International Journal of Engineering & Applied Sciences (IJEAS)
Vol.3, Issue 2(2011)13-21

DRAWING OF TWISTED SQUARE SECTION ROD FROM ROUND BAR: AN ANALYSIS AND SOME EXPERIMENTS

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Received Date: 10 October 2010; Accepted Date: 12 January 2011

Abstract

In this paper, slab method of analysis has been applied to calculate the drawing force necessary to carry out a drawing process of square twisted rod from round bar. Because of the complexity of the metal flow inside the die, analysing the real process is complicated. In this study, the idea is to analyze the equivalent axisymmetric process instead of complicated real process. In equivalent process, in each position on the die axis, perpendicular cross sections on the actual die and the equivalent die have the same area. The obtained analytical results were compared with the experimental results were done for steels and copper alloys rods in diameters of 10, 8 and 6 mm to twisted square section rods with sides of 8, 6 and 5 mm, respectively. Comparison of the experimental and theoretical drawing forces showed an acceptable agreement.

Keywords: Twisted square section rod, Drawing force, Slab method.

Nomenclature

dx	element thickness
F_d	drawing force
k	yield shear stress of the workpiece material
m	shear friction factor $(0 \le m \le 1)$
R_f	equivalent radius in exit of the die
R_o	bar initial radius
λ	helix angle of the die
σ_f	flow stress of the workpiece material.
σ_x, σ_r	stress component along axial and radial directions, respectively.

1. Introduction

Twisted square section rods are used in manufacturing twisted nails with square cross section. Twisted nails guarantee better quality of joints working under cycling loads comparing to the nails made from the round wire [1]. Drawing through the rotating dies is a simple method for manufacturing twisted rods. In this process, like other metal forming processes, notification of drawing force is important. Estimating the required drawing force is essential for designing the die and selecting the machine with enough capacity. The process of drawing through conical dies was analysed by Avitzur using the upper bound method [2]. He analysed drawing process by assuming a spherical velocity field in the zone of plastic deformation. Juneja and Prakash [3] derived an upper bound solution to extrude rod with a polygonal cross-section through straight converging dies, by utilizing a spherical velocity field with a cylindrical surface of velocity discontinuity. Basily [4] analysed the process of drawing of circular wires to square ones. He calculated drawing force by meshing the deformation zone and defining of a spherical velocity field for each node, and finally solved the whole geometry of deformation by use of a computer program. Gunaserka and Hoshino [5] accomplished the upper bound solution in order to analyse drawing and extrusion of circular bars to square section rods through converging dies which were formed by straight lines. In a related investigation, Boer and Webster [6] obtained an upper bound solution to draw square sections from a round billet. Knap [1] described the process and the circumstances of the material deformation in the process of drawing circular wire to twisted square section rod. Ma et al. [7, 8] analysed the process of forward extrusion through rotating dies, theoretically and experimentally. They provided required torque for rotating the die from an external source and also supposed that the angular velocity of the material inside the die changes with a power relation with radius of each position in proportion to apex of virtual conic of the die. Haghighat et al. [9] estimated the drawing force in drawing of twisted square section rod from round bar by using upper bound technique. It is inevitable that an upper bound solution overestimates the loads. On the other hand, slab method of analysis solution fundamentally underestimates the required loads. Consequently, a combination of both solutions is desirable to predict the drawing forces within close limits.

In this study, slab method of analysis based on the equivalent curved die, was utilized for estimating the required force in drawing a circular bar to a twisted square section rod. Some drawing experiments were performed and measured forces were compared with theoretical drawing forces.

2. Description of the process

This process of drawing of twisted square section rod from round bar is shown in Fig. 1. The working surface of the die has a shape which allows the deformation of the round bar into square rod and twisting it, simultaneously. In order to obtain gradual shaping of the cross section during the decrease of its area, the working surface of the die is inclined under a constant angle to the die axis. Due to the existence of the helix angle λ inside the die, the friction force, F_f, acting on the material has two components as shown in Fig. 1.

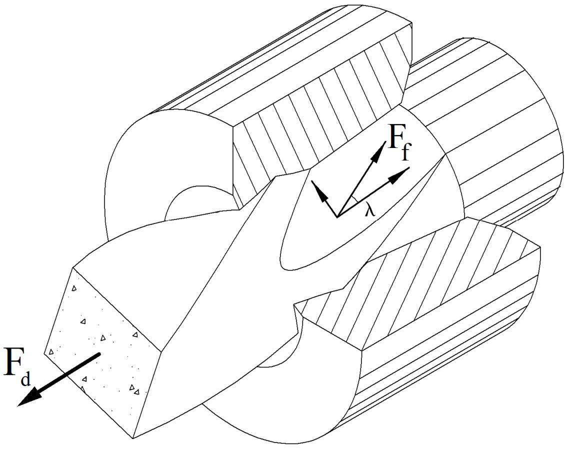


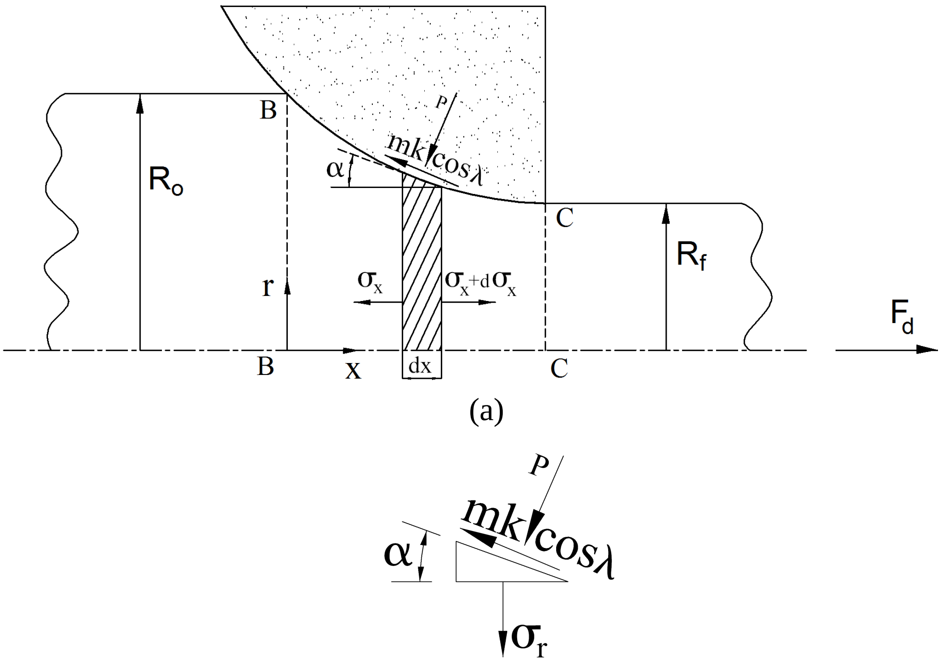
Fig. 1. Drawing process of a circular round bar to a twisted square section rod.

The friction force circumferential component, $F_f \sin\lambda$, causes that die starts to rotate when the drawing process starts.

3. Slab method of analysis

The slab method of analysis was developed by Siebel [10], Karman [11], and Sachs [12]. This method usually underestimates the forming loads involved because it neglects redundant inhomogeneous material deformation. It is an approximate method used for analyzing plastic flow problems. In this method, a slab of elemental or differential thickness is first selected from the deforming material on the planes of which both normal and shear stresses are assumed to act. It is assumed that principal stresses do not vary over the thickness represented by these planes. Based on the assumed stress distribution, a force balance on the elemental slab is made and the resulting differential equations of equilibrium are solved with the appropriate assumptions of yield or flow criterion and the stress boundary conditions.

Because of the complexity of the metal flow inside the die, analysing the real process is complicated. In this study, the idea is to analyze the equivalent axisymmetric process instead of complicated real process. In equivalent process, in each position on the die axis, perpendicular cross sections on the actual die and the equivalent die have the same area. The profile of equivalent axisymmetric curved die is shown in Fig. 2. In this figure, circular bar with initial radius R_o is drawn through the axisymmetric curved die and its radius is reduced to R_f .



(a)

(b)

Fig. 2. Equivalent axisymmetric curved die and its geometric parameters.

The state of stress (based on the cylindrical co-ordinate system) at a small element as shown in Fig. 2a is assumed. The material deforming is seen to be shearing between the die-material interface, thus a shear stress of magnitude mk was assumed to act at at the die-material interface, where m is the shear friction factor $(0 \le m \le 1)$ and k is the yield shear stress of the workpiece material and for Von-Mises' material $(k = \sigma_f / \sqrt{3})$ where σ_f is the flow stress of the workpiece material. Then, by resolving the various forces due to the stresses acting on the slab element along the x-direction and for the equilibrium,

$$\begin{aligned}&\sigma_x \pi (r+dr)^2 - \pi r^2 (\sigma_x + d\sigma_x) + \left(2\pi r \frac{dx}{\cos\alpha}\right) mk \sin\lambda \cos\alpha \\ &+ \left(2\pi r \frac{dx}{\cos\alpha}\right) p \sin\alpha = 0\end{aligned} \tag{1}$$

where x, dx, etc. are as shown in Fig. 2a and σ_r is stress component along axial direction. Neglecting the higher-order small quantities and simplifying, we have

$$\frac{d\sigma_x}{dx} + \frac{2}{r}\left[mk \sin\lambda + p \tan\alpha + \sigma_x \tan\alpha\right] = 0 \tag{2}$$

Next, considering the force equilibrium in the radial direction (as shown in Fig. 2b) and neglecting the higher-order small quantities and simplifying, the following relationship is obtained

$$-\sigma_r (2\pi r) dx + p\left(2\pi r \frac{dx}{\cos\alpha}\right)\cos\alpha - mk \sin\lambda \left(2\pi r \frac{dx}{\cos\alpha}\right)\sin\alpha = 0 \tag{3}$$

where σ_r, σ_θ are stress components along radial and circumferential directions, respectively and $dr = dx \tan\alpha$ .Neglecting the higher-order small quantities and simplifying, the following relationship is obtained

$$-\sigma_r + p - mk \sin\lambda \tan\alpha = 0 \tag{4}$$

Applying the appropriate yield criterion, $\sigma_x - \sigma_r = \sigma_f = 2k$ yields an expression for σ_r as follows

$$\sigma_r = \sigma_x - \sigma_f \tag{5}$$

By placing σ_r from Eq. (5) into Eq. (4), we have

$$p = -\sigma_x + \sigma_f + mk \sin\lambda \tan\alpha \tag{6}$$

Substituting Eq. (6) into Eq. (2), the variation of σ_x with the distance x is obtained as a differential equation in the following form

$$\frac{d\sigma_x}{dx} - \frac{2}{r}\left[\frac{mk \sin\lambda}{\cos^2\alpha} + (2\sigma_x + \sigma_f)\tan\alpha\right] = 0 \tag{7}$$

To obtain a solution to the above equation, the boundary condition $\sigma_x = 0$ at $x = 0$ must be satisfied.

4. Experiments and discussion

In order to verify the theoretical results, experiments using three real rods used as industrial rods have been performed. The materials for the experiments were St 33 and copper and the same as materials used for theoretical study. The stress–strain curves of the materials, St33 and copper, were obtained using tensile test and they are shown in Fig. 3 and Fig. 4, respectively. The chemical compositions of St 33 and copper are shown in Table 1 and Table 2, respectively..

The drawing speed was 1 mm/s. The initial round bars were 6 mm (Case I), 8 mm (Case II) and 10 mm (Case III) in diameters. They are drawn to twisted square section rods with sides of 5, 6 and 8 mm, respectively. The material of drawing dies were tungsten carbide with the helix angles of 83°, 80° and 77° and their lengths were 7, 7 and 10 mm, respectively. Drawing process was operated without lubricant.

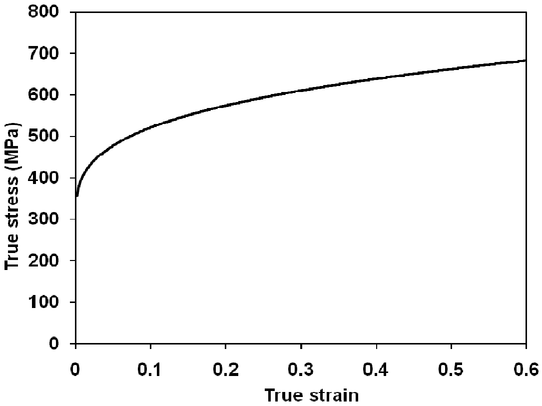


Fig. 3. True stress–strain curve for St 33.

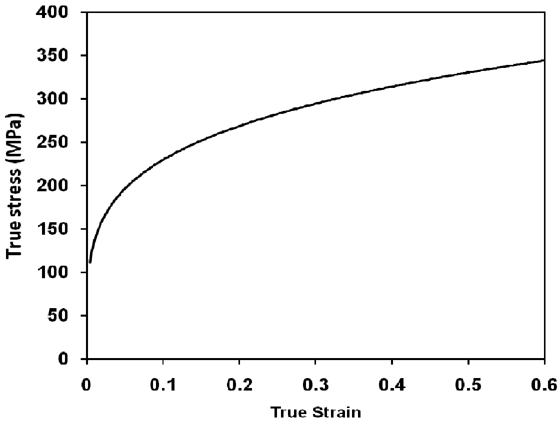


Fig. 4. True stress–strain curve for copper.

Table 1. Chemical compositions of St 33 bars.

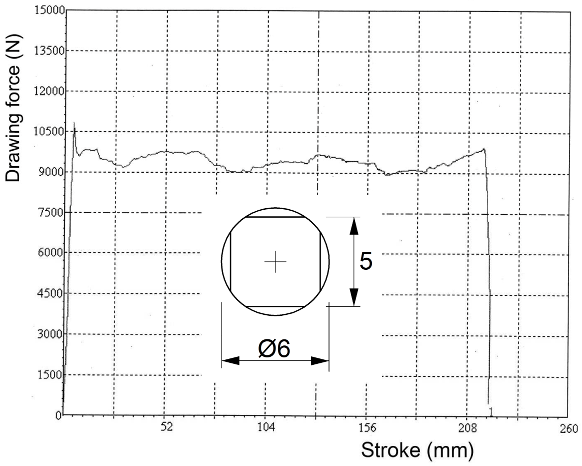
C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co
0.09	0.05	0.41	0.024	0.022	0.05	0.002	0.01	0.002	0.003
Cu	Nb	Ti	V	W	Sn	As	Fe		
0.05	0.005	0.002	0.002	0.02	0.005	0.002	Base		

Table 2. Chemical compositions of copper bars.

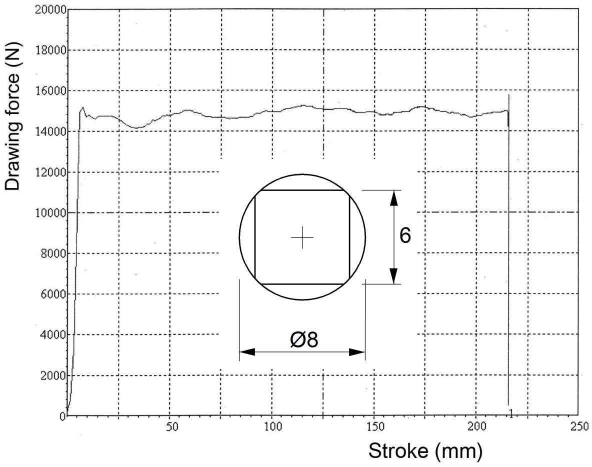
Zn	Pb	Sn	P	Mn	Fe	Ni	Si	Al	S
0.01	0.02	0.01	0.007	0.002	0.005	0.02	0.006	0.014	0.003
Ag	Co	Cu							
0.005	0.01	99.5							

The results of the experiments, measured drawing forces, for these three cases of St 33 and copper rods are shown in Fig. 5 and Fig. 6, respectively.

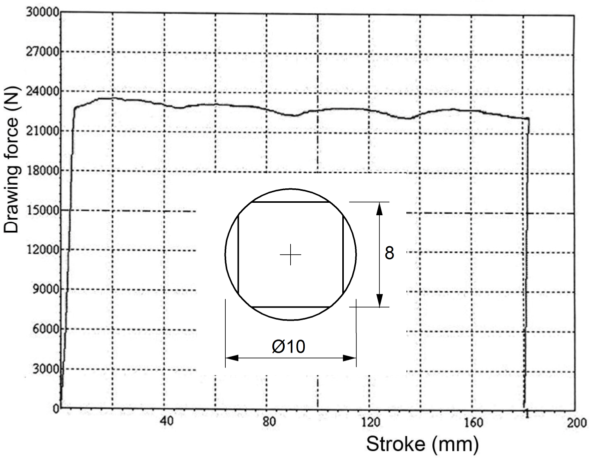
The results of theoretical and experimental data for drawing forces are compared in Table 3 and Table 4. These tables show that the approximated analytical forces are lower than the experimental measured forces. There are two reasons for this matter. The first one is because of using the equivalent die and the second is due to the nature of the slab method of analysis in which the force is under estimated. It only takes into account the homogeneous deformation of the material.



(a) Case I

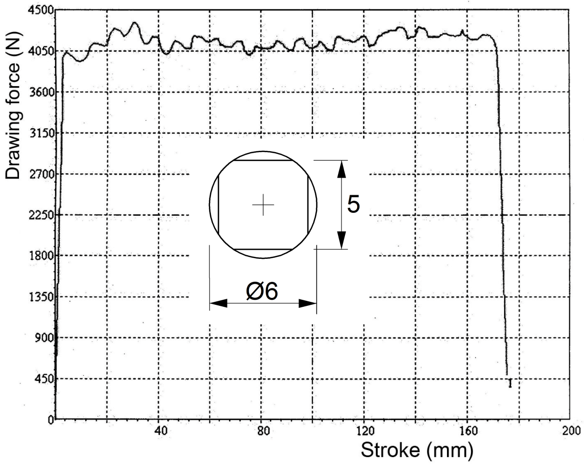


(b) Case II

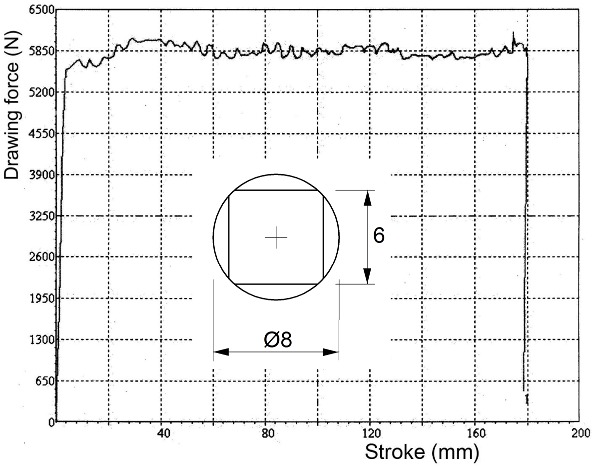


(c) Case III

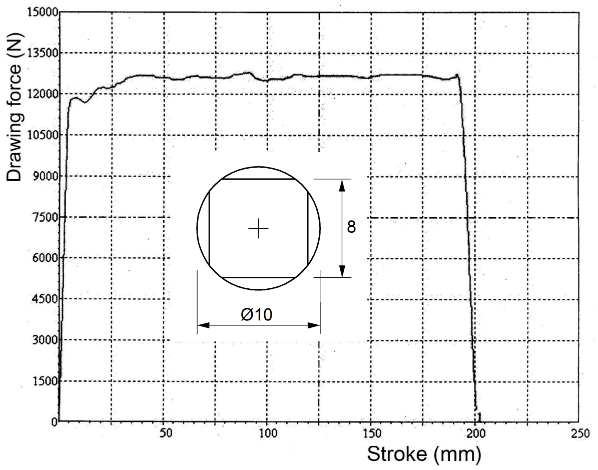
Fig. 5. Experimental drawing forces for three cases of St 33.



(a) Case I



(b) Case II



(c) Case III

Fig. 6. Experimental drawing forces for three cases of copper.

Table 3. Analytical and theoretical drawing forces for three cases of steel.

Case No.	Analytical drawing force (kN)	Experimental drawing force (kN)
I	8.03	9.6
II	12.97	15
III	18.8	22.6

Table 4. Analytical and theoretical drawing forces for three cases of copper.

Case No.	Analytical drawing force (kN)	Experimental drawing force (kN)
I	3.68	4.14
II	4.97	5.85
III	10.66	12.6

6. Conclusions

In the process of drawing of twisted square section rod from circular bar, the drawing force was estimated based on an equivalent axisymmetric curved die by utilizing the slab method of analysis. In order to verify the possibility of the application of theoretical results by using the slab method of analysis, experiments of the shaped drawing for three real industrial products were performed and the results were in acceptable agreement with theoretical results.

Slab method of analysis is very easy to apply and does not require big calculations, but slab method underestimates the extrusion load value to carry out the process, since it only takes into account the homogeneous deformation of the material.

7. References

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