Processing of cylindrical hollow parts: piercing vs. extrusion

R Comănci, L Zaharia, D Nedelcu and L G Bujoreanu
Technical University “Gheorghe Asachi” Iasi, 700050, Romania

E-mail: comaneci@tuiasi.ro

Abstract. As work principle, piercing (P) and backward extrusion (BE) are similar deforming processes. However, working-load, strain and material flow are quiet different depending on real conditions. Since punch diameter d and workpiece diameter D are the defining parameters for both P and BE, there is a critical d/D ratio separating them as distinctive operations. To have a complete description of P and BE in terms of working load and yield pressure as function of d/D ratio, experimental tests and numerical predictions were conducted. Tridimensional finite element analysis (FEA) for different process designs (i.e. different d/D ratios) revealed distinctive evolutions of the material flow establishing the effective limits of P and BE respectively. Experimental and numerical results can be used in practice to provide estimates of working-load, critical yield pressure and tool dimensions for optimal P and BE in processing of cylindrical hollow parts.

1. Introduction

Although piercing (P) - as preliminary forging operation - and backward extrusion (BE) – as final deforming process - are almost identical deforming processes (at least as work principle) there are however some notable differences in terms of working-load, friction, material flow, stress and strain distribution, and tools which have to be revealed. At first sight, the major differences between P and BE seems to be the extrusion ratio (Ao/Af), maximum working-load (Fmax), and punch diameter (d). From extrusion ratio point of view P is considered as a BE with a smaller reduction in cross-section area. Because of that, the material flow has distinctive evolutions: while in P only a small volume of material flows along the head of the punch, in E the material flows along both of die’s wall and punch, the volume of material involved in plastic flow being notable higher (according to the continuity equation). This implies both higher working-loads and friction: in the final stage of the extrusion, the material almost reaches hydrostatic state and the lubricant is ejected. The higher reduction, the bigger working-load and friction. Obviously, P needs smaller punches in diameter and corresponding smaller working-loads. But these are relative variables and they are not related of the workpiece and material itself. For this reason using yield pressure (p/2k) as ratio of normal pressure (p) to the yield stress in shear (2k) becomes more appropriate.

If the yield stress \( \sigma_y = 2k \) evolves with strain \( \epsilon \) according to the well known relation:

\[
\sigma_y = K\epsilon^n
\]  

(1)

where \( K \) is a constant for the given material, \( n \) is the work hardening exponent and \( \epsilon = \ln \frac{1}{1-\left(\frac{d}{D}\right)^2} \) (d and D are revealed in figure 1), we can easily concluded that yield pressure becomes a function of d/D...
ratio. Since punch diameter d and workpiece diameter D are the defining parameters for both P and BE, there is a critical d/D ratio (i.e. critical yield pressure) separating them as distinctive operations.

Work pressure in extrusion/piercing of hollow tubes starting from either initial solid or hollow billets previously processed with different die/mandrel combinations were calculated using slab [1] or upper bound method [2, 3]. Some theoretical and experimental investigations have been dedicated to friction study for different work conditions [4-7]. It was found that friction can play a positive role and consequently the extrusion with active friction using a mobile container was developed [8, 9]. A major difficulty in piercing is obviously the buckling of punch which has – at the beginning of deformation - one end fixed and other end free, situation which then changes during deformation. The punch stability to buckling being smaller, the length of the punch in piercing should be limited and an appropriate punch holder has to be used. But this is not the single problem in piercing: in practice, the centring of the workpiece becomes essential for a successful operation [10]. Moreover, for a smooth shear surface in piercing, a servo press applying a counter pressure is necessary[11]. Despite P is one of the simplest deforming operations, no much information about it can be found in the literature. Moreover, a criterion separating the two operations (i.e. working-load formula, punch vs. workpiece dimensions) is not clearly stated.

To have a complete description of P and BE in terms of working-load and yield pressure as function of d/D ratio, experimental tests and numerical predictions were conducted in this study. Tridimensional FEA for different process designs (i.e. different d/D ratios) aims to reveal possible distinctive evolutions of the material flow establishing the effective limits of P and BE respectively, setting critical yield pressure and corresponding d/D ratio. Experimental and numerical results can be used in practice to provide estimates of working-load, critical yield pressure and tool dimensions for optimal P and BE in processing of cylindrical hollow parts.

2. Experimental materials and procedures

2.1. Finite element analysis
In the present work, a three dimensional model was considered. Commercial finite element code DEFORM 3D was used to carried out the simulations. A commercial available 99.5% aluminum (AA 1050) was used in this study. The stress-strain relationship of the AA 1050 was experimentally obtained by tensile tests carried out according to ISO 6892-1: 2009, using a universal computer-controlled testing machine (Instron 3382). It was found that flow stress evolves with strain according to the following relation: \( \sigma = 151.24 \cdot \varepsilon^{0.18} \) which was indicated in DEFORM 3D as constitutive equation (figure 2).

Eight scenarios were simulated, corresponding to the punch diameter of 5, 6, 7, 8, 10, 15, 20, and 25 mm. As can be seen, the increment in punch diameter decreases in the presumed range of piercing (i.e. from 5 to 8 mm) to accurately capture changes in the material flow and confirm a clear trend of its evolution. All simulations were performed at room temperature, with the same speed of punches compared with experimental speed. Also the friction coefficient between inner die walls and cylindrical billets was assumed to be the same as in experiments (0.12) and it has been considered by other authors [12]. The workpiece (\( \phi 30 \times 42 \) mm) was considered a plastic body in whole
deformation processes. Poisson’s ratio 0.33 and Young’s modulus 69 Gpa were assumed. The hardening behavior is considered isotropic and independent of strain rate at room temperature. The die and the punches were modeled with analytical elastic elements. The tolerance, positioning of the workpiece and die, convergence criteria, re-meshing conditions, and boundary conditions were specified before the execution of the simulation processes. The workpiece was discretized in 32000 tetrahedral elements thus forming a sufficiently fine mesh to reveal localized effects. The volume penalty constant which ensures volume constancy of plastic workpiece with minimum loosing volume during re-meshing had to be specified [13].

Figure 2. Stress-strain curve of the material used in finite element simulations.

2.2. Experimental piercing/extrusion
After FEA, six punches made from hardened AISI 4140 steel having 5, 8, 10, 15, 20 and 25 mm in diameter were prepared for experimental tests (figure 3).

Figure 3. Principle of extrusion/piercing.

Cylindrical specimens of AA 1050 with dimensions of 30 × 42 mm were machined from as-received material. A subsequently annealing at 523K for 3h was performed before P/BE in order to eliminate strain hardening from previous metal-working operations. Processes were conducted at room temperature with a constant speed of 0.6 mm•s\(^{-1}\), using a hydraulic press of 750 kN and a die with 34 mm in diameter consisting in two half-dies reinforced by two outer circular rings forming a close fit with the die (figure 4). The inner diameter of the die was chosen intentionally larger than that of the workpiece to accurately capture the early stages of material flow.
All samples and inner walls of the die were lubricated using zinc stearate which ensures a shear friction coefficient of $\mu = 0.12$\cite{14}. The stroke of punches was 38 mm. During P and BE the working-loads were recorded using a National Instruments data acquisition integrated system and a LabVIEW interface. Figure 5 shows the processed specimens.

3. Results and discussions

3.1. Equations and mathematics

For this study, the material flow becomes the most important because changing in plastic behavior of the material makes the difference between P and BE. As expected, depending on $d/D$ ratio, the material flow had distinctive evolutions, critical ratio being $d/D = 0.3$.

a) for $d/D \geq 0.3$, four stages can be distinguished in material flow as it is suggested by figure 6: flowing along the front head of the punch, upsetting of the material starting around the punch and finishing with full die contact, steady state extrusion, and ending of the extrusion.

Figure 4. The P/BE setup used in experimental tests.

Figure 5. Experimental specimens processed by P/BE.

Figure 6. Representative material flow for $d/D \geq 0.3$ ($d/D = 0.67$).
b) for d/D < 0.3, three stages can be distinguished in material flow as it is suggested by figure 7: flowing along the front head of the punch, steady state piercing, and ending of the piercing with a possible upsetting at the bottom of the workpiece (which becomes negligible when d/D ratio decreases).

![Figure 7. Representative material flow for d/D < 0.3 (d/D = 0.20).](image)

The material flow suggests different ways in changing material shape during deforming processes: with upsetting of the front of workpiece in extrusion and without it in piercing. The experimental results confirmed this hypothesis as can be seen in figure 5.

3.2. Validating of modeling
There are several methods to validate the modeling in simulating deforming processes. Fitting the predicted and experimental working-load is one of them. The level of the maximum load is most interesting from the viewpoint of the die and punch design. The results show that the peak load is reached prior to achieving the steady state and it is higher than the steady state load. This is a normal feature for a strain hardenable material [12]. Figure 8 shows the predicted and experimental load evolution for a middle scenario (i.e. d = 10 mm). The maximum level of working-load and the general evolution are in good agreement with experimental results, confirming the validity of modeling.

![Figure 8. Predicted and simulated working-load for a middle d/D ratio (0.33).](image)
3.3. Piercing vs. extrusion: critical d/D ratio

As shown in both simulated and experimental results (figure 9) the working-load increases with increasing d/D ratio because of higher reduction and friction.

Simulated loads are underestimated because of redundant shear deformation which leads to higher extrusion load. External constraint requires significant internal distortion of the workpiece beyond that strictly necessary for the shape change. This is widely accepted for many deforming processes and especially for drawing\textsuperscript{15}, flow forming\textsuperscript{16}, and extrusion\textsuperscript{3}. For d/D ≥ 0.3 (corresponding to d ≥ 10 mm) the yield pressure remains almost constant having just a slowly decreasing even if working-load increases. According to experimental and FEA results (see figures 5 and 6) this situation clearly corresponds to the extrusion when the material must first fill the container (by upsetting) and then the extrusion can take place. For d/D < 0.3 (corresponding to d < 10 mm), yield pressure suddenly increases with decreasing of d/D ratio even if working-load is getting lower because of smaller reduction. The situation corresponds to piercing without upsetting when the height of the workpiece remains almost unchanged (see figure 5).

The situations can be summarized as follows:
- for d/D ≥ 0.3, F\textsubscript{piercing} > F\textsubscript{upsetting}, extrusion takes place after a previous upsetting;
- for d/D < 0.3, F\textsubscript{piercing} < F\textsubscript{upsetting}, piercing takes place without an upsetting.

![Figure 9. Maximum working-load and yield pressure evolution a) simulation; b) experimental](image)

4. Conclusions

A comparative study between P and BE to separate them as distinctive operations was performed. To have a complete description of P and BE in terms of material flow, working-load and yield pressure as function of d/D ratio, experimental tests and numerical predictions were conducted. Tridimensional FEA confirmed by experiments for different process designs (i.e. different d/D ratios) revealed distinctive evolutions of the material flow establishing the effective limits of P and BE respectively and setting critical d/D ratio as 0.3. It was found that for d/D ≥ 0.3 extrusion takes place after a previous upsetting and for d/D < 0.3 the piercing is that which takes place but without an upsetting. Experimental and numerical results can be used in practice to provide estimates of working-load, critical yield pressure and tool dimensions for optimal P and BE in processing of cylindrical hollow parts.
References

[1] Chitkara N R and Aleem A 2001 Extrusion of axisymmetric tubes from hollow and solid circular billets: a generalized slab method of analysis and some experiments Int. J. Mech. Sci. 43(7) pp 1661-1684

[2] Chitkara N R and Aleem A 2001 Axisymmetric tube extrusion/piercing using die/mandrel combinations: some experiments and a generalized upper bound analysis Int. J. Mech. Sci. 43(7) pp 1685-1709

[3] Narayanasamy R, Ponalagusamy R, Venkatesan R and Srinivasan P 2006 An upper bound solution to extrusion of circular billet to circular shape through cosine dies Mater. Design 27(5) pp 411-4153

[4] Hsu T C and Huang C C 2003 The friction modeling of different tribological interfaces in extrusion process J. Mater. Process. Technol. 140(1-3) pp 49-53

[5] Flitta I and Sheppard T 2003 Nature of friction in extrusion process and its effect on material flow Int. J. Mater. Sci. Technol. 19 pp 837-843

[6] Bakhshi-Jooybari M 2004 A theoretical and experimental study of friction in metal forming by the use of the forward extrusion process J. Mater. Process. Technol. 125-126 pp 369-374

[7] Schikorra M, Donati L, Tomesani L and Kleiner M 2007 The role of friction in the extrusion of AA6060 aluminum alloy, process analysis and monitoring J. Mater. Process. Technol. 191 pp 288-292

[8] Yuan Li F, Liu S J G and He Z B 2008 Research of metal flow behavior during extrusion with active friction J. Mater. Eng. Perf. 17(1) pp 7-14

[9] Muller K B 2003 Indirect extrusion with active friction (ISA) Key Eng Mat. 223-226 pp 323-328

[10] Gordon W A, Van Tyne C J and Moon Y H 2012 Minimizing distortion during extrusions in adaptable dies Int. J. Mech. Sci. 62 pp 1–17

[11] Matsumoto R and Utsunomiya H 2013 Cold Piercing of cylindrical aluminum billet with counter punch pressure Key Eng Mat. 554-557 pp 613-619

[12] Figueiredo R B, Cetlin P R and Langdon T G 2009 The evolution of damage in perfect-plastic and strain hardening materials processed by equal-channel angular pressing Mater. Sci. Eng. A 518 pp 124–131

[13] Defom 3D v 10.0 2009 User’s manual Scientific Forming Technologies Corporation (USA)

[14] Chirita C, Comaneci R, Zaharia L and Hanganu A C 2007 Technological aspects concerning severe plastic deformation by equal channel angular pressing Annals of DAAAM Katalinic B (ed) pp 139-140

[15] Majzoob G H, Fereshteh Saniee F and Aghili A 2008 An investigation into the effect of redundant shear deformation in bar drawing J. Mater. Process. Technol. 201 pp 133–137

[16] Mohebbi M S and Akbarzadeh A 1010 Experimental study and FEM analysis of redundant strains in flow forming of tubes J. Mater. Process. Technol. 210 pp 389–395