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Loading of forming presses by the upsetting of oblique specimens

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Abstract

The upsetting of oblique specimens as a means of loading forming presses with vertical and horizontal forces is a feasible concept, however, due to the changing distribution of conditions at the specimen interface, the scope of this approach needs to be quantified. The plastic deformation of oblique specimens was analysed using an FE code named PLAST2.

The analysis suggests guidelines for the selection of test specimens and the scope of such tests; it is apparent that the lubrication conditions and specimen reduction, and the ratio between the vertical and horizontal forces, do not remain constant over the entire course of the deformation. Hence, the analysis of measurements of the behaviour of the press would be meaningful if the range of uniform behaviour of such tests was observed. © 1997 Elsevier Science S.A.

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1. Introduction

Upsetting is, perhaps, the most commonly exploited metal forming process. In practice, upsetting is used either as a separate forming process or as the primary stage of more complex forming operations. In mechanical testing, upsetting is used for extracting flow curves and friction-dependent parameters and for defining workability. Frequently, upsetting experiments are performed to determine the reliability of analytical and numerical methods, to illustrate specific phenomena which relate to metal flow etc.

In order to evaluate press elasticity, metal specimens with parallel faces are upset, this producing a force which is parallel to the main (normally vertical) axis of the press. This method of loading together with measurements of the elastic deflections of the press enables the development of definition of a vertical and two angular stiffness coefficients of the press [1,2].

However, in many practical cases, the press is loaded not only vertically but also horizontally. The ratio between the horizontal F_H and vertical F_v components of the forming force $\boldsymbol{F}$ may be as high in value as 0.2; hence, these loading conditions would have to be simulated during press elasticity measurements. It is possible to load the press with a hydraulic jack located between two oblique washers (Fig. 1(a)), but friction between the piston and the cylinder renders the method inaccurate. A recently proposed [3] alternative method which is based on the upsetting of oblique specimens (Fig. 1(b)) provides a more representative loading condition.

Unfortunately, this form of upsetting is not common: some aspects of this process have been reported by Ramaekers and Kals [4], who considered the unstable

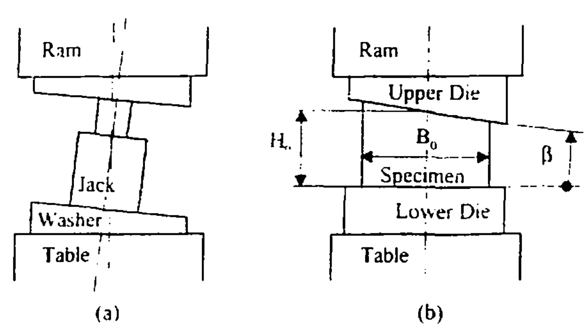

Fig. 1. Methods of loading a press with vertical and horizontal forces: (a) using a hydraulic jack; (b) using the upsetting of an oblique specimen.

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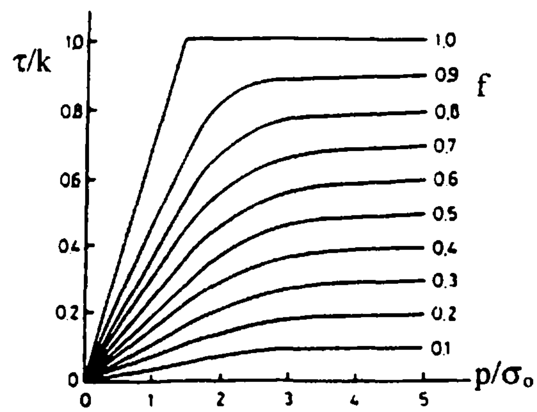

Fig. 2. Relative frictional stress as a function of normal stress and friction factor [7].

flow of material which results from the angular misalignment of the tools. However, Ramaekers and Kals did not provide a detailed insight to the process, thus prior to the use of the upsetting of oblique specimens for press elasticity experiments, a more comprehensive process analysis is required.

2. Method of solution

The upsetting of oblique specimens was simulated using the 2-D finite-element program PLAST2 which was developed at Instituto Superior Tècnico, Lisbon. This program is based on the variational principle which requires that all admissible velocities u_j, which satisfy the conditions of compactibility and incompressibility, make the functional:

$$\Pi = \int_V \bar{\sigma}\dot{\bar{\varepsilon}}\,\mathrm{d}V - \int_{S_F} T_j u_j\,\mathrm{d}S \tag{1}$$

stationary. In this expression $\bar{\sigma}$ is the effective stress, $\dot{\bar{\varepsilon}}$ is the effective strain-rate, T_j is the surface traction, S_F is the surface on which tractions are prescribed and V is the volume. The effective stress and effective strain-rate are defined as follows:

$$\bar{\sigma} = (\tfrac{2}{3}\sigma'_{ij}\sigma'_{ij})^{1/2} \tag{2}$$

$$\dot{\bar{\varepsilon}} = (\tfrac{2}{3}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij})^{1/2} \tag{3}$$

where σ'_{ij} and $\dot{\varepsilon}_{ij}$ are the deviatoric stress and the deviatoric strain-rate, respectively. When the functional Π is given a stationary value, its first order variation $\delta\Pi$ vanishes; i.e. $\delta\Pi = 0$. The definition of incompressibility has the form:

$$\dot{\varepsilon}_v = \dot{\varepsilon}_{kk} = 0 \tag{4}$$

where $\dot{\varepsilon}_v$ is the volumetric strain-rate. In order to take this condition into account, the penalty function method was applied, which requires the modification of the functional Π [5]; the modified functional, Π_1, having the form:

$$\Pi_1 = \int_V \bar{\sigma}\dot{\bar{\varepsilon}}\,\mathrm{d}V + K\int_V \frac{1}{2}(\dot{\varepsilon}_v)^{1/2}\,\mathrm{d}V - \int_{S_F} T_j u_j\,\mathrm{d}S \tag{5}$$

where K is a large positive penalty constant. Now, if the first variation $\delta\Pi_1$ in the functional Π_1 vanishes, then:

$$\delta\Pi_1 = \int \bar{\sigma}\delta\dot{\bar{\varepsilon}}\,\mathrm{d}V + K\int \dot{\varepsilon}_v\delta\dot{\varepsilon}_v\,\mathrm{d}V - \int_{S_F} T_j u_j\,\mathrm{d}S = 0 \tag{6}$$

and both the equilibrium equations and the volume constancy constraint will be, approximately, satisfied simultaneously [5]. The above variational equation is presented in detail in [6].

The elastic deformation of the specimen and dies is neglected and the relationship between the effective strain-rate and the deviatoric stresses is provided by the Levy–Mises flow rule:

$$\dot{\varepsilon}_{ij} = \frac{3}{2}\frac{\dot{\bar{\varepsilon}}}{\bar{\sigma}}\sigma'_{ij} \tag{7}$$

in which $\bar{\sigma}$ for the plastic region is equal to the yield stress σ_0 which, in turn, is defined by the equation:

$$\sigma_0 = C(\bar{\varepsilon})^n \tag{8}$$

where C and n denote the material constants, and $\bar{\varepsilon}$ is the effective strain:

$$\bar{\varepsilon} = (\tfrac{2}{3}\varepsilon_{ij}\varepsilon_{ij})^{1/2} \tag{9}$$

in which ε_{ij} is the strain.

Further, the Wanheim and Bay [7] friction model was applied. According to this model, the frictional stress τ is described by:

$$\tau = f\cdot\alpha\cdot k \tag{10}$$

in which f is the friction factor, α is the ratio between the real and apparent contact areas, and k is the shear yield stress of the work-material, defined by:

$$k = \sigma_0/\sqrt{3} \tag{11}$$

The frictional, τ, and normal, p, stresses at the die–workpiece interface are proportional for $p/\sigma_0 < 1.5$, whilst for $p/\sigma_0 > 3$ the relative frictional stress $\tau/k = f\cdot\alpha$ approaches a constant value which is equal to f (Fig. 2). In order to eliminate the sudden changes of the frictional stress at the neutral point, the following approximation was defined:

$$\bar{\tau} = \boldsymbol{j}\cdot f\cdot\alpha\cdot k\cdot\frac{2}{\pi}\cdot\tan^{-1}\left(\frac{|u_s|}{v_0}\right) \tag{12}$$

in which $\boldsymbol{j}$ is the unit vector in the direction opposite to the velocity u_s of the work-material relative to the die and v_0 is a small positive number in comparison with u_s [6].

Detailed information about PLAST2 is provided in [8]. Metal-flow analysis achieved using PLAST2 compares well with the results of experiment [9].

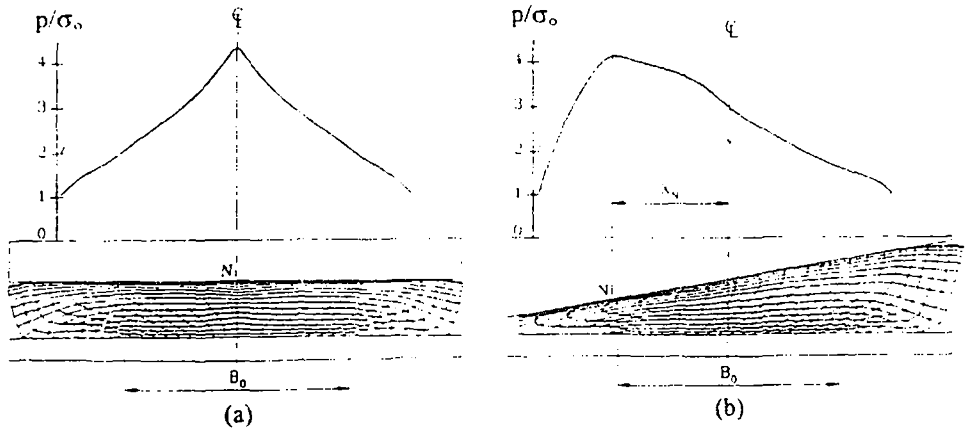

Fig. 3. Distorted mesh for the upsetting of: (a) a parallel specimen; and (b) a wedge-shaped specimen; together with the distribution of normal p and frictional τ stresses.

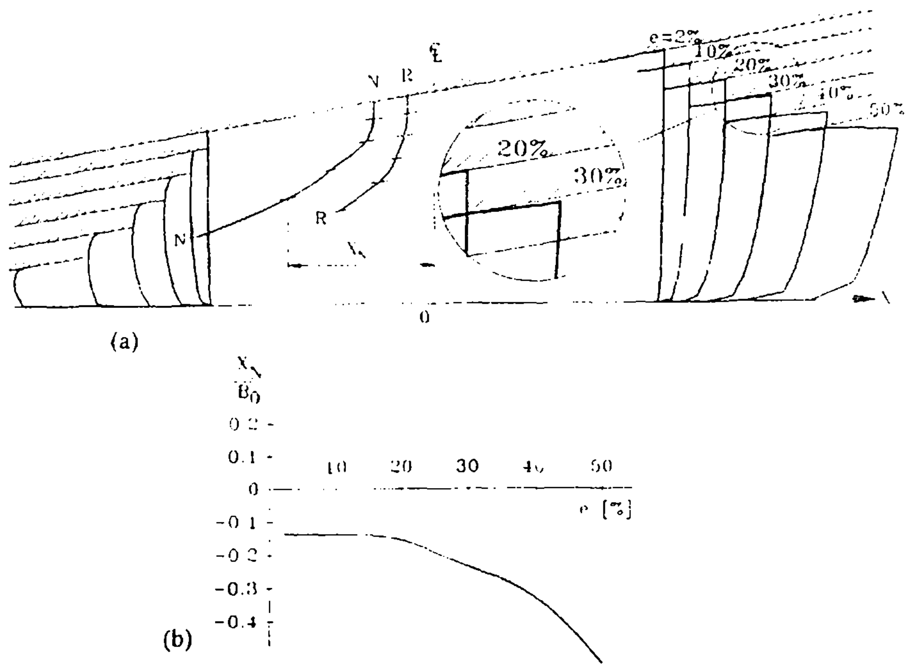

Fig. 4. Presenting: (a) specimen shapes and positions of the neutral point N; and (b) the function $X_N(e)/B_0$ for $f = 0.5$, $\beta = 10°$ and $H_0/B_0 = 0.5$.

3. Assumptions

The following assumptions apply to the analysis:

(i) Plane-strain upsetting conditions prevail.

(ii) Sticking friction prevails on the lower die–specimen interface, whilst the work-material slides relative to the upper die. This assumption corresponds to experimental conditions where the lower die is rough whilst the upper die and the specimen are smooth and well lubricated.

(iii) The relationship between the yield strength and the effective strain rate for mild steel has been assumed to be:

$$\sigma_0 = 740 \cdot (\bar{\varepsilon})^{0.216} \quad \text{(MPa)} \tag{13}$$

(iv) The initial geometry of the specimen is characterised by the ratio H_0/B_0 in which H_0 is the original average height measured along the centre line of the specimen, B_0 is the original width of the specimen and β is the angle between the die and the specimen (refer to Fig. 1).

(v) The ratio:

$$e = \frac{H_0 - H}{H_0} \cdot 100\% \tag{14}$$

is used to define the reduction in height of the specimen, where H is its current height at the center line.

(vi) The following basic parameters were used for the analysis: $H_0/B_0 = 0.5$, $f = 0.5$, $\beta = 10°$. For the analysis, each parameter was varied about these prescribed values, whilst other parameters were retained constant.

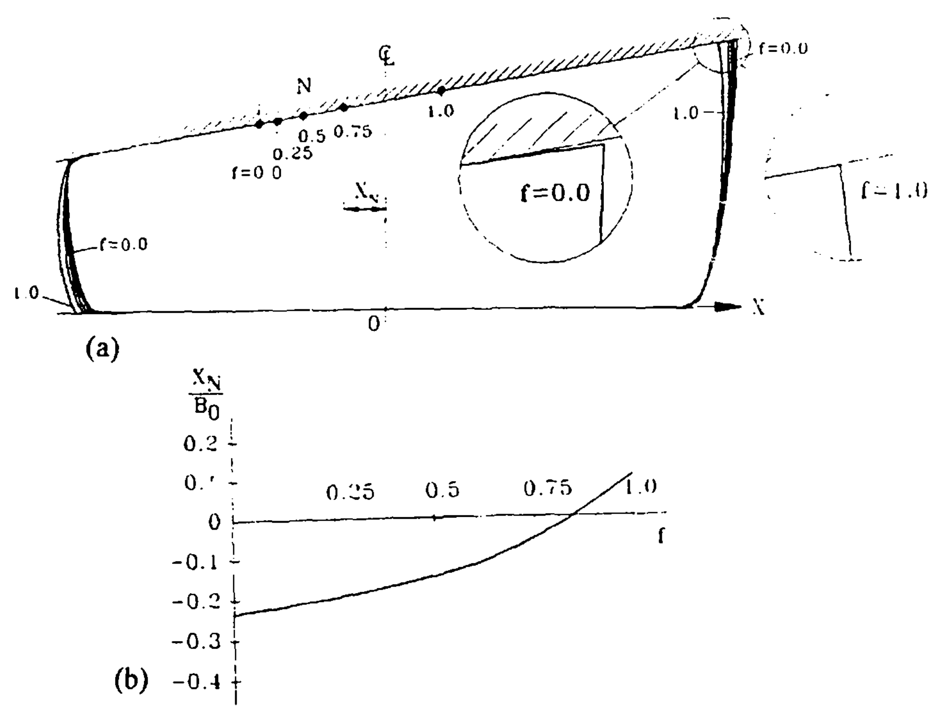

Fig. 5. Presenting: (a) specimen shapes and the position of the neutral point N; and (b) the function $X_N(f)/B_0$ for $e = 20\%$, $\beta = 10°$ and $H_0/B_0 = 0.5$.

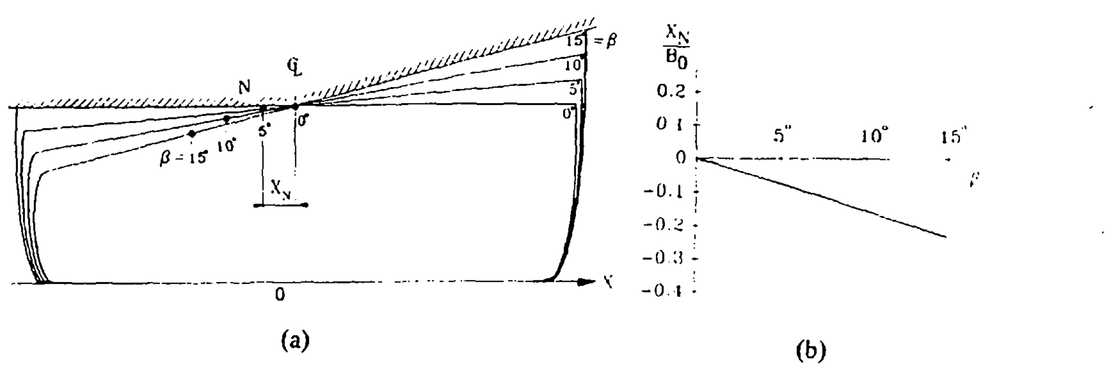

Fig. 6. Presenting: (a) specimen shapes and the position of the neutral point N; and (b) the function $X_N(\beta)/B_0$ for $e = 20\%$, $\beta = 10°$ and $H_0/B_0 = 0.5$.

4. Results

The deformation of parallel and oblique specimens, the latter being characterised by basic parameters, are shown in Fig. 3, together with distributions of relative normal pressures p/σ_0 on the upper face of the specimen. Gaps which can be observed between specimens and the upper dies are due to the difference in friction at the contact surfaces. The deformation of the oblique specimen may be described as follows:

(i) The flow pattern is not symmetrical about the center line.

(ii) A larger volume of metal flows toward the thicker side of the wedge-shaped specimen than towards its thin side.

(iii) The neutral point, N, at which material flow has no tangential component relative to the upper die, is displaced towards the thin side of the specimen.

(iv) A gap between the upper die and the oblique specimen is created at the thick side of the specimen.

The deformation of the oblique specimen is a complex function of the reduction e, the friction factor f, the angle β and the ratio H_0/B_0. Specimen shapes are shown in Fig. 4(a) for different reductions and constant $f = 0.5$, $\beta = 10°$ and $H_0/B_0 = 0.5$. The line N–N represents the position of the neutral point over the course of the upsetting whilst the line R–R refers to the displacements location of the resultant forming force. For a small value of reduction, the relative coordinate X_N/B_0 of the neutral point remains practically constant (Fig. 4(b)), but for greater reductions, the ratio X_N/B_0 changes significantly. The trans-sectional value of deformation refers to the development of the gap between the upper die and the specimen: this is shown magnified in Fig. 4(a). Since the gap changes the contact area between the specimen and the upper die, the neutral point moves towards the thin side of the specimen.

Specimen forms for $e = 20\%$, $\beta = 10°$ and $H_0/B_0 = 0.5$ are shown in Fig. 5 for various friction factors. The following observations are made:

(i) The creation of the gap depends on the friction factor: for $f = 0$ the gap prevails at an early stage of the deformation whilst for $f = 1.0$ the formation of the gap is not initiated.

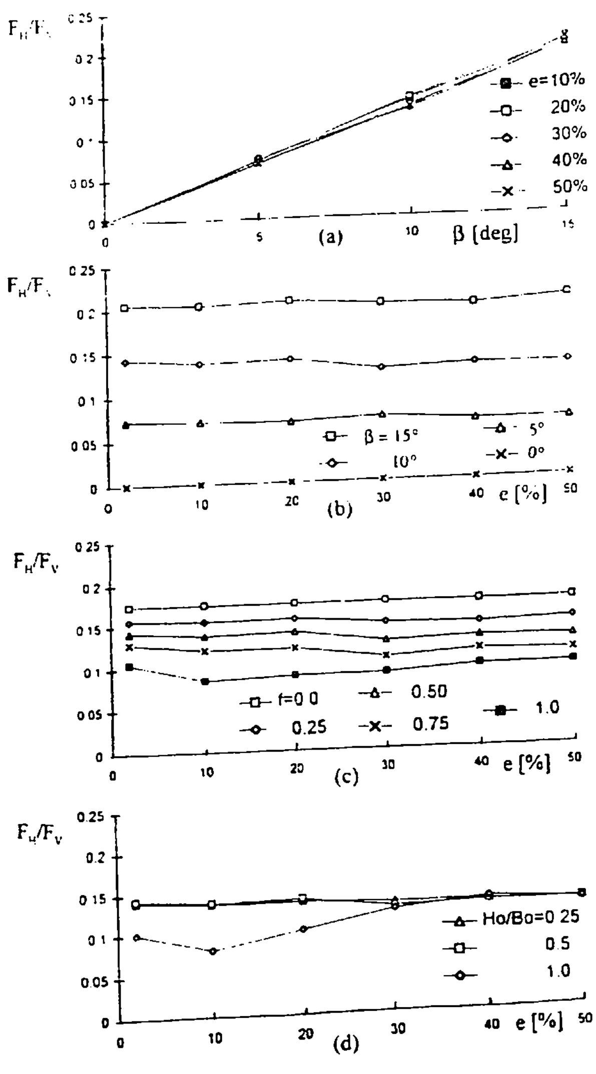

Fig. 7. The ratio F_H/F_V as a function of process parameters: (a) $(F_H/F_V)(\beta)$ for different values of e and $f = 0.5$, $H_0/B_0 = 0.5$; (b) $(F_H/F_V)(e)$ for different values of β and constant $f = 0.5$, $H_0/B_0 = 0.5$; (c) $(F_H/F_V)(e)$ for different values of f and constant $\beta = 10°$, $H_0/B_0 = 0.5$; (d) $(F_H/F_V)(e)$ for different H_0/B_0 and constant $\beta = 10°$, $f = 0.5$.

(ii) The friction factor has a greater influence on the location of the neutral point than the specimen form.

The practically linear function $X_N(\beta)/B_0$ for constant e, f and H_0/B_0 is shown in Fig. 6(b). A conclusion drawn is similar to that in the previous case: the angle β influences the position of the neutral point rather then the form of the axial section of the deformed specimen.

The resultant upsetting force $F(F_H, F_V)$ is inclined relative to the central line. Since the work-material slides along the upper surface towards both the thick and the thin sides of the specimen, it follows that the angle of inclination of the resultant force γ would be smaller in value then the angle β of the inclination of the upper die, i.e.:

$$\gamma = \tan^{-1}\frac{F_H}{F_V} < \beta \tag{15}$$

The function $(F_H/F_V)(\beta)$ for different values of e, constant f and H_0/B_0 is shown in Fig. 7(a), from which it can be observed that the ratio F_H/F_V does not depend on the level of e. In this specific case the following equation applies:

$$\frac{F_H}{F_V} = 0.0132 \cdot \beta[\text{deg}] \tag{16}$$

This feature suits press elasticity experiments, as it simplifies the use of data pertaining to the force ratio The function $(F_H/F_V)(e)$ for selected β and constan f and H_0/B_0 (Fig. 7(b)) confirms the above feature

Fig. 7(c) and 7(d) show that, during the press stiff ness experiments, both low friction and a low valu of H_0/B_0 should be ensured. If it is the case, the ratic F_H/F_V remains practically independent of the speci men reduction. The departure of the trend $(F_H/F_V)(e$ for $H_0/B_0 = 1.0$ (Fig. 7(d)) from the other graphs re sults from using too large a specimen, the latter un dergoing bending at the early stage of deformation

Relationships between the vertical component o the unit forming force (related to the specime length) and the reduction e are shown schematicall in Fig. 8. On the basis of Fig. 8(b), it can be con cluded that, for a relatively small deformation, th vertical component of the forming force is practicall independent of the angle between the dies, includin the case $\beta = 0$. This feature simplifies the procedu for the selection of specimens for press elasticity mea surements. The vertical component of the formin force may be calculated from the commonly-know equation for the upsetting of a parallel-faced spec men.

The third feature of the resultant force is the point of i application. The position of this point has been defined Fig. 4(a) in a form of line R–R. The point of the for application follows the neutral point. Hence, conclusio which have been drawn for the neutral point app

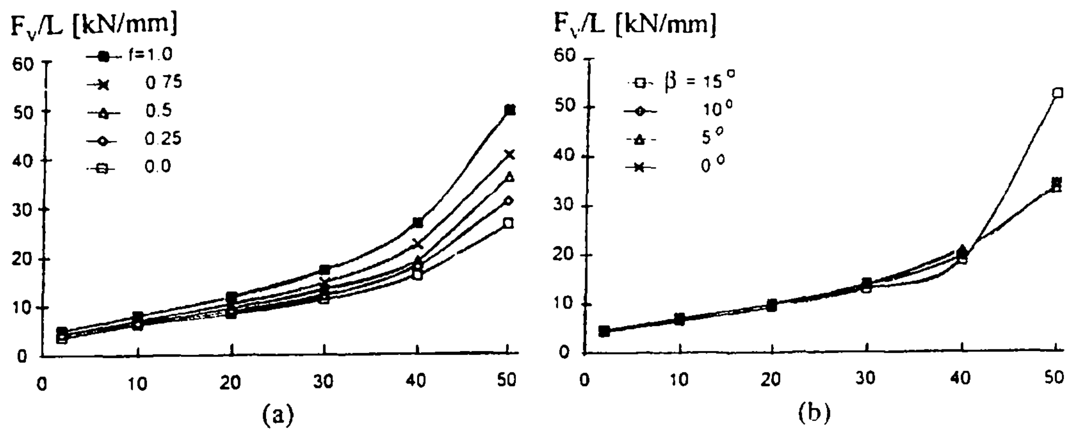

Fig. 8. The relative vertical component of the forming force F_V/L as a function of process parameters: (a) for selected values of f and $\beta = 10°$, $H_0/B_0 = 0.5$; (b) for selected values of β and $f = 0.5$, $H_0/B_0 = 0.5$.

equally well to the point of application of the resultant force.

5. Conclusions

1. For constant friction and constant relative height of the specimen, H_0/B_0, the ratio between the horizontal and vertical components of the forming force, F_H/F_V, depends mainly on the specimen/upper-die inclination β.

2. It is possible to chose an oblique specimen so that the ratio F_H/F_V remains practically independent on the specimen reduction. In order to achieve this, the following conditions should be fulfilled: (i) the specimen reduction should be kept relatively low, e.g. for $f = 0.5$ it should not exceed 20%, whereas for higher friction a greater reduction is permissible; (ii) the relative specimen height H_0/B_0 should be less than 0.5; and (iii) friction on the specimen/upper-die interface should be kept relatively low.

References

[1] E. Doege, Static and dynamic stiffness of presses and some effects on the accuracy of workpieces, *Ann. CIRP*, *29* (1980).

[2] DIN 55 189, *Ermittlung von Kennwerten für Pressen der Blechverarbeitung bei statischer Belastung*, Teil 1,2, 1988.

[3] K. Chodnikiewicz, Balendra R. and T. Wanheim, A new concept for the measurement of press stiffness, *J. Mater. Process. Technol.*, *44* (1994) 293–299.

[4] J.A.H. Ramaekers and J.A.G. Kals, Instable material flow in extrusion and upsetting, *Ann. CIRP*, *31* (1992).

[5] O.C. Zienkiewicz and K. Morgan, *Finite Element and Application*, Wiley, New York, 1983.

[6] S. Kobayashi, S.I. Oh and T. Altan, *Metal Forming and the Finite-Element Method*, Oxford University Press, New York, Oxford, 1989.

[7] N. Bay and T. Wanheim, Real area of contact and friction stress at high pressure sliding contact, *Wear*, *38* (1976) 201–209.

[8] P.A.F. Martins, J.M.C. Rodrigues and M.J.M. Barata Marques, Numerical and experimental simulation of cold forging processes, *XIII Seminário National de Forjamento, UFRGS, Porto Alegre, Brazil, 1993.*

[9] M. Arentoft, S.B. Petersen, J.M.C. Rodrigues, P.A.F. Martins, R. Balendra and T. Wanheim, Review of the research on the injection forging of tubular materials, *J. Mater. Process. Technol.*, *52* (1995) 460–471.