INSTABLE MATERIALS FLOW IN EXTRUSION AND UPSETTING

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SUMMARY.

In spite of precisely controlled tooling the shape and dimensions of extruded cans sometimes vary considerably during production. As appeared from observations this phenomenon happens in all forming operations which include an upsetting process such as upsetting, heading, flattening, backward can extrusion etc.

Further, experiments brought up the evidence of an instable shift of the neutral point or plane in the flowfield of the material. A first analytical approach to the explanation of this phenomenon is given for plane strain conditions and a constant friction stress. As a relevant result it is found that, under certain conditions, an instable material flow is connected with imperfections in the lubrication and the geometry of the billet etc. Seeing that there is a direct relationship between instable material flow and quality defects of the products the necessity of understanding this phenomenon for a better control of forming operations is evident.
INTRODUCTION

This note deals with the phenomenon of instable material flow in metal forming operations which involve an upsetting process, such as upsetting and backward can extrusion. In order to discuss the principal backgrounds of flow instability some simplifications are made:
- plane strain,
- constant yield stress $\sigma_f$,
- constant friction $\tau = m \sigma_f / \sqrt{3}$.

Nevertheless, the conclusions from the analysis might be useful for better process control in production.

THE FRICTION CONCEPT

From practical experience the amount of friction between tool and billet appears to have an important effect on the stability of material flow in bulk forming operations. Some experiments have been carried out to establish the magnitude of friction in upsetting operations. The experiments showed that the constant friction law suits best for our aims. However, the shear stress $\tau$, and so the coefficient $m$, is not constant during the process. In Fig. 1 a representative graph of the coefficient $m$ is given, depending on the punch displacement $s$.

![Coefficient of friction m vs punch displacement s](image)

**Fig. 1.** The coefficient of friction $m$ in relation with the punch displacement $s$ in an upsetting process.

The upsetting process starts with a value zero of the friction shear stress. During a certain period it is approximately constant ($m \approx 0.2 \div 0.4$). After a critical increase of contact area $m$ increases steeply to a maximum value of 1.
INSTABILITY OF THE UPSETTING PROCESS

Analysis of the process by means of the slab-method results in the well-known "friction hill" expression for plane strain (fig. 2):

\[
\frac{\sigma_x}{\sigma_f} = \frac{1}{\sqrt{3}} m \frac{2x - b}{h} \quad (1)
\]

\[
\frac{\sigma_z}{\sigma_f} = -\frac{2}{\sqrt{3}} (1 + \frac{m}{2} \frac{b - 2x}{h}) \quad (x \geq 0)
\]

As a result of actual disturbances of the lubrication and therefore of the shear stress distribution, there will generally be a shift \( \Delta b \) of the neutral plane as a consequence of equilibrium (fig. 3).

So, for the distribution of the stress \( \sigma_x \), we obtain:

\[
\frac{\sigma_x}{\sigma_f} = -\frac{m}{\sqrt{3}} \frac{2x + b + 2\Delta b}{h} \quad (x \leq 0)
\]

\[
\frac{\sigma_x}{\sigma_f} = -\frac{m + \Delta m}{\sqrt{3}} \frac{b - 2\Delta b - 2x}{h} \quad (x \geq 0)
\]

Fig. 2. The plane strain (\( \varepsilon_y = 0 \)) upsetting test with the theoretical friction hill.

- \( b \) width of the sample,
- \( h \) current height,
- \( \tau \) shear stress in the contact zone between tool and billet.
The condition of equilibrium of forces in the neutral plane \((x = 0)\) leads to:

\[
(5) \quad \frac{\Delta b}{b} = \frac{1}{2} \frac{\Delta m}{2m + \Delta m}
\]

From an upperbound approach the same result is acquired.
Eq. (5) together with fig.1 demonstrates the instability of lubricated upsetting in the beginning of deformation. In this situation, with \( m = 0 \), we have:

\[
\frac{\Delta b}{b} = \frac{1}{2}
\]

This represents extremely instable material flow.

Fig. 4. Upsetting with a misalignment of the tooling.

\( \alpha \) misalignment,

\( h_m \) current height of the sample for \( x = -\Delta b \).

As another case we analyse the consequences of a tool misalignment \( \alpha \) (fig. 4). The stress distribution can be approached by:

\[
\frac{\sigma_x}{\sigma_f} = \frac{2}{\sqrt{3}} \left(1 + \frac{m}{\tan \alpha} + \frac{m}{2} \tan \alpha\right) \ln \frac{2h - b \tan \alpha}{2h} \quad (x \geq 0)
\]

\[
\frac{\sigma_x}{\sigma_f} = \frac{2}{\sqrt{3}} \left(1 - \frac{m}{\tan \alpha} - \frac{m}{2} \tan \alpha\right) \ln \frac{2h + b \tan \alpha}{2h} \quad (x \leq 0)
\]

with \( h = h_m - (x + \Delta b) \tan \alpha \) and \( m \geq \alpha \)

\( \sigma_f \) ultimate stress,
From this, for $\alpha << 1$, can be obtained:

$$\frac{\Delta b}{b} \approx \frac{1}{2} \frac{\alpha}{m}$$

Similar conclusions as before can be drawn. It is evident that the distribution of strain in upsetting and heading operations might be less uniform as generally is assumed. Many observations supporting this conclusion were made.

**BACKWARD CAN EXTRUSION**

As a first case we consider a situation with an error $\Delta a$ in the alignment of punch and die in the beginning of the process (fig. 5)

![Diagram of backward can extrusion with incorrect alignment](image)

**Fig. 5.** Backward can extrusion with incorrect alignment.
- $a \pm \Delta a$: wall thickness,
- $\Delta a$: misalignment,
- $\dot{u}$: punch velocity,
- $\dot{u}_w$: wall velocity,
- $h_o$: thickness of the billet.

Because of the misalignment $\Delta a$ there will be a difference in wall thickness. Moreover there will be a shift $\Delta b$ of the neutral plane which causes a non uniformity in the wall velocity $\dot{u}_w$. 
So the final height of the product will not be equal. In the ideal situation ($\Delta a = 0$) the displacement velocity of the wall is:

\[
(9) \quad \dot{u}_w = \frac{1}{2} \frac{\dot{b}}{a}
\]

Further the relative difference in velocity:

\[
(10) \quad \Delta \dot{u}_w = \frac{\dot{u}_{w+} - \dot{u}_{w-}}{\dot{u}_w}
\]

will be calculated.

In our upperbound approach the billet is divided in four zones: two corner zones and two bottom zones at the left and right hand side of the neutral plane. The velocities are:

\[
(11) \quad \dot{u}_x = \dot{u} \frac{x}{h_o}
\]

\[
(12) \quad \dot{u}_z = - \dot{u} \frac{z}{h_o}
\]

in the two bottom zones $-\left(\frac{b}{2} + \Delta b\right) \leq x \leq \left(\frac{b}{2} - \Delta b\right)$ and:

\[
(13) \quad \dot{u}_x = \dot{u} \frac{b/2 - \Delta b}{a - \Delta a} \cdot \frac{b/2 - \Delta b + a - \Delta a - x}{h_o}
\]

\[
(14) \quad \dot{u}_z = \dot{u} \frac{b/2 - \Delta b}{a - \Delta a} \cdot \frac{z}{h_o}
\]

for $\left(\frac{b}{2} - \Delta b\right) \leq x \leq \left(\frac{b}{2} - \Delta b + a - \Delta a\right)$

and:

\[
(15) \quad \dot{u}_x = \dot{u} \frac{b/2 + \Delta b}{a + \Delta a} \cdot \frac{b/2 + \Delta b + a + \Delta a - x}{h_o}
\]

\[
(16) \quad \dot{u}_z = \dot{u} \frac{b/2 + \Delta b}{a + \Delta a} \cdot \frac{z}{h_o}
\]

for $\left(\frac{b}{2} + \Delta b + a + \Delta a\right) \leq x \leq b/2 + \Delta b$

With these velocities the total amount of power, per unit of length, in the process is calculated:

\[
(17) \quad P = \sigma_f b \dot{u} \left[ 4 + m \frac{\dot{b}}{h_o} \left( 1 + \frac{4(\Delta b)}{b} \right) ^2 \right] \frac{h_o}{b} +
\]

\[
+ \frac{1 + m}{4} \frac{h_o}{a} \left( 1 - \frac{2\Delta b}{b} \right) \left( 1 + \Delta a/b \right) + \frac{m}{2} \frac{a}{h_o} \left( 1 + 2 \frac{\Delta a}{a} \frac{\Delta b}{b} \right)
\]

With:

\[
(18) \quad \frac{\partial P}{\partial \Delta b} = 0
\]
the shift of the neutral plane is found:

\[
\frac{\Delta b}{b} = \left(1 + \frac{1}{4m} \frac{h_o^2}{ab} \right) \frac{1}{a} \Delta a \quad \text{(for } \frac{\Delta a}{a} \ll 1) \]

From eq. (9), (10), (14) and (16) it can be derived, with \( z = h_o \),

\[
\Delta \tilde{u}_w = 4 \frac{\Delta b}{b} - 2 \frac{\Delta a}{a}
\]

and so with eq. (19):

\[
\Delta \tilde{u}_w = \left(1 + \frac{1}{m} \frac{h_o^2}{ab} \right) \frac{a}{b} - 2 \frac{\Delta a}{a}
\]

**Fig. 6.** The relative difference in wall velocity \( \Delta \tilde{u}_w \) (eq.21).
From fig. 6 it can be concluded that thin walled products from billets with a relative large thickness (\(h_o/b > 0.2\)) tend to instable material flow. Moreover a "good" lubrication promotes instable flow. fig. 7 shows the resulting shape by unequal wall velocity.

Fig. 7. Unsymmetrical shape due to instable material flow.

**THE STRESSES IN THE WALL**

After the first part of the wall has been formed a new situation arises. In a circular can a uniform wall velocity is going to be forced. So, in our model, we get:

\[
\Delta \dot{u}_w = 0
\]

and with eq. (20):

\[
\frac{\Delta b}{b} = \frac{1}{2} \frac{\Delta a}{a}
\]

As a consequence of this there will be introduced axial forces in the wall (\(F_w\) in fig. 8).
Fig. 8. Backward can extrusion by a misalignment \( \Delta a \) causing wallforces \( F_w \).

For a relatively small misalignment \( (\Delta a/a \ll 1) \) the stresses due to the wallforces \( (\sigma_{zw}) \) are established to:

\[
\frac{\sigma_{zw}}{\sigma_f} = \pm \frac{1}{\sqrt{3}} \left( -m \frac{b}{h} + \frac{h}{b} + \frac{m+1}{2} \left( \frac{h}{a} - \frac{a}{h} \right) + 2m \frac{h}{a} \right) \frac{\Delta a}{a}
\]

As can be seen from fig. 9 a stabilization of the process is apparently possible under certain conditions of friction and geometry. Besides that a change of sign of the wallstresses is suggested rather surprisingly for higher values of \( m \). In that case the wallstresses are reaching values up to the yieldstress of the material. And as a consequence buckling and fracture might be introduced. (fig. 10).
Fig. 9. The stresses in the wall $\sigma_{zw}$ (eq. 23).

Fig. 10. Extruded can, damaged due to misaligned tooling.
CONCLUSIONS

In a first plane strain approach of instable material flow in upsetting and extrusion it appears to be possible to explain the phenomenon. It is found that instabilities of the process are connected with imperfections in the lubrication, alignment of the tooling and billet geometry. Seeing the direct relationship between instable flow and quality defects of the product the better understanding of the phenomenon certainly contributes to a better control of forming operations.

REFERENCES

B. Avitzur; "Metal forming", M. Dekker (1980).