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Adiabatic and friction heating on the open die extrusion of solid and hollow bodies

K. Srinivasan [a], P. Venugopal [b,*]

[a] KREC, Suratkal, Karnataka, India

[b] Metal Forming Laboratory, Department of Metallurgical Engineering, Indian Institute of Technology, Chennai, Madras 600 036, India

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Abstract

This paper deals with an experimental investigation concerning the open die extrusion (ODE) of three materials of varying physical properties and mechanical properties. Two geometrical configurations (solid and tube) and two methods (by direct and indirect techniques) were considered to examine the influence of these variables in the generation and retention of heat in the deformation zone with the objective of ensuring a greater achievable strain. Studies reveal that solid configuration supports the retention of heat as against tubular configuration. Low thermal conductivity, density, specific heat and high flow stress which characterise 99Ti make this material an excellent candidate for ODE as opposed to AISI 1020 steel and aluminium, which fail to meet all the above physical and mechanical properties. The indirect technique reduces the friction factor and thus enables greater strains to be achieved. © 1997 Elsevier Science S.A.

Keywords: Adiabatic and frictional heating; Heat retention in the deformation zone; Open die extrusion

1. Introduction

Open die extrusion (ODE) is an economical route to extrude solid and hollow parts, since this technique is characterised by the elimination of the container in the tooling. The force component arising due to the work-piece and the container wall is eliminated, ensuring more efficient force/energy management in cold extrusion processes. This technique borders with the hydrostatic extrusion process and thus its potential in the conventional status has to be exploited. The disadvantage of this technique is seen in terms of difficulties in achieving greater strains, and in handling greater ratios of billet length to diameter, per push. The possibility of buckling or upsetting of the unsupported billet for greater strains (therefore a greater punch pressure) forms a limitation of the technique.

Recent publications of the present authors [1,2] have shown that by exploiting the generation and retention of the adiabatic and frictional heating in the deformation zone, greater strains are possible as opposed to theoretically predicted strains, concerning the open die extrusion of solid rods. The transformation of cold to warm conditions in the deformation zone should be ensured in-situ whereby the punch pressure can be kept lower than the flow stress of the unsupported billet. This helps in arriving at greater strains in the ODE. Resorting to the inverted type of extrusion, a higher relative velocity between the work material and the die is ensured and thus the friction factor is reduced. The possibility of reducing the punch pressure further can be aimed at. The decreased punch pressure with respect to the flow stress of the material at the die entry favours ODE.

The generation and retention of the adiabatic and frictional heating are dependent on the physical and mechanical properties (such as specific heat, density and flow stress), whilst the surface area to volume ratio in the deformation zone is another parameter affecting the retention of the heat in the deformation zone.

* Corresponding author. Fax: +91 44 2350509.

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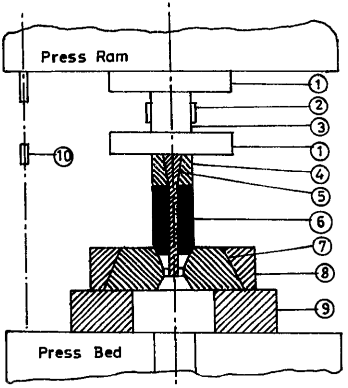

Fig. 1. Experimental set-up for ODE. (1) Hard plate; (2) strain gauge; (3) load cell; (4) sleeve; (5) mandrel; (6) hollow billet; (7) die ring; (8) shrink ring; (9) bolster; (10) LVDT.

2. Scope of the paper

The present paper is devoted to the examination of the generation and retention of the heat in the deformation zone for direct and indirect extrusions (relative velocity) of commercially pure titanium, AISI 1020 steel and commercially pure aluminium (varying physical and mechanical properties). Besides the above, the investigation is also focussed on extruding solid and hollow bodies (geometrical variable) to enumerate the role played by the surface area to volume ratio.

Earlier work [3] on the conventional extrusion of 99.9Ti revealed that the lower the resident temperature, the better the condition of heat generation in the deformation zone. Thus, in the present work, the resident forming temperature was confined to 303 K (cold-working temperature). It was reported in Ref. [3] that the forming speed (strain rate) had little influence in reducing the punch pressure until a strain of 0.4 for the

Table 1
Flow equation properties estimated from solid and ring compression tests

Metal	K (MPa)	n	μ	S_y (MPa)
99Ti	1100	0.34	0.14	390
CP Al	180	0.21	0.14	55
AISI 1020 steel	815	0.27	0.10	270

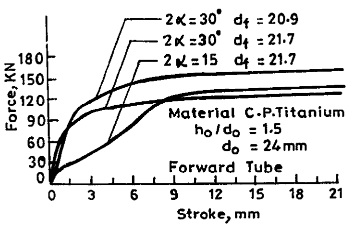

Fig. 2. Typical punch force–stroke diagram for forward tube extrusion.

work material 99.9Ti extruded at cold-working temperature, both for tubes and solid rods. Thus, the influence of the strain rate in the present work assumes less importance, as the strains involved presently are low.

3. Experimental

3.1. Specimen preparation for extrusion and compression tests

The work materials cited in the above section were prepared for experimentation as follows. The as-received 99.9Ti of 40 mm diameter was forged to 30 mm diameter and annealed at 973 K for 2 h. (A special coating of Glass 8221 was given to eliminate the harmful effect of N_2, H_2 and O_2 whilst heating the rods prior to the hot forging.) AISI 1020 steel and CP aluminium were annealed at 1123 and 673 K, respectively, for 1 h. The annealed rods were machined to 24 mm diameter and 36 mm height, with regard to solid billets for extrusion; 24 mm outer diameter (o.d.), 10 mm inner diameter (i.d.) and 36 mm height, with regard to hollow billets for extrusion. Cylindrical specimens of 25 mm diameter, height 37.5 mm and ring specimens of (o.d.):(i.d.):height = 6:3:2 were prepared to enable the compression tests from which the flow equation and coefficient of friction could be obtained. These data were essential for the computation of theoretical forces concerning the ODE, besides the limiting upsetting stress. Four different die angles of 12, 15, 25 and 30° were used for extrusion strains of 0.15, 0.25, 0.28 and 0.43 (for solid rods), and 0.18, 0.25, 0.35, 0.45 and 0.54 (for tubular extrusions.) MoS_2 paste was used as lubricant. The tool set up for extrusion studies is shown in Fig. 1. The experiments were done on a 1000 kN hydraulic press. For direct extrusion, the die was made stationary and the workpiece was pushed into the die, whereas for indirect extrusion, the die was moved and

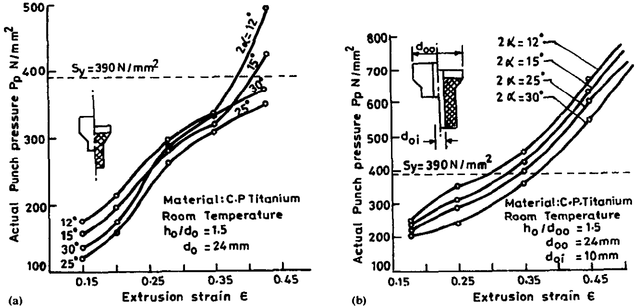

Fig. 3. Punch pressure against strain for: (a) rods; and (b) tubes.

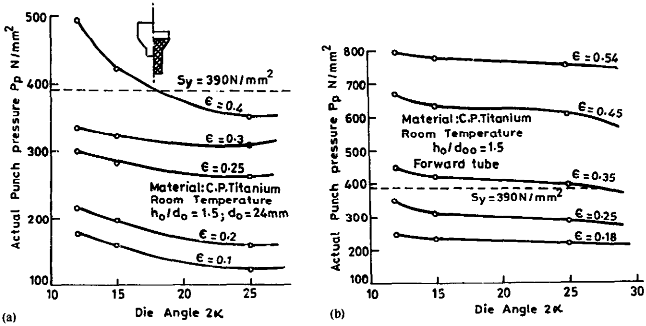

Fig. 4. Actual punch pressure against die included angle for: (a) rods; and (b) tubes.

the workpiece was pushed against the movement of the die. Force–stroke diagrams were registered with a load cell, an LVDT and an X–Y plotter.

4. Results and discussion

4.1. Compression test

The strength coefficient K, the strain hardening exponent n, and the coefficient of friction μ estimated in compression tests are entered in Table 1 for the three work materials.

4.2. Extrusion tests

A typical punch force–stroke diagram is presented in Fig. 2. The presence of a peak through force (common in conventional extrusion with a container) is conspicuously absent, characterising the ODE process. The maximum load divided by the area of the cross-section of the billet under the punch gives the actual punch pressure. Typical punch pressure dependence against strain and die angle is shown in Figs. 3 and 4 for solid and tubular configurations. When the actual punch pressure reaches the flow stress value, the limit of the pure ODE process is said to have been reached. The corresponding strain is supposed to be the achievable

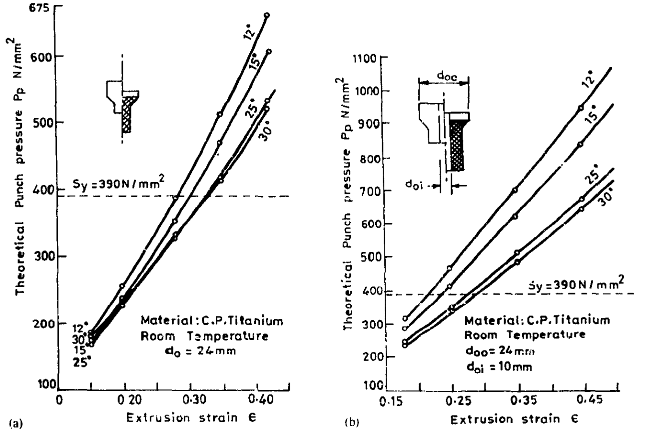

Fig. 5. Theoretical punch pressure against strain for (a) rods; and (b) tubes.

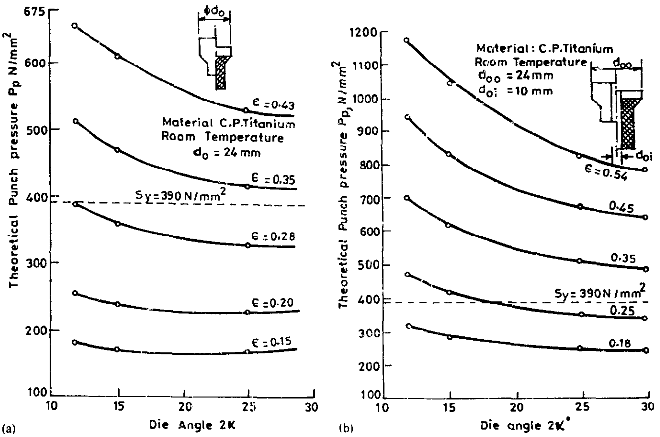

Fig. 6. Theoretical punch pressure against die angle for: (a) rods; and (b) tubes.

limit strain for the ODE. Reference to the above figures reveals that the optimal angle at which the actual punch pressure is minimum is 25° for a solid rod and 30° for a tube. Figs. 5 and 6 show the punch pressure dependence on die angle and strains as obtained from theoretical calculations (see Appendix A) using the compression test data. Comparison of Figs. 3 and 6 reveals that the actual pressures are lower than the theoretical pressures, the adiabatic heating and frictional heating in the deformation zone being responsible for this favourable difference.

4.3. Adiabatic heating and frictional heating for solid and tube ODE

The temperature rise due to adiabatic heating for rod and tube ODE is given by:

$$\Delta T_{\mathrm{Ad}} = \frac{\beta\sigma\varepsilon}{\rho C}$$

and the temperature rise due to friction at the die–billet interface is:

$$\Delta T_{\mathrm{Fr}} = \frac{\mu\sigma_{\mathrm{N}} V_{\mathrm{R}} \cos\alpha D t A}{\rho C V}$$

These two temperature aspects transform the isothermal extrusion into an in-situ warm extrusion which is responsible for the observed lower values of punch pressure. In the tube extrusion, another source of heating arises due to the billet–mandrel interfacial friction.

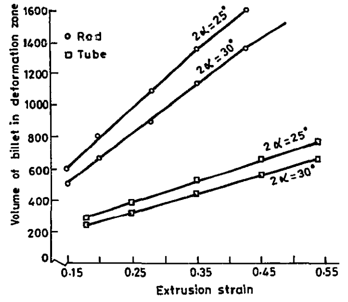

Fig. 7. Volume of metal in the deformation zone.

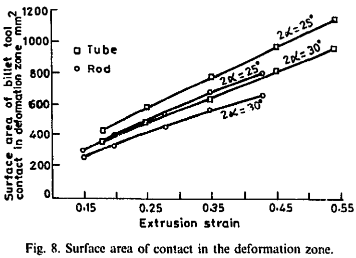

Fig. 8. Surface area of contact in the deformation zone.

Thus, the contribution of the heat rise in tube extrusion is expected to be more effective in reducing the punch pressure. For the heat rise discussed above to be effective, it should be retained in the deformation zone.

For a given strain, the temperature rise due to adiabatic heating is the same for both solid rods and tubes. Due to the geometrical difference between the two, the mass of metal in the deformation zone for the tube is less than for the rod, as can be seen from Fig. 7. Hence, the advantages of heat increase in the tubular extrusion are readily seen. However, for a given angle and therefore for a given geometry, the surface area is more for the tube than for the rod, as can be seen in Fig. 8. The surface area assumes significance from the point of view of heat loss from the deformation zone through the tooling. Further, there is also heat conduction through the unsupported billet, the sleeve and the mandrel above the deformation zone (see Fig. 1). In the case of tubular extrusion, due to less mass, uniform heating of the entire stock is facilitated, as opposed to localised heating in the solid extrusion. It is thus observed from Fig. 9(a) and (b) that the punch pressure is greater for tube extrusion than it is for the solid geometry, which is against the expected trend.

4.4. Influence of materials

The ratio of the punch pressure to the upsetting stress (for optimal angle) ($P_{\mathrm{p}}/S_{\mathrm{y}}$) against strain for the three materials is presented in Fig. 10(a)–(c). If the $P_{\mathrm{p}}/S_{\mathrm{y}}$ ratio reaches unity, the pure ODE process terminates and the combined upsetting and extrusion process sets in, defeating the merits of the pure ODE process. Comparison of Figs. 9 and 10 reveals that the difference in punch pressure (P_{p}) between rod and tube is more for aluminium and steel than for titanium. Reference to Fig. 10 reveals that at a strain of 0.30, the percentile difference concerning the $P_{\mathrm{p}}/S_{\mathrm{y}}$ ratio for tubes and rods is 54% for aluminium, 48% for steel and 15% for titanium. The corresponding values in the inverted technique (please refer to Fig. 11(a)–(c)) are 43, 41 and 5%, respectively. The difference in punch pressure is maximum (between solid and tube) for aluminium due to the lower heat generation and retention in the deformation zone (high specific heat, low flow stress and high thermal conductivity), despite its density being the lowest amongst the three materials investigated. Concerning the titanium which has low specific heat, density, thermal conductivity and high flow stress, the heat generation and retention is maximum. The figures for steel lie between those for the two materials. Table 2 contains the physical properties of the three materials. The product ρC is also maximum for steel compared to the other two materials.

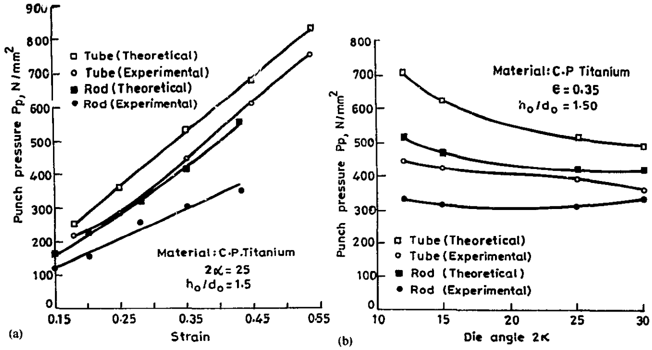

Fig. 9. Comparison of rod and tube ODE against: (a) strain; and (b) die angle.

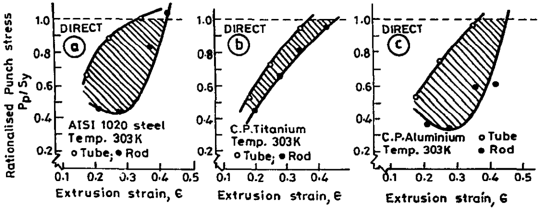

Fig. 10. Comparison of punch pressure for solid rods and tubes for all materials in the direct mode.

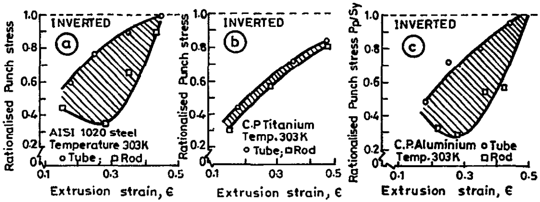

Fig. 11. As per Fig. 10, but for the indirect mode.

4.5. Comparison of direct and inverted techniques

The difference in the P_p/S_y ratio has been observed to be lower for the inverted technique with respect to the direct technique, as can be seen from Figs. 10 and 11. The achievable strains for the inverted technique are more than those for the direct technique, since the friction factor reduces with increasing relative velocity. For a relative velocity increased by a factor of 2 in the case of 99Ti, a 33% reduction in friction factor is attained, resulting in a 37% reduction in punch pressure. The comparable values for AISI 1020 and commercially pure aluminium are observed to be: a 13% reduction in friction factor and a 16% reduction in

Table 2
Physical properties

Metal	$1/\rho C$	ρ (g cm^{-3})	C (J (kg·K)$^{-1}$)	λ (W mK^{-1})
99Ti	0.42	4.51	518	16.4
CP Al	0.408	2.70	913	230.3
AISI 1020	0.303	7.85	420	63

punch pressure; a 12.5% reduction in friction factor and a 15% reduction in punch pressure, respectively.

5. Conclusions

Open die extrusion investigations on commercially pure titanium, AISI 1020 steel and commercially pure aluminium (varying physical and mechanical properties) by direct and indirect techniques (relative velocity) for solid and tubular configurations (geometrical variable) to examine the heat generated and retained in the deformation zone, with the objective of increasing the achievable strains, reveal the following:

(1) The influence of heat increase is greater for solid rods than it is for tubes, since heat loss and heat generation are neutralised in the case of tube extrusion. The greater ratio of surface area to volume in the case of tubular geometry is responsible for the above.

(2) Material with low density, thermal conductivity, specific heat and high flow stress will be an excellent candidate for open die extrusion. This is substantiated by 99Ti with respect to the other two materials.

(3) Increased relative velocity contributes to reducing the punch pressure, thereby increasing the achievable strains. This effect is observed to be pronounced in 99Ti.

6. Nomenclature

A	die–billet interface area in the deformation zone
A_0	initial cross-sectional area of billet
A_1	final cross-sectional area of extrude
C	specific heat
K	strength coefficient in the flow equation
n	strain-hardening exponent in the flow equation
P_p	punch pressure
ΔT	temperature increase in the deformation zone
ΔT_{Ad}	adiabatic temperature increase
ΔT_{Fr}	temperature rise due to friction
V	volume of metal in the deformation zone
V_R	ram velocity

Greek letters

α	semi-die included angle
β	0.95, a constant factor
ε	extrusion strain $(A_0-A_1)/A_0$
λ	thermal conductivity
μ	friction factor
ρ	density
σ_N	stress normal to surface
σ_{fm}	mean flow stress, see flow equation
σ_0/S_y	yield stress/upsetting stress in compression, see flow equation

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Appendix A

The theoretical punch pressure calculations (an example) for the open die extrusion of 99Ti is furnished in this appendix. The mathematical expression used is based on that in Ref. [4].

(a) For solid forward open die extrusion:

$$P_p = \sigma_{fm}\left[\frac{2}{3}\alpha + \left(1 + \frac{2\mu}{\sin 2\alpha}\right)\varepsilon\right]$$
$$= 516.77[(25/3)(\Pi/180) + (1 + 0.28/\sin 25)0.25]$$
$$= 289.95 \text{ N mm}^{-2}$$

where $2\alpha = 25°$, $\mu = 0.14$, $\varepsilon = 0.25$ and $\sigma_{fm} = 516.77$ N mm^{-2}, see flow equation.

(b) For hollow/tubular forward open die extrusion:

$$P_p = \sigma_{fm}\left[\frac{\alpha}{2} + \left(1 + \frac{2\mu}{\sin 2\alpha}\right)\varepsilon + \left(\frac{\mu}{\tan\alpha}\right)\left(\frac{A_1}{A_0}\right)\varepsilon\right]$$
$$= 516.77[(15/2)(\Pi/180) + (1 + 0.28/\sin 30)0.25$$
$$+ (0.14/\tan 15)(0.78)(0.25) = 344.33 \text{ N mm}^{-2}$$

where $2\alpha = 30°$, $\mu = 0.14$, $\varepsilon = 0.25$, $\sigma_{fm} = 516.77$ N mm^{-2}, $(A_1/A_0) = 0.78$.

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