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Hardness–stress–strain correlation in titanium open die extrusion: an alternative to visioplasticity

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Abstract

A heterogeneous process such as open die extrusion has been done on CP titanium and the extent of heterogeneity has been determined. The pressure for carrying out the process has been calculated theoretically, measured experimentally and calculated indirectly from hardness measurement in the deformation zone. Hardness–stress–strain correlation is very useful here. A nomogram has been given so that knowing, α, μ, ϵ and hardness, the punch pressure can be read off. It is a ready-reckoner that is very relevant for the shop floor in industry or the laboratory. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Open die extrusion; Punch pressure; Heterogeneous deformation; Adiabatic heating; Nomogram

1. Introduction

Open die extrusion is a heterogeneous process in which the deformation is non-uniform in the die. Local variations in stress and strain occur in the deformation zone. A study of these will enable an estimation to be made of the average punch pressure and also whether defect free extrudes can be produced. One approach to this is using the visioplasticity technique [1–3], but this is a complicated and time-consuming affair involving complex equations. A computer is needed for faster and accurate evaluation. Here an alternative is suggested. By doing a simple compression test one can establish a relationship between hardness and strain on the one hand and stress and strain on the other hand [4–6]. From these, hardness and stress can be related. Once this is done, the hardness can be measured in the deformation zone of extruded part and from this stress and strain can be established. Isohardness and isostrain profiles can be drawn. Also, from this the average punch pressure can be estimated. Here such a simple approach to local stress and local strain variation is highlighted, with respect to the open die extrusion of titanium.

2. Experimental

As-received commercial purity titanium rods of 40 mm diameter were forged to 30 mm diameter and annealed at 973 K for 2 h, a coating of glass 8221 being applied (to prevent embrittlement) before heating and forging. From these rods test samples of h_0=36 mm and d_0=24 mm were machined and compression testing was done with $(h_0/d_0)=1.5$. The stress–strain curve was established. Hardness was measured on partially upset samples at different strains, at the centre around the vertical axis, and a relationship established between hardness and strain ($\ln h_0/h_f$) along the axis. From the above two, measurements, hardness to stress correlation was achieved.

Open die extrusion was carried out on split commercially pure titanium (d_0=24 mm; h_0/d_0=1.5) samples for different die exit diameters and angles keeping die entry diameter constant. Force–stroke diagrams were obtained using a load cell, an LVDT, an amplifier and an X–Y recorder. The actual punch pressure was calculated using the equation:

$$P_{\text{pexp.}} = \frac{F_{\text{expt}}}{A_0}.$$

For open die extrusion F_{expt} is constant (for a given material, die angle and extrusion strain) throughout the stroke, except for the initial sloping line corresponding to

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Table 1
Strain distribution in deformation zone for CP titanium at room temperature with $2\alpha=25$ and $h_0/d_0=1.5$

ε	Theory		Expt.	
	$\varepsilon_{\mathrm{vmax}}$	$\varepsilon_{\mathrm{vmin}}$	$\varepsilon_{\mathrm{vmax}}$	$\varepsilon_{\mathrm{vmin}}$
0.15	0.37	0.20	0.25	0.2
0.20	0.43	0.25	0.31	0.18
0.28	0.51	0.33	0.32	0.23
0.35	0.59	0.40	0.32	0.20
0.43	0.67	0.47	0.35	0.20

the filling of the die from the entry to the exit at the beginning of the operation. In the deformation zone several hardness measurements were done parallel and perpendicular to the axis of the billet at intervals of 2 mm using a Vickers Hardness Tester. Isohardness profiles were established and isostrain profiles calculated from the hardness–strain relationship. The average hardness in the deformation zone was calculated and from hardness–stress relationship the mean flow stress was established. From this punch pressure was calculated for a given strain and die angle using the equation:

$$P_{\mathrm{pth}} = \sigma_{\mathrm{fm}}[(2\alpha/3) + (1 + 2\mu/\sin 2\alpha)\varepsilon].$$

The theoretical strain distribution was calculated from the following equation using a computer:

$$\varepsilon_{\mathrm{v}} = \sqrt{1 + (3/4)(r_0/r_i)\tan\alpha(\varepsilon) + (2/3)(r_0/r_i)\tan\alpha}$$

and compared with the experimental strain distribution from isostrain plots, as shown in Table 1.

3. Results

Flow stress vs. strain and hardness vs. strain are shown in Fig. 1. A log–log plot of stress vs. strain (ε) and hardness vs. strain are shown in Fig. 2. From these it can be inferred that:

$$\text{Hardness (VHN)} = 300\varepsilon^{0.28}, \quad (1)$$

$$\sigma_{\mathrm{fm}} = 1100\varepsilon^{0.336}, \quad (2)$$

$$\sigma_{\mathrm{fm}} = (3.2)\ (\text{Hardness}). \quad (3)$$

Isostrain and isohardness plots are shown in Fig. 3 for different die angles and different extrusion strains. The theoretical strain distribution in the deformation zone is shown in Fig. 4 for different die angles and extrusion strains. It is found that the theoretical maximum local strain is greater when compared to what is found in reality. This is due to the effect of heating (adiabatic and frictional) in the deformation zone. The punch pressure calculated from the hardness measurement in the deformation zone is shown in Fig. 5(a) and (b), the equation used being:

$$P_{\mathrm{pH}} = 3.2\ [\text{Average hardness}][(2\alpha/3 + [1 + (2\mu/\sin 2\alpha)]\varepsilon].$$

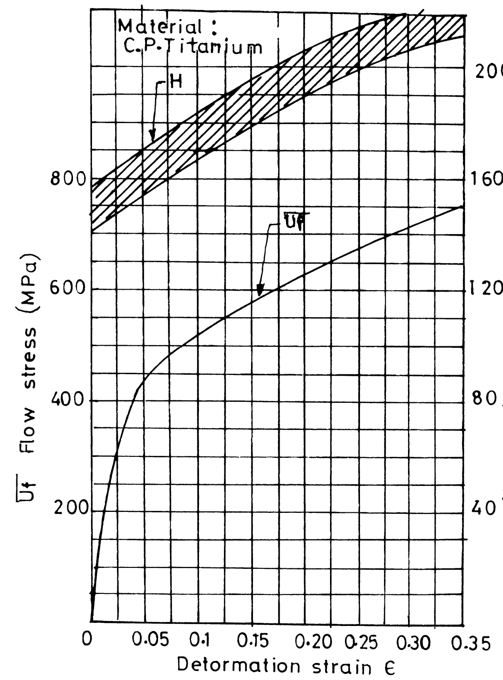

Fig. 1. Variation of hardness and flow stress with deformation strain.

For $2\alpha=25$, $\varepsilon=0.28$ and $d_f=20.4$ the average hardness in the deformation zone is 194 VHN, and the corresponding punch pressure is 410 MPa using the above equation. A nomogram already given [7,8] has been modified for estimating the punch pressure from knowing the hardness in VHN, the die angle, the strain and the friction coefficient. For a semi-die angle α of 12.5, a friction coefficient (μ) of 0.10, an extrusion strain (ε) of 0.2 and a hardness of 194 VHN, P_p=410 MPa. The nomogram is shown in Fig. 6.

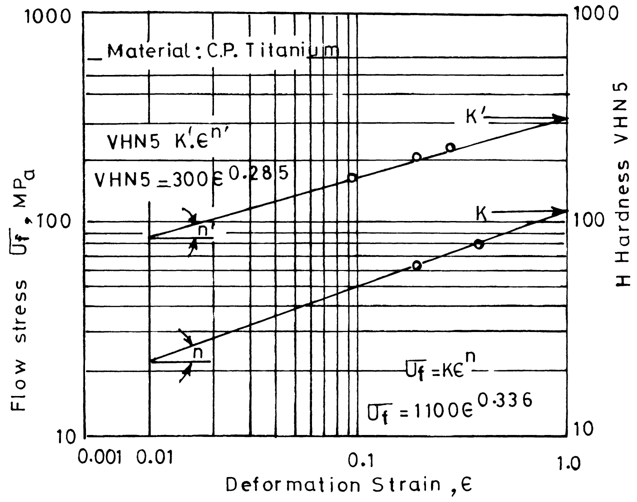

Fig. 2. Log–log plot of hardness and flow stress against deformation strain.

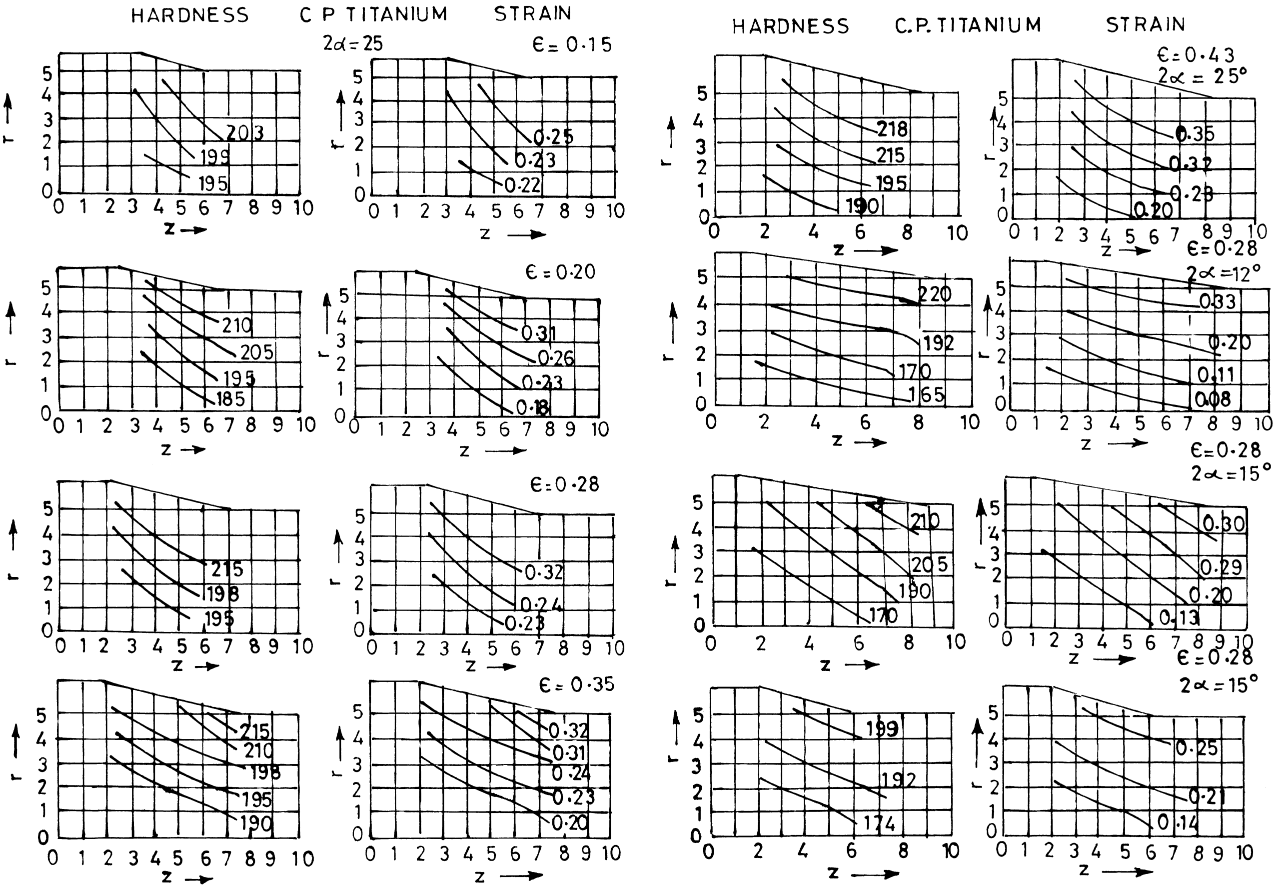

Fig. 3. Figures characterising the hardness to strain correlation.

4. Discussion

By relating hardness to stress an estimation of the flow stress and an attendant calculation of punch pressure for ODE is possible by measuring the average hardness in the deformation zone. It was reported earlier [9] that a true stress vs. true strain curve can be established for the plastic portion from hardness measurements. There is a similarity in the shape of the flow curve and the hardness curve. However, the method is empirical, since the complex stress distribution at the indentation precludes a straight-forward relationship with the stress distribution in tension or compression test. All the same it is a simple and useful method. Hardness is related to flow stress linearly, with the constant of proportionality being 3.2 for titanium, as given in Eq. (3).

From the isostrain and isohardness plots it can be seen that the billet above the deformation zone shows no appreciable change in strain and hardness. This implies that the billet acts as a rigid punch with no upsetting having taken place. This is corroborated by the measurement of the diameter on the unextruded portion just above the deformation zone, which remained equal to the diameter of the original billet. This confirms that open die extrusion only has taken place, without any upsetting. The radial deformation is zero along the axis of the billet and gradually increases as one moves away from the axis, being maximum near to the die wall. Also, the deformation is maximum at the die exit and minimum at, the die entry, this being brought out clearly in Fig. 3.

The hardness measured at all points in the deformation zone at intervals of 2 mm varies from point to point due to inhomogeneous deformation. The variation of hardness from the surface to the core of the extrude in the deformation zone provides the order of severity of heterogenous deformation and is confirmed by the isostrain plots, which provides a clue as to failure or defects in the extrude. The percentage heterogeneity is found to be 20 for titanium at an angle of 25° (the optimum angle, having the least forces) and an extrusion strain of 0.28. Open die extrusion is closer to hydrostatic extrusion in terms of ensuring homogenous deformation. Hydrostatic extrusion permits the use of a low included angle (die angle) and open die extrusion has a low angle for the least force ($2\alpha_{\mathrm{opt}}$ 25°), hence the comparison will be meaningful. It is reported [10] that for the hydrostatic extrusion of aluminium with $2\alpha_{\mathrm{opt}}$ at 30°, the heterogeneity could be around 16% and in the case of open die extrusion of aluminium (at $2\alpha=25°$ and $\epsilon=0.28$) it is 23%. For steel the respective figures are 10% and 25%. The

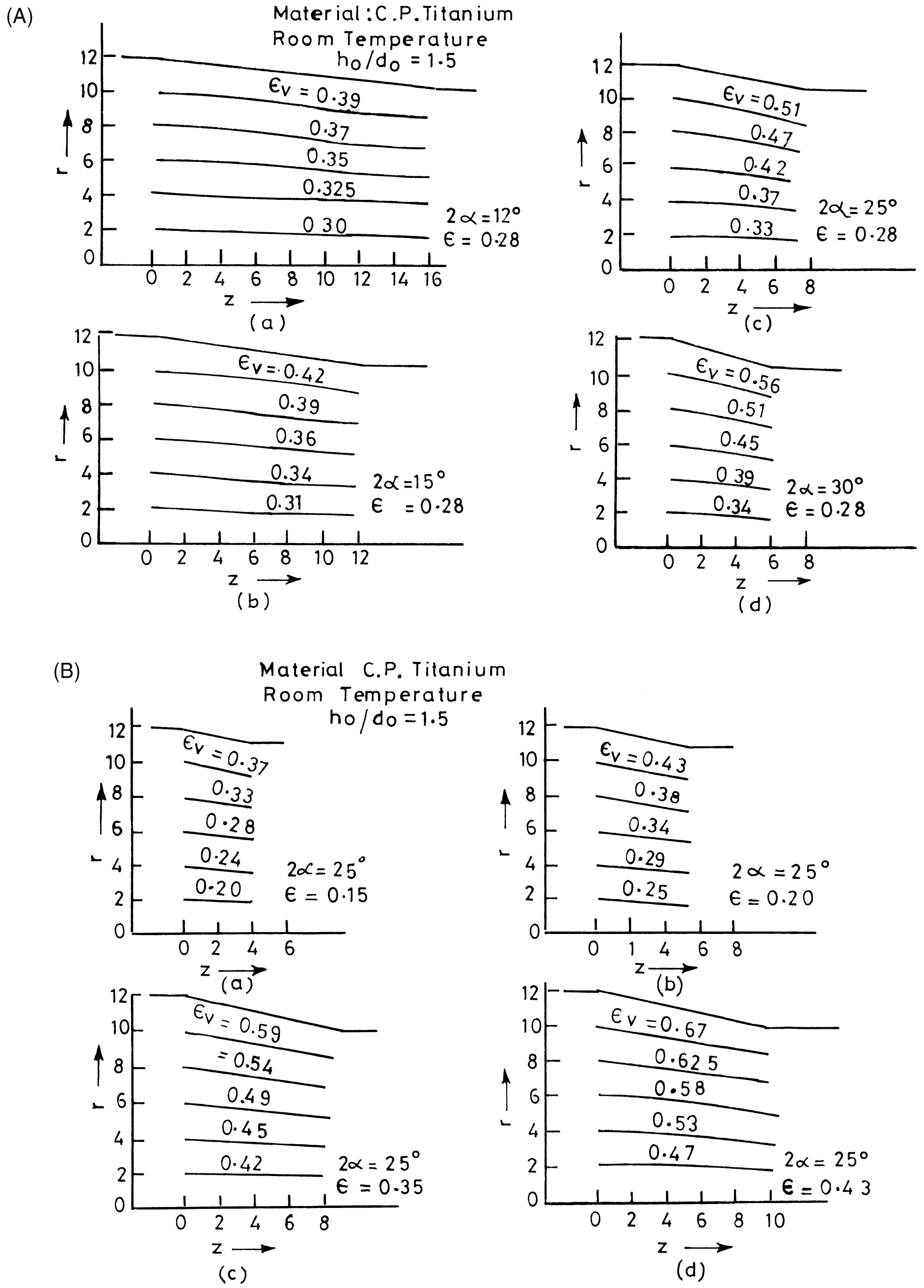

Fig. 4. Presenting: (A) theoretical strain distribution in the deformation zone for different angles at constant strain; and (B) theoretical strain distribution for different strains at the the optimum angle.

authors have not come across any value in the literature, for titanium. However, the present investigation on the ODE of titanium has shown the heterogeneity to be 20%, which is the least compared to steel and aluminium. This is due to the low thermal conductivity of titanium and a consequent increase in the retention of the temperature in the deformation zone due to adiabatic and frictional heating acting for a longer time [11–13].

The local strains are less in the experimental samples than as calculated, theoretically because of the temperature rise in the deformation zone due to adiabatic and frictional heating. Such heating is substantial in commercial purity titanium because of its low density, low specific heat and high flow stress.

The punch pressure calculated from the hardness values in the deformation zone is the highest. The process of taking the hardness itself work hardens the material. The theoretical punch pressure comes next and experimental punch pressure is the lowest due to the softening caused by the temperature rise in the deformation zone.

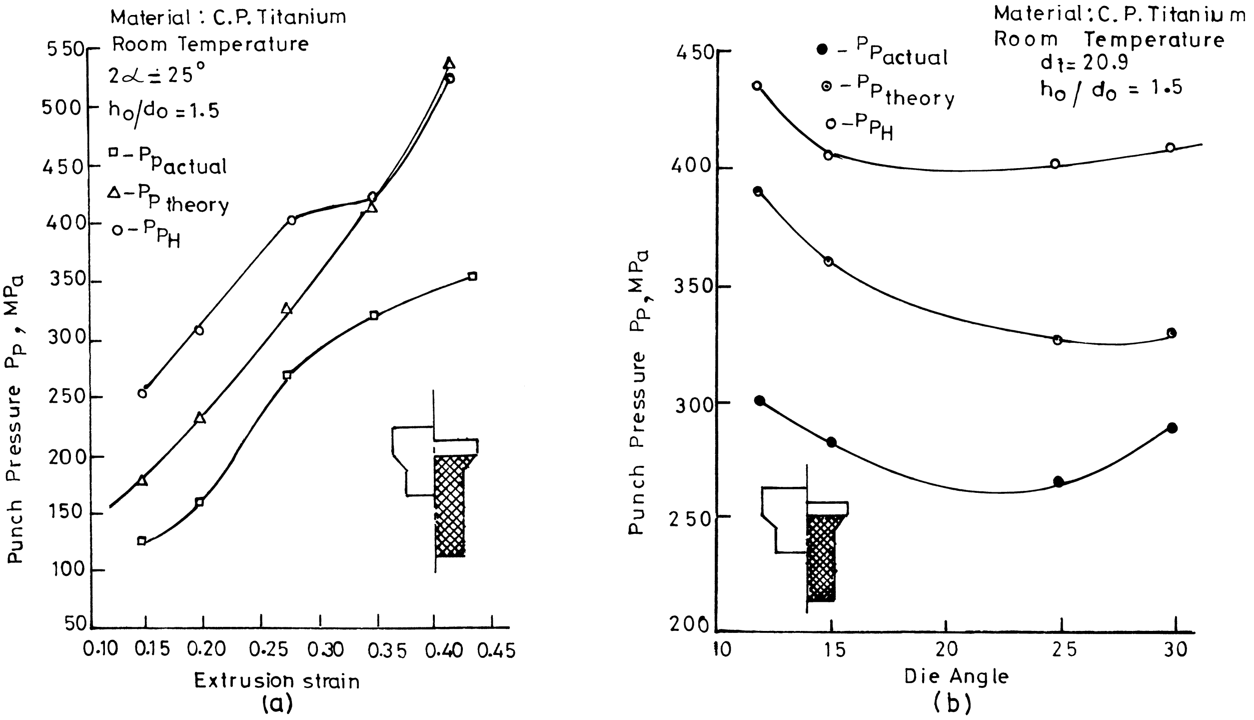

Fig. 5. Comparison of punch pressures as given by theory, experiment and hardness as a function of (a) strain and (b) angle.

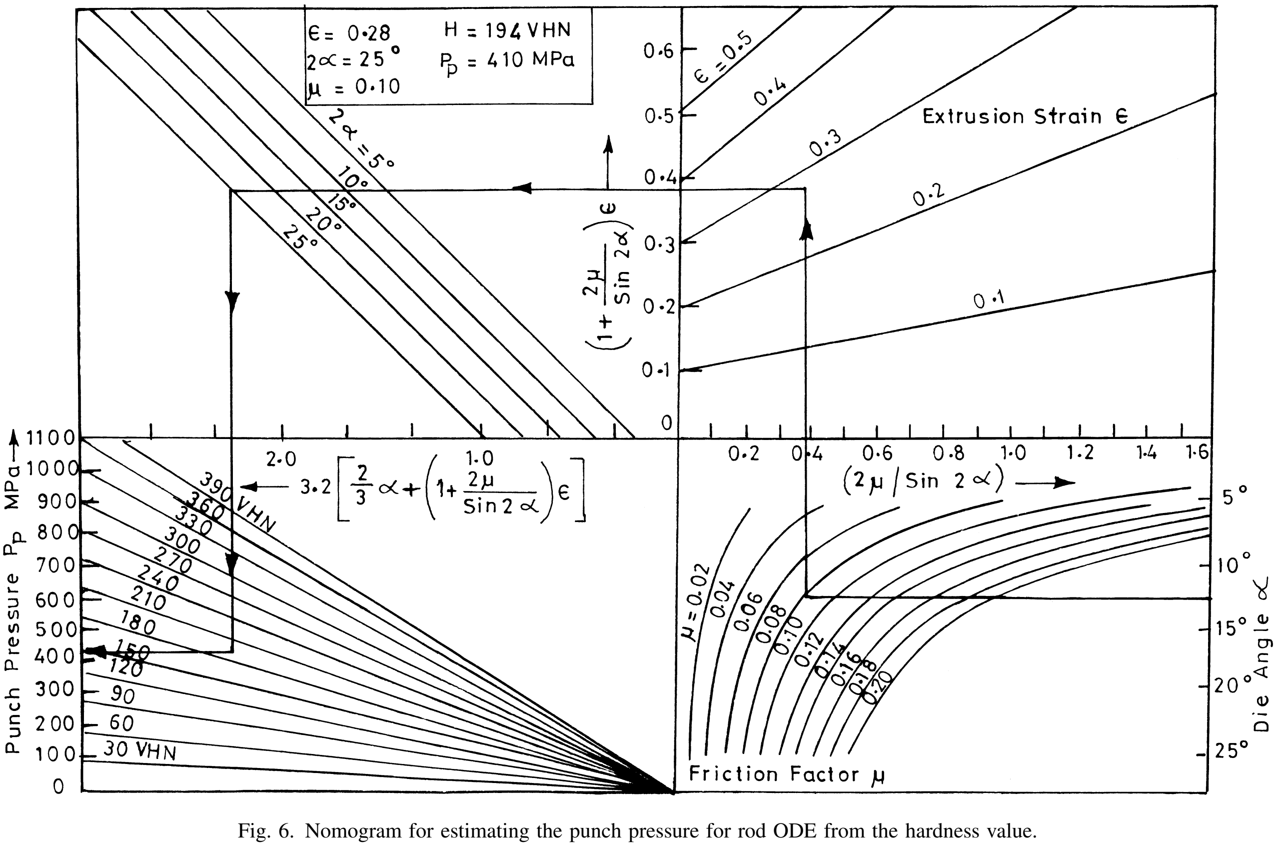

Fig. 6. Nomogram for estimating the punch pressure for rod ODE from the hardness value.

5. Conclusions

Open die extrusion is attractive for titanium, as homogeneous deformation can be ensured to a large extent due to the influence of adiabatic heating.

Hardness measurement in the deformation zone can be an useful tool to characterize local strain variations. It is simple and easy to perform, simple and is less time consuming compared to tedious visioplastic analysis.

The relationship between flow stress and hardness is linear and between hardness and strain is exponential.

The punch pressure for ODE as estimated form hardness measurement (for $2\alpha=25^\circ$ and $\varepsilon=0.28$) is 405 N/mm^2. The theoretical and experimental punch pressures are 328 and 265 N/mm^2, respectively. Therefore P_p from hardness measurement is an over-estimate. A nomogram can also be used for this, giving a value of 410/mm^2.

6. Nomenclature

A_f	final extrude cross-sectional area
A_0	initial billet cross-sectional area
α	semi die angle
d_o	initial diameter of the billet
ε	extrusion strain
ε_v	volumetric strain
h_0	initial billet height
h_f	final billet height
h_i	instantaneous height of the billet
h_0/d_0	height to diameter ratio
μ	friction factor
σ_fm	mean flow stress
K	strength coefficient
n	strain-hardening exponent
P_p	punch pressure
P_pth	theoretical punch pressure
P_pexp	experimental punch pressure
P_PH	punch pressure from hardness
r_0	radius at die entry
r_f	radius at die exit
r_i	instantaneous radius

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