Journal of Manufacturing Engineering, March 2010, Vol. 5, Issue 1, pp 31-37

DUCTILITY IMPROVEMENT OF HARD -TO- WORK MATERIALS

***Sukhwinder Singh Jolly[1] and Bedi D S[2]**

[1]Sri Sukhmani Institute of Engineering and Technology, Dera Bassi, Punjab – 140507, India
[2]Institute of Engineering and Technology, Bhaddal, Punjab –140108, India

ABSTRACT

The working range is limited to the strain range starting from elastic point to instability point. In the ductile or soft materials the working range is usually very large but in the hard-to-work (Titanium in this case), this range is very small. In this paper attempt has been made to improve the ductility of Titanium (one of the hard-to-work material) under plane strain conditions and actual strain conditions. It has been found that there is 15.5 % increase in the ductility of the material with plane strain conditions and with actual strain conditions there is 10.5 % increase in the ductility. Bridgeman has confirmed experimentally that many materials flow plastically under high hydrostatic stress. Hydrostatic stress is one whose value is same along the three axes. Thus hydrostatic stress is contributory factor for increase in the ductility of the material. Thus working range of hard-to-work materials increase which helps in providing wider range for working on materials like Titanium and its alloys.

Keywords: *Ductility Improvement, Hard-to-work Materials, Plane Strain Conditions*

1. Introduction

In metal forming, the working range is limited between the yield point and the instability point of the respective stress-strain curve of the material. In the so called ductile or soft materials the working range is usually very large and in the so called 'hard-to-work' materials, this range is relatively very small. Thus these so called hard-to-work materials like titanium and its alloys viz Incoloy, Inconel and Stainless steel are difficult to work due to following factors:

(a) Higher Stress level for a given strain.
(b) Small range of strain between yield point and instability point.

Factor (a) leads to greater load requirement for prescribed strain and factor (b) reduces the working range of the material in which it could be plastically deformed without causing instability. The cumulative effect of these factors makes these materials difficult to work upon and thus is commonly known as hard-to-work materials.

Bridgeman has confirmed experimentally that many materials which are normally brittle will flow plastically under high hydrostatic stress. Hydrostatic stress is one where its value is same along the three axes. In other words it is synonymous with increased hydrostatic pressure. [1]

Singhal et al., [2] studied the Shear spinning of long tubes. This paper presents the results of experiments conducted on commercially pure titanium, Incoloy 825, Inconel 600 and Stainless Steel AISI-304. It is concluded that the process can be used on a commercial basis for producing long, small-bore, thin-wall, high precision tubing in hard-to-work materials, particularly when the volume required prohibits heavy investments.

Singhal et al., [3] presented a generalized expression for the estimation of the power required in the spinning of long tubes, in which the material is assumed to be perfectly plastic and to obey the Von Mises criterion of yielding, and the tools are assumed to be rigid. The analysis is applied to the case of the spinning of long tubes in Stainless Steel, where the calculated axial force is compared with the force whilst conducting actual Shear Spinning experiments. Singhal and Prakash [4] carried out an experimental study of Shear Spinning of tubes of hard-to-work materials. This paper presents the details of the efforts made to produce the high precision thin wall long tubes in Stainless Steel, titanium, incoloy and Inconel. Shear spinning technology for manufacture of long thin wall tubes of small bore has been discussed by Prakash and Singhal [5].

Quigley and Monaghan [8] presented solution to the difficulties that a finite element modeling of spinning faces. Gotoh and Yamashita [9] studied the effect of shearing speed on the quality of shape and edge-face of the sheared-off products.

Wong et al., [10] introduced process details of spinning and flow forming. The state of the art is

**Corresponding Author - E- mail: ssjolly2004@yahoo.co.in*

© SME

described and developments in terms of research and industrial applications are reviewed. Levy et al., [11] shown in their paper that with the increased use of tubular steel products, especially for hydro forming applications, it is important to be able to predict the performance of tube form sheet tensile tests. Jansson et al., [12] carried out the studies on process parameter estimation for the tube hydroforming process. One of the main concerns when designing such a process is to avoid burst pressure. Bortot et al., [13] studied the determination of flow stress of tubular material for hydroforming applications. Mori et al., [14] discussed about hot shear spinning of cast Aluminium alloy parts in their paper.

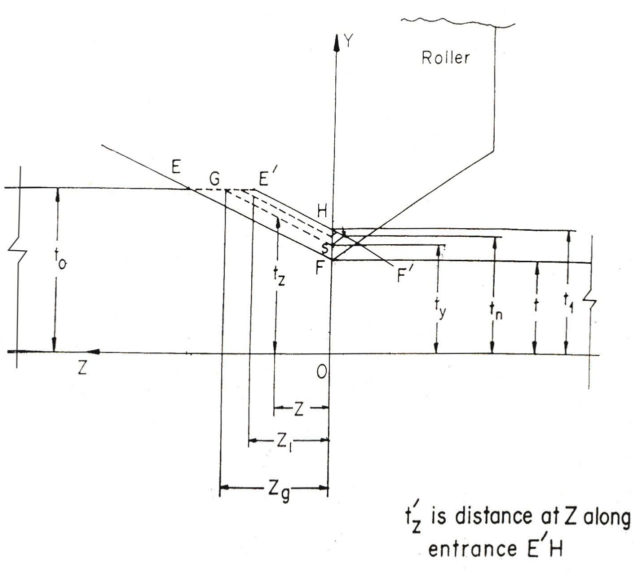

Fig. 1 (a)

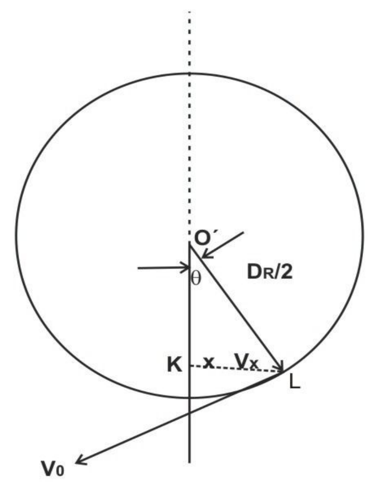

Fig. 1 (b)

2. Analysis

Figs. 1(a), (b), show how the thickness is being reduced by pulling the tube inside the rollers. The x-axis coincides with the direction of the movement of the movement of contact surface of the rollers and z-axis is parallel to the axis of the tube. The rollers have angular speed ω and from this V_0 which is the velocity of the deforming material in the tangential direction to the tube at the contact point between roller and deforming tube are calculated.

2.1 Strain rates

Strain rate in *x*-direction is given by

$$\frac{D_R}{2}\sin\theta = x$$

$$\sin\theta = \frac{2x}{D_R}$$

$$\cos\theta = \left[1 - \frac{4x^2}{D_R^2}\right]^{1/2}$$

Strain rate

$$\dot{\epsilon}_x = \frac{\partial V_x}{\partial x} = \frac{\partial}{\partial x}\left\{-V_0\left(1 - \frac{4x^2}{D_R^2}\right)^{1/2}\right\}$$

$[V_x = -V_o \cos\theta]$

$$= (-V_0)\frac{1}{2}\left(1 - \frac{4x^2}{D_R^2}\right)^{-1/2}\left(-\frac{8x}{D_R^2}\right)$$

$$= (-V_0)\left(-\frac{4x}{D_R^2}\right)\left(1 - \frac{4x^2}{D_R^2}\right)^{-1/2}$$

© SME

$$\dot{\epsilon}_x = \frac{\dfrac{4xV_0}{D_R^2}}{\sqrt{1-\dfrac{4x^2}{D_R^2}}} = \frac{4xV_0}{D_R^2\left(1-\dfrac{4x^2}{D_R^2}\right)^{1/2}} \qquad (1)$$

Strain rate in z-direction is give by

$$\dot{\epsilon}_z = \frac{\partial V_z}{\partial z} = \frac{\partial}{\partial z} KV_0$$

$$= \frac{\partial}{\partial z} \mathrm{K}\omega\left(-2t + \sqrt{\frac{D_R^2}{4} - x^2} - z\tan\alpha \right)$$

$$= -\mathrm{K}\omega \tan\alpha \qquad (2)$$

Strain rate in the y-direction can be found by applying Bridgeman Law

$$\frac{dV}{dt} = 0$$

In terms of strain rate

$$\dot{\epsilon}_x + \dot{\epsilon}_y + \dot{\epsilon}_z = 0$$

$$\dot{\epsilon}_y = -(\dot{\epsilon}_x + \dot{\epsilon}_z)$$

$$= -\left[\frac{4xV_0}{D_R^2\left[1-\dfrac{4x^2}{D_R^2}\right]^{1/2}} - \mathrm{K}\omega\tan\alpha \right]$$

$$= K\omega\tan\alpha - \frac{4xV_0}{D_R^2\left[1-\dfrac{4x^2}{D_R^2}\right]^{1/2}} \qquad (3)$$

The equivalent plastic strain is defined as

$$\dot{\epsilon} = \sqrt{\left[\frac{2}{3}\left\{(\dot{\epsilon}_x - \dot{\epsilon}_y)^2 + (\dot{\epsilon}_y - \dot{\epsilon}_z)^2 + (\dot{\epsilon}_z - \dot{\epsilon}_x)^2\right\}\right]}$$

$$= \left\{\frac{2}{3}\left[(\dot{\epsilon}_x - \dot{\epsilon}_y)^2 + (\dot{\epsilon}_y - \dot{\epsilon}_z)^2 + (\dot{\epsilon}_z - \dot{\epsilon}_x)^2\right]\right\}^{1/2}$$

$$= \left\{\frac{2}{3}\left[(\dot{\epsilon}_x + \dot{\epsilon}_x + \dot{\epsilon}_z)^2 + \{-(\dot{\epsilon}_x + \dot{\epsilon}_z) - \dot{\epsilon}_z\}^2 + (\dot{\epsilon}_z - \dot{\epsilon}_x)^2\right]\right\}^{1/2}$$

$$= \left\{\frac{2}{3}\left[(2\dot{\epsilon}_x + \dot{\epsilon}_z)^2 + (-\dot{\epsilon}_x - 2\dot{\epsilon}_z)^2 + (\dot{\epsilon}_z - \dot{\epsilon}_x)^2\right]\right\}^{1/2}$$

$$\frac{2}{3}\left[4\dot{\epsilon}_x^2 + \dot{\epsilon}_z^2 + 4\dot{\epsilon}_x\dot{\epsilon}_z + \dot{\epsilon}_x^2 + 4\dot{\epsilon}_z^2 + 4\dot{\epsilon}_x\dot{\epsilon}_z + \dot{\epsilon}_z^2 + \dot{\epsilon}_x^2 - 2\dot{\epsilon}_z\dot{\epsilon}_x\right]$$

$$= \left\{\frac{2}{3}\left[6\dot{\epsilon}_x^2 + 6\dot{\epsilon}_z^2 + 6\dot{\epsilon}_z\dot{\epsilon}_x\right]\right\}^{1/2}$$

$$\dot{\epsilon} = \sqrt{4[\dot{\epsilon}_x^2 + \dot{\epsilon}_z^2 + \dot{\epsilon}_x\dot{\epsilon}_z]}$$

$$\dot{\epsilon} = \sqrt{4\left[\frac{16x^2V_0^2}{D_R^4\left(1-\dfrac{4x^2}{D_R^2}\right)} + K^2\omega^2\tan^2\alpha + \frac{4xV_0(-K\omega\tan\alpha)}{D_R^2\left[1-\dfrac{4x^2}{D_R^2}\right]^{1/2}}\right]}$$

$$\dot{\epsilon} = \sqrt{4\left[\frac{16x^2V_0^2}{D_R^4\left(1-\dfrac{4x^2}{D_R^2}\right)} + K^2\omega^2\tan^2\alpha - \frac{4xV_0K\omega\tan\alpha}{D_R^2\left[1-\dfrac{4x^2}{D_R^2}\right]^{1/2}}\right]}$$

Put $J = \dfrac{4xV_0}{D_R^2\left(1-\dfrac{4x^2}{D_R^2}\right)^{1/2}}$

$$\dot{\epsilon} = \sqrt{4\left[J^2 + K^2\omega^2\tan^2\alpha - JK\omega\tan\alpha\right]} \qquad (4)$$

3. Ductility Improvement

Experiments conducted by Bridgeman [6] showed that hydrostatic pressure increases the ductility of metals and alloys. Ductility improvement under plane-strain conditions and actual strain conditions has been calculated.

3.1 Yield under plane-strain conditions

Plane strain is defined as a condition in which (a) the flow is everywhere parallel to a given plane, say the (x, y) plane, and (b) the motion is independent of z. Thus one principal strain-increment, say $d\epsilon_2$, is zero. It follows that if there is no volume change $d\epsilon_1 = -d\epsilon_3$, assuming no elastic deformation, that is assuming an incompressible rigid-plastic material. The deformation is thus pure shear-strain. It is assumed that pure shear strain is produced by pure shear stress [7].

 © SME

When we apply Von Mises yield criterion and upper bound technique then, it is convenient to suppose that the diameter of the tube remains constant, and that the wall thickness alone is changed during tube making. There is then no hoop strain, and plane-strain conditions can be assumed. Let $d\in_1$, $d\in_2$ and $d\in_3$ be the principal components of an increment of strain. Then

$$\overline{d\in} = \sqrt{\frac{2}{3}(d\in_1^2 + d\in_2^2 + d\in_3^2}$$

In uniaxial test

$$d\in_2 = -\frac{1}{2}d\in_3 = d\in_1$$

$$\overline{d\in} = \sqrt{\frac{2}{3}\left[\left(-\frac{1}{2}d\in_3\right)^2 + \left(-\frac{1}{2}d\in_3\right)^2 + (d\in_3)^2\right]}$$

$$= \sqrt{\frac{2}{3}\left[\frac{d\in_3^2}{4} + \frac{d\in_3^2}{4} + d\in_3^2\right]}$$

$$= \sqrt{\frac{2}{3}\left[\frac{6\ d\in_3^2}{4}\right]}$$

$$= \sqrt{\frac{2}{3}\left[\frac{3}{2}\ d\in_3^2\right]} = d\in_3$$

Thus $\frac{\overline{d\in}}{d\in_3} = 1$

In plane strain conditions

$d\in_2 = 0$, $d\in_1 = -d\in_3$

$$\overline{d\in} = \sqrt{\frac{2}{3}\left[(-d\in_3)^2 + (o)^2 + (d\in_3)^2\right]}$$

$$= \sqrt{\frac{2}{3}(d\in_3^2 + d\in_3^2)}$$

$$\sqrt{\frac{2}{3}x2d\in_3^2} = \frac{2}{\sqrt{3}}d\in_3$$

$$\overline{d\in} = 1.155\,d\in_3$$

$$\frac{\overline{d\in}}{d\in_3} = 1.155$$

Thus percentage increase in ductility

$$\frac{1.155-1}{1}\mathrm{X}\,100 \qquad = 15.5\%$$

3.2 Yield under actual conditions

In this case the actual values of ε_x, ε_y and ε_z are calculated and analysis is carried out for finding increase in ductility.

$$\dot{\in}_x = \frac{\partial \mathrm{v}_x}{\partial x}$$

$\because$ $v_x = -v_0 \operatorname{Cos}\theta$

$$\dot{\in}_x = \frac{\partial}{\partial x}(-\mathrm{v}_0\cos\theta)$$

$$\mathrm{V}_0 = \omega\left[\frac{D_R}{2} - \left\{z\tan\alpha + \frac{D_R}{2}(1-\cos\theta)\right\}\right]\cos\theta$$

$$\dot{\in}_x = -\omega\frac{\partial}{\partial x}\left[\frac{D_R}{2} - \left\{z\tan\alpha + \frac{D_R}{2} - \frac{D_R}{2}\cos\theta\right\}\right]\cos\theta$$

$$Sin\theta = \frac{x}{D_R\!\diagup 2}$$

$$= \omega\frac{\partial}{\partial x}\left[z\tan\alpha - \frac{D_R}{2}\cos\theta\right]\cos\theta$$

$$= \omega\frac{\partial}{\partial x}\left[\frac{D_R}{2}(1-\cos\theta) - \frac{D_R}{2}\cos\theta\right]\cos\theta$$

$$\because z\tan\alpha = \frac{D_R}{2}(1-\cos\theta)$$

$$= \omega\frac{\partial}{\partial x}\left[\frac{D_R}{2} - \frac{D_R}{2}\cos\theta - \frac{D_R}{2}\cos\theta\right]\cos\theta$$

$$= \omega\frac{\partial}{\partial x}\left[\frac{D_R}{2}(1-2\cos\theta)\right]\cos\theta$$

$$\because \frac{D_R}{2} = \frac{x}{\sin\theta}$$

$$= \omega\frac{\partial}{\partial x}\left[\frac{x}{\sin\theta}(1-2\cos\theta)\right]\cos\theta$$

$$= \omega\frac{\cos\theta}{\sin\theta}(1-2\cos\theta)$$

© SME

$$\dot{\in}_x = \omega \cot\theta(1-2\cos\theta)$$

$$d\in_x = \dot{\in}_x\ dt$$

$$= \omega \cot \theta\ (1-2 \cos \theta)\ dt$$

$$\because dt = \frac{d\theta}{\omega}$$

$$\int d\in_x = \int_{\theta_1}^{\theta_2} \omega\cot\theta(1-2\cos\theta)\frac{d\theta}{\omega}$$

$$\in_x = \int_{\theta_1}^{\theta_2} \cot\theta(1-2\cos\theta)d\theta$$

$$\int_{\theta_1}^{\theta_2} (\cot\theta - 2.\cos\theta.\cot\theta)d\theta$$

$$\int_{\theta_1}^{\theta_2} \cot\theta\ d\theta - 2\int_{\theta_1}^{\theta_2} \frac{\cos^2\theta}{\sin\theta}d\theta$$

$$\int_{\theta_1}^{\theta_2} \cot\theta\ d\theta - 2\int \frac{1-\sin^2\theta}{\sin\theta}d\theta$$

$$\int_{\theta_1}^{\theta_2} \cot\theta\ d\theta - 2\int_{\theta_1}^{\theta_2} (\mathrm{cos}ec\theta - \sin\theta)d\theta$$

$$\left|\log\sin\theta\right|_{\theta_1}^{\theta_2} - 2\left|\log(\mathrm{cos}ec\theta - \cot\theta)\right|_{\theta_1}^{\theta_2} - 2\left|\cos\theta\right|_{\theta_1}^{\theta_2}$$

$$\in_x = \left|\log\frac{\sin\theta}{(\mathrm{cos}ec\theta-\cot\theta)^2}\right|_{\theta_1}^{\theta_2} - 2\left|\cos\theta\right|_{\theta_1}^{\theta_2}$$

$$\dot{\in}_z = \frac{\partial(\mathrm{v}_z)}{\partial z} = \frac{\partial}{\partial x}(\mathrm{KV}_0)$$

$$\mathrm{V}_0 = \omega\left[\frac{D_R}{2} - \left\{z\tan\alpha + \frac{D_R}{2}(1-\cos\theta)\right\}\right]$$

$$\dot{\in}_z = \frac{\partial}{\partial z}K\omega\left[\frac{D_R}{2} - \left\{z\tan\alpha + \frac{D_R}{2}(1-\cos\theta\right\}\right]$$

$$= \frac{\partial}{\partial z}K\omega\left[\frac{D_R}{2} - z\tan\alpha - \frac{D_R}{2} + \frac{D_R}{2}.\cos\theta\right]$$

$$= -K\omega\frac{\partial}{\partial z}\left[z\tan\alpha - \frac{D_R}{2}\cos\theta\right]$$

$$= -K\omega\frac{\partial}{\partial z}\left[z\tan\alpha - z\tan\alpha\frac{\cos\theta}{1-\cos\theta}\right]$$

$$\because z\tan\alpha = \frac{D_R}{2}(1-\cos\theta)$$

$$= -K\omega\frac{\partial}{\partial z}\left[z\tan\alpha\left(1-\frac{\cos\theta}{1-\cos\theta}\right)\right]$$

$$= -K\omega\frac{\partial}{\partial z}\left[z\tan\alpha\left(\frac{1-\cos\theta-\cos\theta}{1-\cos\theta}\right)\right]$$

$$= -K\omega\tan\alpha\frac{(1-2\cos\theta)}{(1-\cos\theta)}$$

$$= K\omega\tan\alpha\frac{(2\cos\theta-1)}{(1-\cos\theta)}$$

$$\dot{\in}_z = K\omega\tan\alpha\left(\frac{2\cos\theta\text{ -}1}{1\text{-}\cos\theta}\right)$$

$$\dot{\in}_{z=}\frac{d\in_z}{dt} = K\omega\tan\alpha\frac{(2\cos\theta-1)}{(1-\cos\theta)}$$

$$d\in_z = K\omega\tan\alpha\frac{(2\cos\theta-1)}{1-\cos\theta}dt$$

$$= K\omega\tan\alpha\frac{(2\cos\theta-1)}{1-\cos\theta}\ \frac{\mathrm{d}\theta}{\omega}$$

$$\because dt = \frac{d\theta}{\omega}$$

$$\int d\in_z = K\tan\alpha\int_{\theta_1}^{\theta_2}\left(\frac{(2\cos\theta-1)}{1-\cos\theta}\right)\ \mathrm{d}\theta$$

$$\in_z = K\tan\alpha\int_{\theta_1}^{\theta_2}\left(\frac{(2\cos\theta-1)}{1-\cos\theta}\right)\ \mathrm{d}\theta$$

$$= K\tan\alpha\int_{\theta_1}^{\theta_2}\frac{2(1-2\sin^2\theta/2)-1}{2.\sin^2\theta/2}d\theta$$

$$= K\tan\alpha\int_{\theta_1}^{\theta_2}\frac{1\text{-}4\sin^2\theta/2}{2\sin^2\theta/2}d\theta$$

$$\in_z = K\tan\alpha\int_{\theta_1}^{\theta_2}\frac{1\text{-}4\sin^2\theta/2}{2\sin^2\theta/2}d\theta$$

© SME

$$= K\tan\alpha\int_{\theta_1}^{\theta_2}\left(\frac{1}{2}\frac{1}{\sin^2\theta/2}-2\right)d\theta$$

$$= K\tan\alpha\int_{\theta_1}^{\theta_2}\left(\frac{1}{2}\cos ec^2\theta/2-2\right)d\theta$$

$$= K\tan\alpha\left[-\frac{1}{2}.\frac{\cot\theta/2}{1/2}-2\theta\right]_{\theta_1}^{\theta_2}$$

$$\in_z = -K\tan\alpha\left[\cot\theta/2+2\theta\right]_{\theta_1}^{\theta_2}$$

A computer programme was run to find the values of $\in_x$ and $\in_z$

$\in_x$ = -0.589

$\in_z$ = 6.047

$\in_x+\in_y+\in_z = 0$

$\in_y = -(\in_x+\in_z)$

= -(-0.589+6.047)

= - 5.458

$$\bar{e} = \sqrt{\frac{2}{3}\left[\in_x^2+\in_y^2+\in_z^2\right]}$$

$$= \sqrt{\frac{2}{3}\left\{(-0.589)^2+(-5.458)^2+(6.047)^2\right\}}$$

$$= \sqrt{\frac{2}{3}\left\{(0.346)+(29.789)+(36.566)\right\}}$$

$$= \sqrt{\frac{2}{3}\left[66.70\right]} = \sqrt{44.46} = 6.667$$

$$\frac{\bar{e}}{\in_z} = \frac{6.667}{6.047} = 1.102$$

This %age increase in ductility

$$\frac{1.102-1}{1}X100 = 10.3\% \approx 10.5\%$$

Thus, it shows that there is 15.5% increase in the ductility of the material with plane strain conditions and with actual conditions there is 10.5% increase in the ductility. In the case of plane strain conditions it is assumed that diameter of the tube remains constant however in actual conditions there is negligible difference in diameter taking place. Thus, the difference in ductility increase may be due to this assumption.

4. Conclusion

i. The working range in the case of hard-to-work materials is less. Improvement in the ductility of the Titanium, one of the hard-to-wok materials has been calculated under plane strain conditions as well as actual strain conditions.

ii. There is 15.5 % increase in the ductility of the material with actual strain conditions there is 10.5% increase in the ductility of hard-to-work material. Thus ductility of the hard-to-work material increases.

iii. Bridgeman has confirmed experimentally that many materials flow plastically under high hydrostatic stress. Hydrostatic stress is one whose value is same along the three axes. Thus the presence of hydrostatic stress is contributory factor for increase in the ductility of hard-to-work materials.

iv. Tubes of Titanium and its alloys find great use in nuclear industry as well as spacecrafts. This analysis will be of help in the tube making of hard-to-work materials. The working range of hard-to-work materials will increase which will help in providing wider range for working on materials like Titanium and its alloys.

References

1. *Johnson W and Mellor P B (1966), "Plasticity for Mechanical Engineers", D. Van Nostrand Company Ltd., London.*

2. *Singhal R P and Das S R (1987), "Some Experimental Observations in the Shear Spinning of Long Tubes", Journal of Mechanical Working Technology, Vol. 14, 149-157.*

3. *Singhal R P, Saxena P K and Prakash Rajnish (1990), "Estimation of Power in Spear Spinning of Long Tubes in Hard-to-work Materials", Journal of Material Processing Technology, Vol. 23, 29-40.*

4. *Singhal R P and Prakash Rajnish (1990), "An Experimental Study of Shear Spinning of Tube of Hard-to-work Materials, Advanced Technology of Plasticity, Vol. 2, 853-857.*

© SME

5. *Prakash Rajnish and Singhal R P (1995), "Shear Spinning Technology for Manufacture of Long Thin Wall Tubes of Small Bore", Journal of Materials Processing Technology, Vol. 54(1-4), 186-192.*

6. *Bridgman P W (1955), "Investigations on Large Plastic Deformation and Fracture", Foreign Publishing House, U.S.S.R. Academy of Sciences.*

7. *Rowe G W (2002), "Principles of Industrial Metal Working Process", CBS Publishers and Distributors, New Delhi.*

8. *Quigley E and Monaghan J (2000), "Metal Forming: An Analysis of Spinning Process", Journal of Materials Processing Technology, Vol. 103, 114-119.*

9. *Gotoh M and Yamashita M (2001), "A Study of High-rate Shearing of Commercially Pure Aluminium Sheet", Journal of Material Processing Technology, Vol. 110(3), 253-264.*

10. *Wong C C, Dean T A and Lin J (2003), "A Review of Spinning, Shear Forming and Flow Forming Processes", International Journal of Machine Tools and Manufacture, Vol. 43(14), 1419-1435.*

11. *Levy B S, Van Tyne C J and Stringfield J M (2004), "Characterizing Steel Tube for Hydroforming Applications", Journal of Materials Processing Technology, Vol. 150(3), 280-289.*

12. *Jansson M, Nilsson L and Simonsson K (2007), "On Process Parameter Estimation for the Tube Hydroforming Process", Journal of Materials Processing Technology, Vol. 190(1-3), 1-11.*

13. *Borto, P, Ceretti E and Giardini C (2008), "The Determination of Flow Stress of Tubular Material for Hydroforming Applications", Journal of Materials Processing Technology, Vol. 203(1-3), 381-388.*

14. *Mori K I, Ishiguro M and Isomura Y (2009), "Hot Shear Spinning of Cast Aluminium Alloy Parts", Journal of Materials Processing Technology, Vol. 209(7), 3621-3627.*

Nomenclature

K	Constant of volume constancy
V_z	Velocity of pull of tube parallel with mandrel along its perpendicular axis
V_o	Velocity of the deforming material in the tangential direction to the tube at the contact point between the roller and deforming tube.
D_r	Diameter of the roller
V_x	Velocity in the circumferential direction parallel to V_o of the element situated at angle θ with the vertical.
α	Half cone angle of the mandrel/angle of the roller
t_o	Thickness of tube hollow/work piece/blank
t	Thickness of the finished tube
θ	Inclination of an element in the deformation zone situated at angle with the vertical.
$\dot{\in}$	Strain rate
$\dot{\in}_x$, $\dot{\in}_y$, $\dot{\in}_z$	Strain rates in three coordinate directions
ω	Angular speed of the roller.

Acknowledgements

The first author offers his thanks to Prof. Devinder Singh for providing assistance in Computer programming, to Ms. Sunaina for her help in solving the equations of the analysis.

© SME