

## Strain, stresses and forces in blanking

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Auteurs: dr.ir. J.A.H. Ramaekers  
Prof.ir. J.A.G. Kals

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## STRAIN, STRESSES AND FORCES IN BLANKING

Dr.Ir. J.A.H. Ramaekers  
Prof.Ir. J.A.G. Kals

Laboratory for Forming Technology  
Eindhoven University of Technology  
Eindhoven, Netherlands

### SUMMARY

A Theoretical model describing the shearstresses and forces in blanking operation is presented. Deviations caused by friction, strain rate and fracture are discussed. A high degree of agreement between theory, experiments and practical experience is found.

### 1. INTRODUCTION

Engineering operations such as bar cropping, punching, blanking and trimming come under the heading of shearing processes[1]. With the exception of the isostatic component in the stress state, these processes can be described by the "simple shear" deformation model.

Shearing processes are widely used in metalworking. Much research, mostly with a directly practical aim, has already be done [1,2,4,6,12,13]. The present paper aims at a more theoretical approach to the shearing processes.

The actual strains in the shear zone are investigated with the aid of hardness measurements [7,9]. Assuming the validity of the simple shear model, a forth-path diagram and a formula relating the shear factor to the material properties are obtained.

Some technically important aspects of these forming operations cannot be explained by the simple theory alone. In fact compression and bending also play an important role. Geometrical factors, such as sheet thickness and clearance between punch and die, tool design (fine blanking) and the friction forces between tool and workpiece determine these secondary processes and thus the amount of isostatic stress in the shearzone. Crack initiation and therefore the dimension of the smooth-sheared zone, the back-pull force and the tool life are determined mainly by these factors.

## 2. THE PUNCHING OPERATION

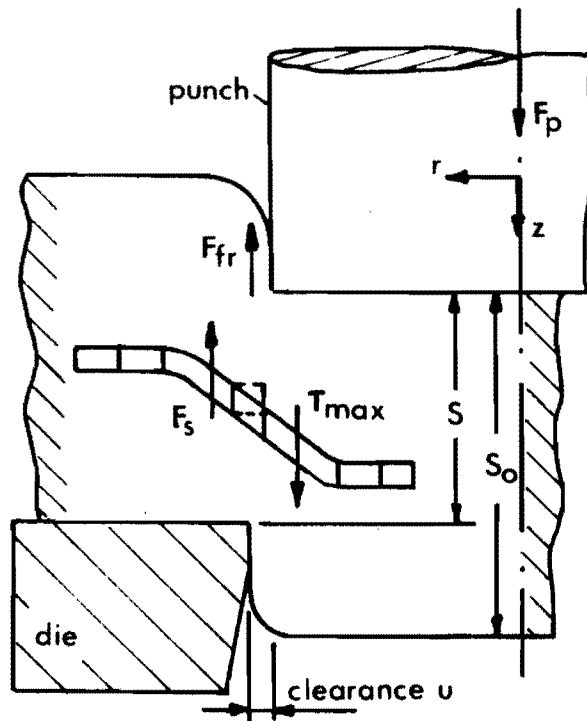


Fig. 2.1. The idealized model of the punching process.

First the description based on the simple shear model will be developed. Deviations caused by bending, compression and friction will be discussed later.

The maximum effective strain in the narrowest section,  $s$ , was determined by hardness measurements over the shear zone [7,9], giving

$$(2.1) \quad \bar{\epsilon}_s = \sqrt{\frac{3}{n}} \ln \frac{S_0}{s}$$

where  $n$  is the strain hardening coefficient in Ludwik's Law.

$$(2.2) \quad \sigma_F = C (\bar{\epsilon} + \epsilon_0)^n$$

with the maximum shear stress

$$(2.3) \quad \tau_{\max} = \frac{1}{\sqrt{3}} \sigma_F'$$

the equilibrium of forces on the slug gives

$$(2.4) \quad F_s = \frac{1}{\sqrt{3}} L s C \left( \frac{\sqrt{3}}{n} \ln \frac{s_0}{s} + \epsilon_0 \right)^n$$

where L is the length of the edge.

In a reduced form, with

$$(2.5.) \quad F^* = \frac{F}{L s_0 C}$$

Eq. (2.4) can be written as

$$(2.6) \quad F^*_s = \frac{1}{\sqrt{3}} \frac{s}{s_0} \left( \frac{\sqrt{3}}{n} \ln \frac{s_0}{s} + \epsilon_0 \right)^n.$$

Fig. 2.2 shows some theoretical and experimental results. The experimental data are given in Table 1.

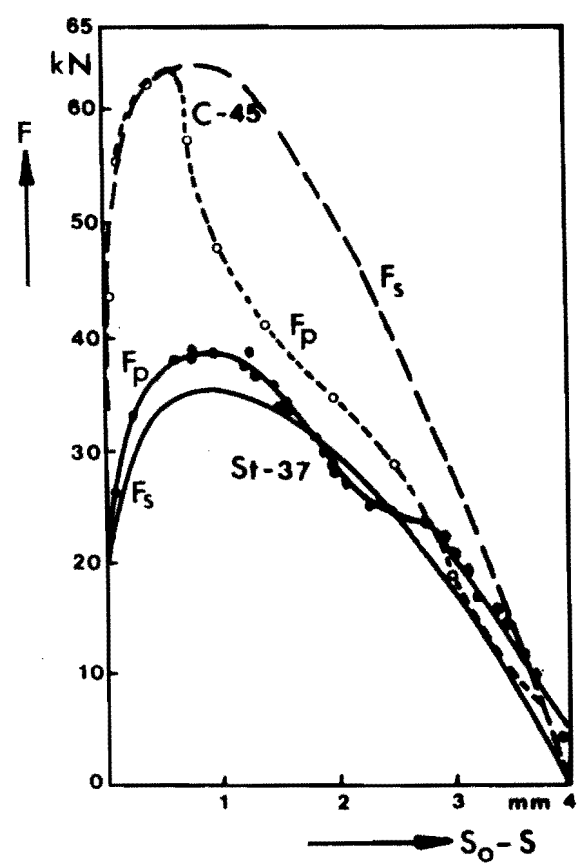


Fig. 2.2. Force-path curves of the punching process

### 3. THE MAXIMUM SHEAR FORCE

Differentiation of Eq. (2.6),  $dF^*/ds = 0$ , leads to the critical strain

$$(3.1) \quad \bar{\epsilon}_c = \sqrt{3n} - \epsilon_0$$

and the maximum force

$$(3.2) \quad F_{smax}^* = \frac{1}{\sqrt{3}} \left( \frac{n}{e} \sqrt{\frac{3}{n}} \right)^n \exp \left( \epsilon_0 \sqrt{\frac{n}{3}} \right).$$

For extremely cold-rolled sheet ( $\epsilon_0 \geq \sqrt{3n}$ ) the shear force reaches its maximum for  $s = s_0$ , so that

$$(3.3) \quad F_{smax}^* = \frac{1}{\sqrt{3}} \epsilon_0^n \quad (\epsilon_0 \geq \sqrt{3n})$$

Some results are shown in Fig. 3.1. The experiments of Krämer [8] were carried out on a fine-blanking device at low speed. The effect of strain rate and crack formation is eliminated in this way. On mechanical presses, speeds are such that an increase of five to ten percent in maximum force can be expected. From Fig. 3.1 it can be concluded that Eq. (3.2) nearly always provides reliable data for practical purposes.

material	C [ $\frac{N}{mm^2}$ ]	n [-]	$\epsilon_0$ [-]	d [mm]	$s_0$ [mm]	symbol	reference
st 37	680	0.26	0	10	4	o	[7]
C 45	1170	0.24	0	10	4	•	[7]
RVS 3.16 (stainl.st.)	1500	0.53	0.05	10	4	v	
C10	220	0.11	0	40	5	x	[8]
Ma8	190	0.22	0	40	5	Δ	[8]
Al 99.3	150	0.26	0	40	5	+	[8]

Table 1. The experimental data.

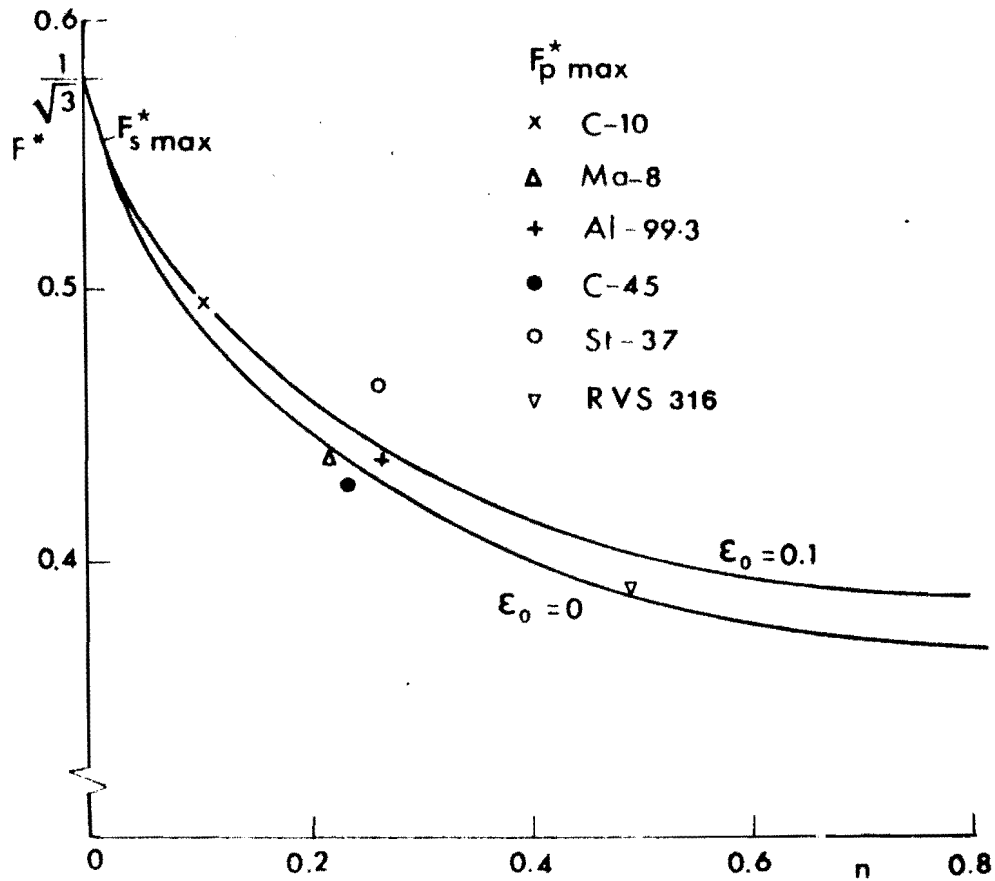


Fig. 3.1. The maximum force  $F_{p \max}^*$  in relation to the material properties  $n$ ,  $\epsilon_0$ .

#### 4. THE SHEAR FACTOR $s_f$

In practice commonly the relationship

$$(4.1) \quad F_{p \max} = L \cdot s_0 \cdot R_m \cdot s_f$$

is used to calculate the maximum force in blanking or punching.  $R_m$  is the ultimate tensile strength of the material and  $s_f$  the shear factor [1,2,6]. From Eq. (2.2)  $R_m$  can be derived as

$$(4.2) \quad R_m = C \left(\frac{n}{e}\right)^n \exp(\epsilon_0) \quad (\text{for } \epsilon_0 \leq n)$$

For cold-rolled sheetmetal with  $\epsilon_0 \geq n$  it yields

$$(4.3) \quad R_m = C \epsilon_0^n$$

Taking the maximum shear force equal to the maximum punch force it can be derived that

$$(4.4) \quad s_f = \frac{1}{\sqrt{3}} \left(\frac{\sqrt{3}}{n}\right)^n \exp\left(\epsilon_0\left(\frac{\sqrt{3}}{n} - 1\right)\right) \text{ for } \epsilon_0 \leq n$$

$$s_f = \frac{1}{\sqrt{3}} \left(\frac{\sqrt{3n}}{\epsilon_0}\right)^n \exp\left(\epsilon_0 \frac{\sqrt{3}}{n}\right) \text{ for } n \leq \epsilon_0 \leq \sqrt{3}n$$

and that  $s_f = \frac{1}{\sqrt{3}}$  for  $\epsilon_0 \geq \sqrt{3}n$ .

Fig. 4.1 shows the relation between the shear factor  $s_f$  and material properties  $n$  and  $\epsilon_0$ . The theoretical values show close agreement with the values commonly used in practice [1,2,6,12].

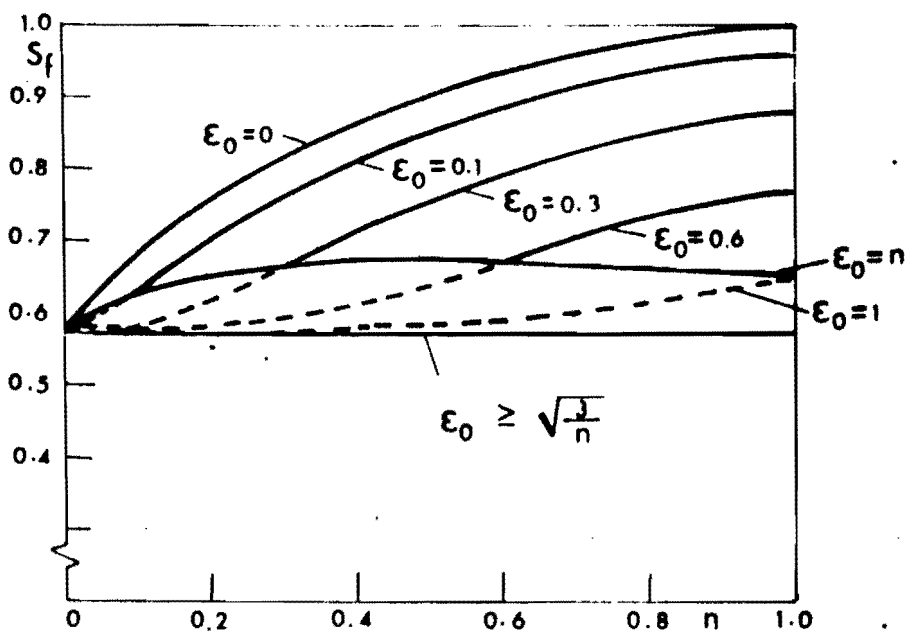


Fig. 4.1. The shear factor  $s_f$  in relation to material properties  $n$ ,  $\epsilon_0$ .

## 5. THE FRICTION FORCE

In the contact area between tool and workpiece the validity of the constant-friction model is assumed to be

$$(5.1) \quad \tau_{FR} = \frac{m}{\sqrt{3}} \sigma_F$$



From Eq. (2.1) the strain in the contact area can be written as a function of the z-coordinate (see Fig. 2.1), so that

$$(5.2) \quad \bar{\epsilon}(z) = \sqrt{\frac{3}{n}} \ln \frac{s_0}{s_0 - z} + \epsilon_0$$

Thus the friction force between punch and sheet becomes

$$(5.3) \quad F_{Frp} = \frac{m}{\sqrt{3}} L \cdot C \int_0^z \left( \sqrt{\frac{3}{n}} \ln \frac{s_0}{s_0 - z} + \epsilon_0 \right)^n dz$$

Calculations prove that sufficiently accurate results are obtained by neglecting the effect of the strain hardening. Taking  $n = 0$  this yields

$$(5.4) \quad F_{Frp}^* = \frac{m}{\sqrt{3}} \left( 1 - \frac{s}{s_0} \right)$$

The total punch force is then calculated as

$$(5.5) \quad F_p^* = F_s^* + \frac{2}{\sqrt{3}} m \left( 1 - \frac{s}{s_0} \right)$$

Table 2 gives the results of some calculations. In most cases the contribution of the friction to the maximum force is negligible compared with the maximum shear force.

## 6. THE BACK-PULL FORCE

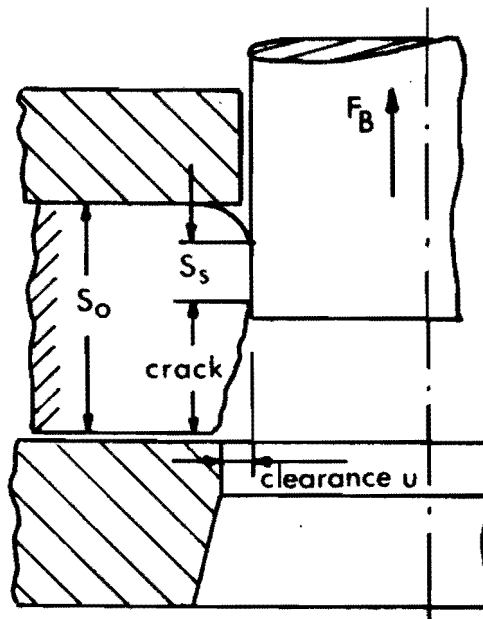


Fig. 6.1. The back-pull force  $F_B$ .

In addition to shearing, compression and bending also play a role in the punching process. These processes define the isostatic-stress component in the shear zone. In fine blanking, for example, the isostatic stress is such that no fracture occurs and a fully smooth-sheared cut is made, so that  $s_s = s_0$ . Normally the smooth-sheared length  $s_s$  is between thirty to fifty percent of the original sheet thickness  $s_0$ .

From Eq. (5.4) it can be concluded that

$$(6.1) \quad F_B^* = \frac{m}{\sqrt{3}} \frac{s_s}{s_0}$$

Experiments have been carried out to determine the connection between clearance  $u$ , smooth-sheared length  $s_s$  and back-pull force  $F_B$ . The results are given in Figs. 6.2, 6.3 and 6.4.

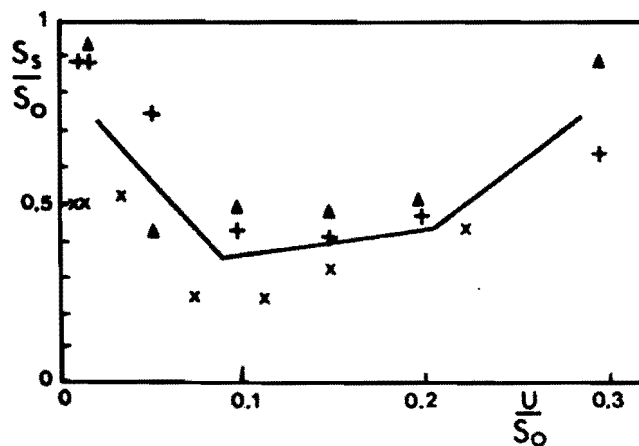


Fig. 6.2. The smooth-sheared length  $s_s$  in relation to the clearance  $u$ .

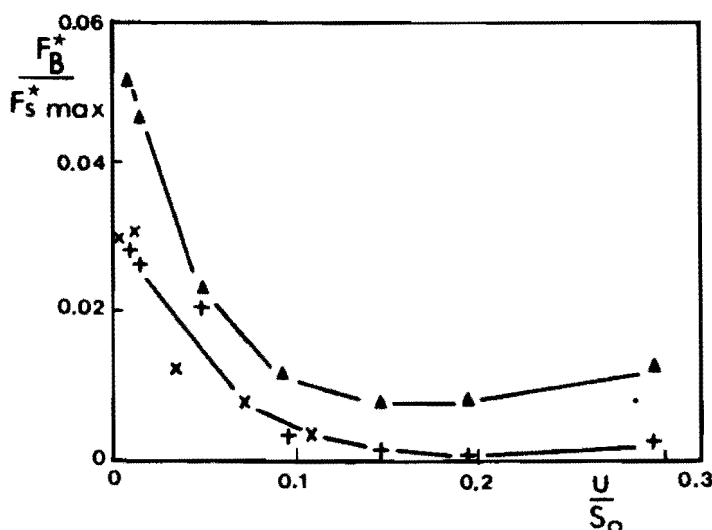


Fig. 6.3. The related back-pull force in relation to the clearance.

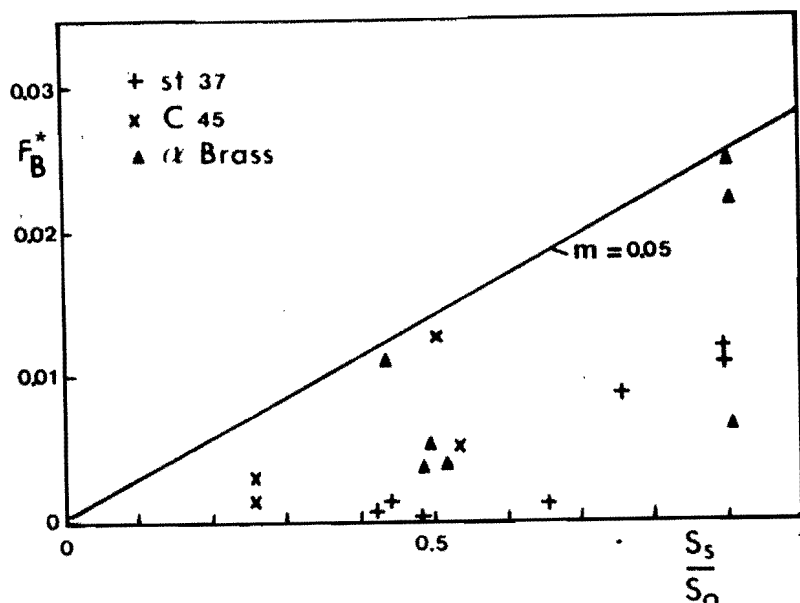


Fig. 6.4. The back-pull force  $F'_B$  in relation to the smooth-sheared length  $s_s$ .

The results of the experiments are partly in agreement with common practice. A clearance value of 10 to 15% of the sheet thickness is in fact good in view of the minimum value of the back-pull force. The commonly used value of the back-pull force ( $F_B = 0.1 F_p$ ) seems to be rather high, a much lower one being generally sufficient. The clearance value is also recommended by several authors, for instance U.P. Singh [11], with respect to tool life.

In practice the undesirable situation sometimes arises that the friction factor reaches higher values. The calculated results of some arbitrarily chosen examples are given in Tabel 2.

As can be seen from Table 2 a high friction factor directly influences the back-pull force, where the maximum punch force only increases noticeably for higher values of the strain-hardening exponent. As can be concluded from literature [13] punching of small holes, especially in austenitic stainless steel, sometimes causes trouble. In that case the choice of the correct tool material and proper lubrication are essential. In our own experiments, fracture of the punch already occurred after forty strokes.

$s_s/s_o = 0.5$ ; $\epsilon_o = 0$						
n	0.05		0.25		0.5	
m	0.05	0.5	0.55	0.5	0.05	0.5
$F_{max}^*$	0.52		0.43		0.3	
$F_{pmax}^*$	0.53	0.54	0.44	0.52	0.40	0.52
Rm/C	0.82		0.55		0.43	
Sf	0.64	0.66	0.80	0.94	0.93	1.22
$F_B^*$	0.014	0.144	0.014	0.144	0.014	0.144
$F_B^*/F_{pm}^*$	0.03	0.27	0.003	0.28	0.04	0.28

Table 2. Calculated values of arbitrarily chosen examples (Eqs. 3.2, 4.1, 4.2, 5.5, 6.1).

## 7. LUBRICATION

Experiments were carried out with copper sheet, with and without lubrication. Results are given in Figs. 7.1. and 7.2.

In explanation of the above, the following is assumed: Because the friction force suppresses the radial displacement of the sheet material near the shear zone, the isostatic stress increases. An increase of the isostatic stress causes an increase of the smooth-sheared length  $s_s$  and therefore of the back-pull force  $F_B$  [14].

The friction factor  $m$  is calculated from Eq. (6.1). Fig. 7.2. gives a representation of the results. It also clearly shows the effect of the lubricant on the freshly-cut surface.

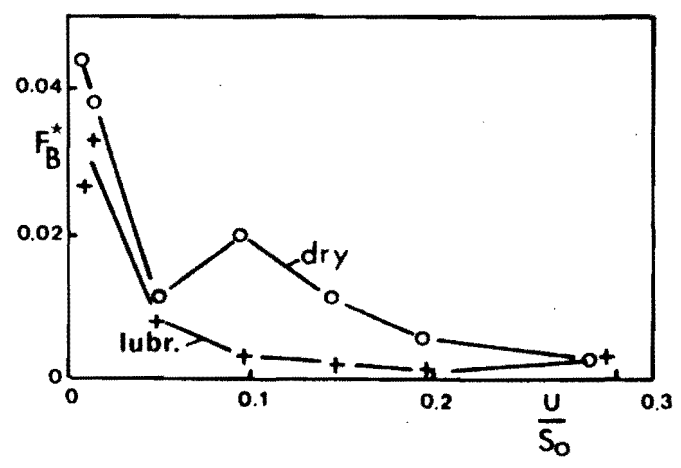
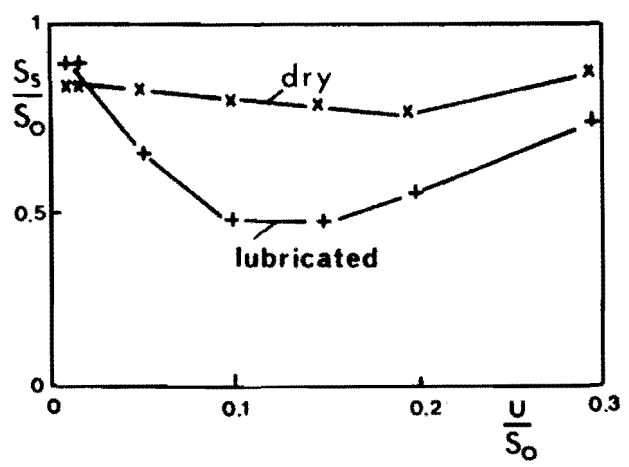


Fig. 7.1. Smooth-sheared length  $s_s$  and back-pull force in relation to the clearance.

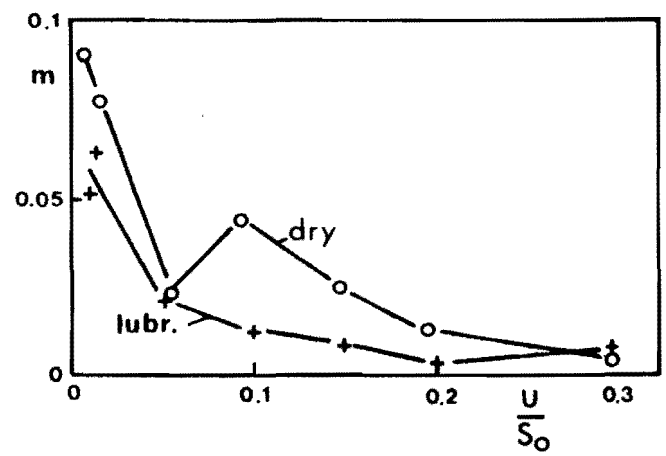


Fig. 7.2. The friction factor  $m$  in relation to the clearance  $u$ .

## 8. CONCLUSIONS

1. Formulas for the blanking force and the shear factor are derived by means of the simple shear deformation model.
2. When blanking on mechanical presses (c-frame press) the strain rates are such that an increase of 5 to 10% in the maximum force can be expected.
3. When punching relatively brittle materials - for example C-45 compared to St 37 - crack initiation can occur before the theoretical maximum shear force is reached. Some decrease in the maximum force, compared with the theoretical value, will therefore take place.
4. Friction forces normally have a minor influence on the punch force. A combination of a high value of the strain-hardening exponent and of the friction factor causes an increase in the maximum force of 30% or even more.
5. Back-pull forces normally are in the range of 5% of the punch force or even less. A high value of the friction factor causes an increase in the back-pull force up to 30% of the punch force. In combination with a high value of the characteristic stress  $C$  the backpullforce can reach such high values that the punch breaks. Austenitic stainless steels are particularly problematic in this respect.
6. The function of lubrication in punching is threefold:
  - . cooling of the tool,
  - . reduction of the isostatic stress, and the smooth sheared length,
  - . reduction of the friction of the freshly-cut surface.
7. A correct choice of the clearance, good lubrication and optimum tool design [11] is important with respect to tool life.

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