoing theory and furnish the flow stress required for calculating the working forces, the spinning test and the plane strain compression test were conducted on aluminum alloys.

3. 1. Spinning Test

The experimental work of shear spinning was carried out on a spinning machine, Autospin 5060, and working forces were measured by three components tool dynamometer which was specially designed and manufactured as shown in Fig. 4.

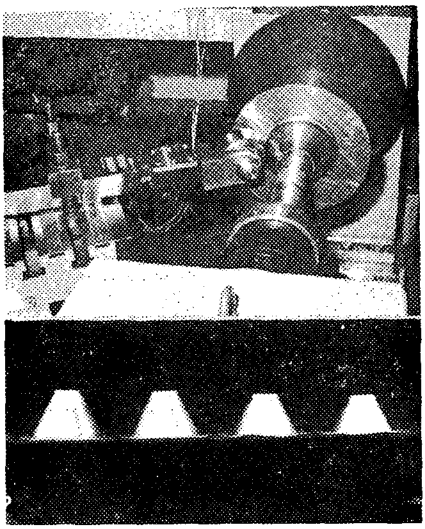


Fig. 4 Exipermental set-up and worked cones.

The experimental values were recorded on the data corder (7404, Hewlett Packard Co.) and signal conditioner (Type 1-080, Bell & Howell Co.)

After the blank was spun into a cone, the final thickness t_f was checked according to Eq. (1) by using the ultrasonic pulse echo type thickness gage (Model CL 204 K-B Co.) The test conditions employed in the spinning tests are given in Fig. 5 and 6.

3. 2. Plane-strain Compression Test

The compression and shear test are most effective to obtain the deformation characteristics applicable to several metal working operations as shear spinning process. In order to maintain the equality between the test specimen and the blank for spinning, the plane-strain compression tests are applied.

The experiments were done for three kinds of specimens, Al 1100-0, Al 1100-H 14 andAl 6061-0.

And each specimen was compressed to get extension along three directions, 90°, 45°, and

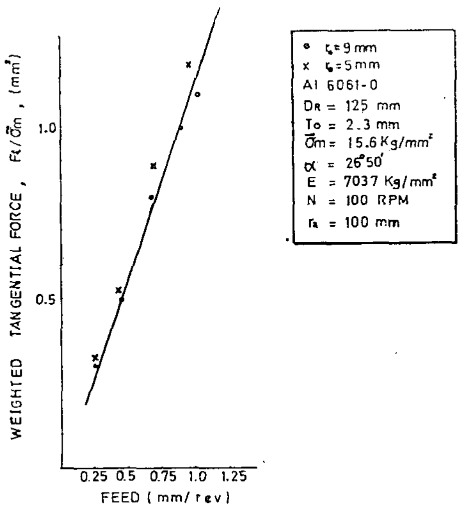


Fig. 5 Relaticns between tangential forces and feed of roller f (Effect of round-off of roller).

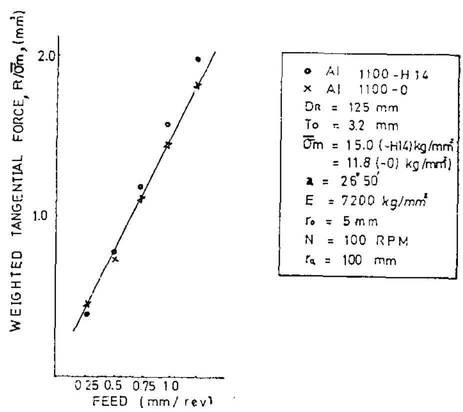


Fig. 6 Relations between tangential forces and feed of roller f (Effect of material properties).

0°, to the rolling direction of the original sheet.

The experimental values are taken, with the mean value of the three kinds of specimen for each tested material, in which the linear least square method was applied.

4. Discussion

The experimental working forces and the calculated results of spinning process are shown in Fig. 5 and 6. Measured working forces are in reasonable agreement with the calculated forces for all working conditions.

Reviewing Fig. 5, it is found that the change of round-off of roller gives small difference of working forces, namely small r_0 gives higher tangential forces. The effect of material properties can be shown in Fig. 6. Both of strain-hardening material, Al-1100-0 and non-strainhardening material, Al-1100-H 14 give fairly good agreement with theoretical values. In the calculation of theoretical values, the mean effective stress, $\bar{\sigma}_m$ is the flow stress of material at the mean effective strain, $\bar{\epsilon}_m$, which is given by

$$\bar{\epsilon}_m=\frac{1}{r_c-r_b}\int_{r_b}^{r_c}\frac{\cot\phi_2}{\sqrt{3}}\cdot dr$$
$$=\frac{r_0-\sqrt{r_0^2-(r_c-r_b)^2}}{\sqrt{3}(r_c-r_b)} \qquad (17)$$

The mean effective stress, $\bar{\sigma}_m$ is the average value of $\bar{\sigma}$ in the deforming region in equation (10). So that the flow stress of material at the mean effective strain $\bar{\epsilon}_m$ is the mean effective stress, $\bar{\sigma}_m$.

KOBAYASHI et al.[4] used the mean effective stress as follows

$$\bar{\sigma}_m=\int\bar{\sigma}d\bar{\epsilon}\Big/\int d\bar{\epsilon} \qquad (18)$$

Which is independent of the history of deformation in the deforming zone.

5. Conclusion

(1) A simplified solution of shear spinning of cones by a pure shear model coincides with the lower upper-bound solution derived in the present paper.

(2) The tangential force is linearly propontional to the yield limit $\bar{\sigma}_m$, blank thickness t_0, feed of roller f and cosine of the included semi cone angle α.

(3) Theoretical values can be applied to strain-hardening materials as well as non-strainhardening materials.

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